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Faculty of Mathematics and Physics
Astronomical Institute

HABILITATION THESIS

Petr Zasche

Eclipsing binaries as crucial objects

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1 Introduction

The role of stars in current astrophysical research is undisputable. The stars are the objects which were responsible for the most important astronomical discoveries during the last century. We learned about the thermonuclear reactions thanks to the stars. It were the stars, which helped us to understand the Sun and processes going on in our Solar system. Moreover, the stars were used for deriving the precise distances to the other galaxies and to calibrate a distance ladder in the close Universe.

The 20^{th} century learned us about the fact that most stars live in pairs or even higher order systems. These so-called binaries (or multiples) play a crucial role in our understanding of the Universe and its rules. The discovery of the very first double stars is a few centuries old. These stars were mostly a so-called visual doubles (i.e. two distant point sources on the sky, mostly separated a few arcseconds). However, since then the advancement of the detection technique brings us a new and fresh insight into the close doubles down to the level of a few mili-arcseconds (see chapter 3.1 below).

One specific type of binaries, so-called eclipsing binaries, provides us with a unique insight to the basic physical parameters of the stars. These can be used as distance indicators, reveal us their chemical composition, physical sizes and masses as well as about their evolution status, or the presence of another components or even the exoplanets in these systems (see chapter 4 below).

The observational sampling and problems with the ground-based telescopes were the most important limitations. However, nowadays this problem diminishes partly due to the large surveys and the satellite data. Their precision and time coverage is extraordinary. And in addition to that also the catalogues are often freely available for the public. All of these led to the unprecedented increase of known eclipsing binaries in the last decade (see chapter 4.2 below).

Therefore, one can ask whether a study of such an object like eclipsing binary can bring us some new information or new insight to the topic? Are these the front-end objects on the battlefield of current astrophysical research? We can definitely answer "yes", because we can study the long term evolution of the orbits, detect the dynamical effects, test the individual evolutionary models or the role of Kozai cycles in these systems, study the multiplicity in theories and modelling, ... (see chapter 5 below).

2 The role of eclipsing binaries

2.1 Multiplicity

Most of the stars in our Galaxy could be found as members of binary or multiple stellar systems, see e.g. Duchêne & Kraus (2013). Moreover, recent analysis of large set of close binaries (Pribulla & Rucinski 2006) indicates that even most of the binaries are parts of more complex multiple systems. According to this study about 59 ± 8 % of the northern-hemisphere contact binaries are members of the multiple stellar systems. The sample of binaries was analyzed very precisely, some distance-independent techniques were used, and the selection effects were also discussed. Besides that, a similar study on spectroscopic binaries by Tokovinin et al. (2006) revealed that 63 ± 5 % of such systems are parts of multiples. Hence, as one can see the stellar multiplicity in general is quite common phenomena among the stars. This also applies to the higher order multiples. Eggleton & Tokovinin (2008) published a study from which arises that also about 30 % of triples are in fact quadruples.

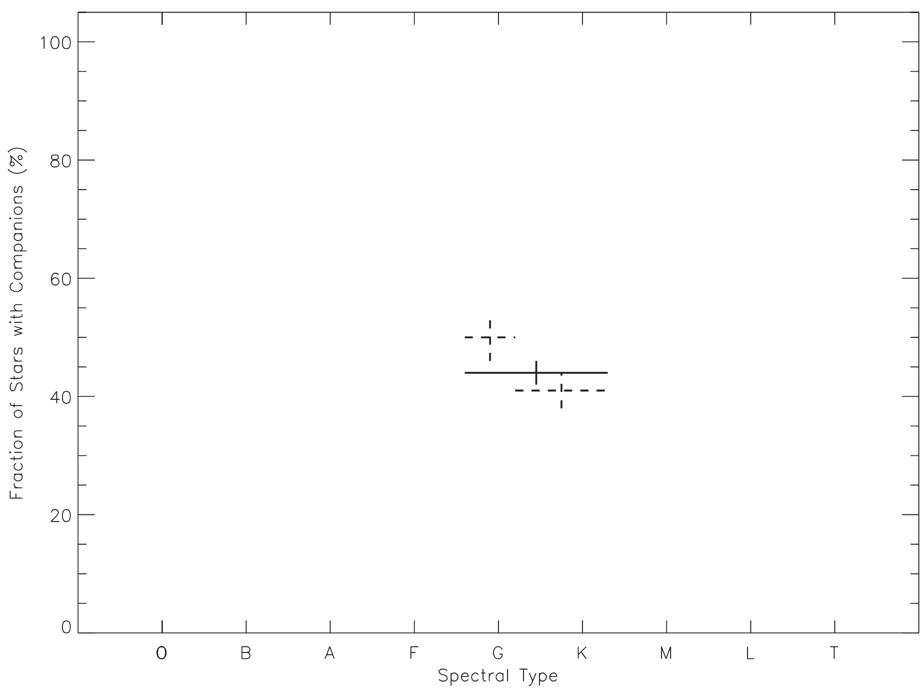

Figure 1: Multiplicity fraction of stars with respect to its spectral type (Raghavan et al. 2010).

Therefore, one can ask whether our Sun only an exception? There was found that the multiplicity fraction strongly depends on the spectral type, i.e. the higher the stellar mass, the higher the probability that it also has some companion. This finding is plotted in Fig. 1, taken from Raghavan et al. (2010).

2.2 Discovering the eclipsing binaries

All of these issues can be taken as very promising when looking for new eclipsing binaries. During the last few centuries there were discovered a few thousands eclipsing binaries (first one probably by a naked eye being an Algol itself - a "Demon Star"). However, the discovery of a new eclipsing binary was typically a pure coincidence when observing another close by target. It became quite a routine but also favorite task also for the amateur astronomers worldwide (several hundreds of new discoveries).

However, the main impact had the large surveys such as ASAS (Pojmanski 1997), SuperWASP (Pollacco et al. 2006), NSVS (Woźniak et al. 2004), or others. These photometric surveys observed the particular target once per couple of days or weeks typically. Therefore, the construction of the light curve of a binary has to be done using the data spanning over many orbital cycles. More focus on these databases is given below in section 4.1.

Much more efficient was the project KEPLER (Borucki et al. 2010). Its main advantage was the unprecedented accuracy of the photometry due to the fact that it observed from the space not influenced by the Earth's atmosphere. Moreover, the other important advantage of such survey was the fact that it observed the particular part of the sky almost continuously over a time period of several years. Hence, the selection effects were strongly weakened. We can assume that most of the eclipsing binaries in the Kepler field of view were detected down to the magnitude 15 but also with the periods up to 1-2 years. Such a completeness cannot be reached with the ground-based data.

Dealing with the eclipsing binaries and their discovery one needs to consider several limitations. At first, the problematic issue is typically the orbital period itself. Due to data sampling, daily aliases or meteo conditions the longer periods were only hardly reachable and the phase light curves only poorly covered (first selection effect). Another limitation is the depth of photometric eclipses. If the decrease is not adequately deep, we can only hardly detect such a binary. Many examples of only very shallow minima can be found in the Kepler database, which cannot easily be observed from the ground (second selection effect). Position on the sky also plays a role. In history most of the observations were carried out from the northern hemisphere, hence the number of eclipsing binaries on the southern sky was limited. And moreover, also the location of such a star in the very dense fields (milky way or clusters) is usually a serious complication (third selection effect).

In spite all of these facts, there are nowadays known about more than 100000 eclipsing binaries on the sky. The richest databases of eclipsing binaries come from the Catalina survey (Drake et al. 2014), and OGLE. From the most complete sample of stars in the Kepler field there arises that the fraction of eclipsing binaries is of about 1.4 % of the target stars.

2.3 Observations

Observations of eclipsing binaries are still mostly based on photometry and spectroscopy. Combination of these two techniques still represents the most accurate method how to derive the star's masses, diameters, temperatures, luminosities, or even the distance. Due to all these reasons the observations of eclipsing binaries still presents a non-negligible part of the observing time in world observatories.

However, the number of stars with good spectroscopy where we can derive the basic physical properties of both components is still rather limited. The strict accuracy limit of 2 % for the masses and radii meets only about 170 eclipsing systems (Southworth 2015). The most problematic is usually the long-term collecting of the spectra as well as photometry. Observing time on larger observatories is expensive and the time allocation commitees better prefer different up-to-date topics.

For the photometry the situation is a bit more promising. One needs only smaller telescope and the observing time is not so hard to obtain. Many automatic telescopes and surveys provide us with unique photometric data covering large time span with anyhow reduced accuracy. With a moderate-size telescope up to 0.5-meter one is able to obtain reliable photometry (with the error of the order of 0.01 mag) up to the 17-magnitude star. With a larger telescope of about 1.5-meter one can get a similar quality data for the stars up to the 20 magnitude.

2.4 Parameters

The physical parameters of both eclipsing components can lie in very wide range. The same apply for the orbital parameters for such a system. We know binaries with components from the high-mass end of the main sequence (e.g. a well-known naked-eye δ Orionis), as well as from the opposite low-mass end (e.g. CM Dra). And similarly also for the orbital periods, we have a system ϵ Aur with its orbital period of about 27 years, but also of about 43 minutes only for NSVS 6024870.

As was mentioned above, the crucial role of eclipsing binaries in current astrophysical research yields from the fact that a combination of photometry together with the spectroscopy can be used for deriving the basic physical and orbital parameters of such system. How it works? The radial velocities RV_i as derived from the spectra are directly connected with the orbital parameters via a well-known relation

$$RV_i = \gamma + K_{3-i}(\cos(\omega_1 + \nu(t)) + e\cos\omega_1),$$

where γ, K_i, e, and ω are the parameters of the orbit. From this equation and using the Kepler's law there arises that a semimajor axis can be computed from:

$$a_j \sin i = \frac{P}{2\pi} K_j \sqrt{1-e^2},$$

where the most problematic limitation is the inclination angle i. And here at this point the lucky orientation of eclipsing binaries (i.e. close to the 90°) comes into its crucial role.

Having the powerful tools being able to construct a model of eclipsing binary (such as the PHOEBE (Prša & Zwitter 2005) , Binary Maker (Bradstreet 2005), Fotel (Hadrava 2004), or others) one can also get the physical parameters of the components as well as of the orbit. Hence, the masses, radii, luminosities, $\log g$, or the periods, eccentricities, or even the mutual inclinations for the multiples can be derived only via using the photometry together with the spectroscopy of particular eclipsing binary. Using all these parameters one can also derive its distance independently of other techniques. Such a method is nowadays routinely used even for the brightest sources outside of our Galaxy, for eclipsing binaries in M31 see e.g. (Ribas et al. 2005), or in M33 see (Bonanos et al. 2006). For the sample of eclipsing binaries known nowadays in the field of galaxy M31 see Fig. 2.

2.5 The role of multiplicity

As was already mentioned earlier in section 2.1, many eclipsing binaries are parts of the more complex systems of triples, quadruples, or even higher order multiples. Also from our studies there resulted that the quadruples or even quintuples are nothing rare in our Galaxy. If Eggleton & Tokovinin (2008) mentioned that of about 30 % of triples of their sample are in fact quadruples, from our published paper (Zasche et al. 2009) and its updates there arises that of about 36 % of our sample of triples are multiples of higher order.

However, one can ask whether any such statistics is adequately independent of selection effects. What if the eclipsing binaries are preferably found in multiple systems? Could there be some connection between the two orbits and their orientation, ratios of periods, etc. ? Some hints of answers for these still open questions of current stellar astrophysics can be found e.g. in Goodwin et al. (2007), Tokovinin (2007), and Kroupa (2009).

There arises that almost all stars were form in multiple systems. However, the N-body dynamics causes expelling the least massive member of the system and makes the remnant more stable. If we call the inner strongly gravitationally bounded system the "hard" and the outer only weakly bounded system the "soft", then we can also mention a so-called Heggie-Hills law that states that "hard binaries get harder while soft binaries get softer" (Goodwin et al. 2007). The dynamical stability criterion sets relatively strict limits to the ratio of the inner and outer periods, i.e. for the circular orbits

$$P_{out}/P_{in} \leq 4.7.$$

And finally, the Kozai cycles with tidal friction (Eggleton & Kisseleva-Eggleton 2006) is a likely mechanism producing the short period inner subsystems of many observed multiples.

However, there are still some obvious discrepancies between the models and the observations. The field stars seem to contain too many quadruples and quintuples, which the numerical modelling is not able to predict. And also the discrepancy between the empirical and theoretical stability criterion remains a mystery (Tokovinin 2008b). Nevertheless, the study of eclipsing binaries as parts of the multiple systems can help us solving some of these problems.

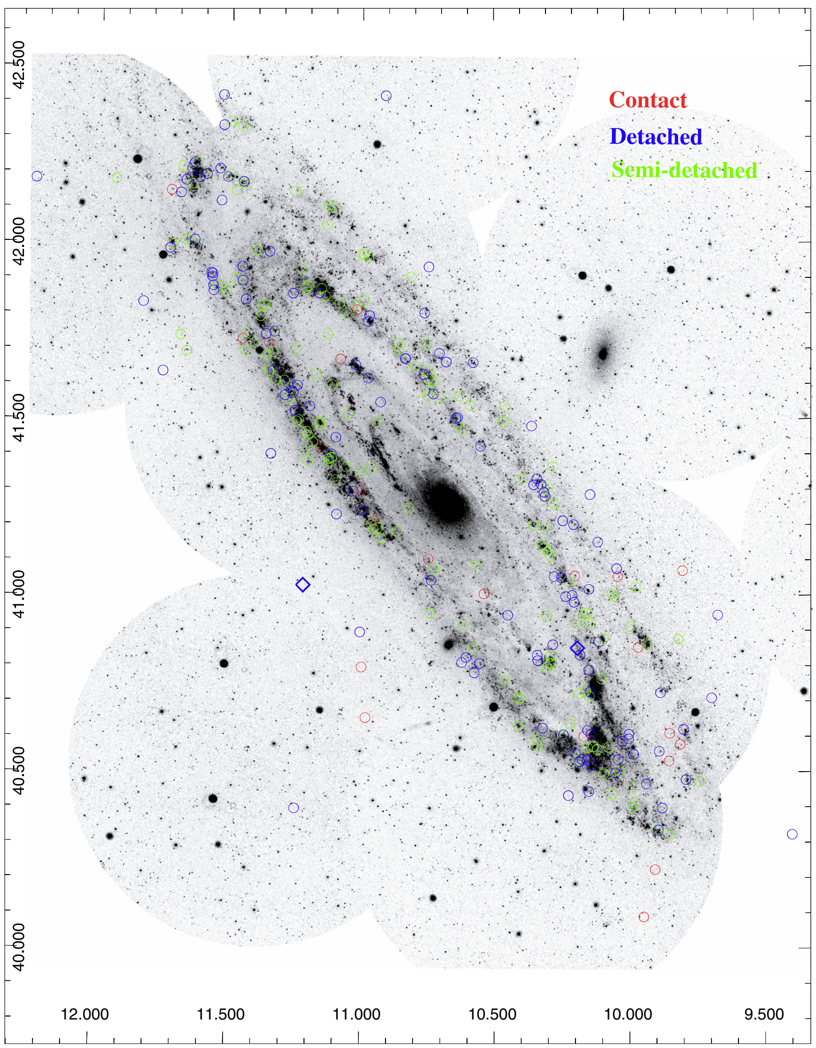

Figure 2: The eclipsing binaries in the galaxy M31 (Lee et al. 2014).

3 Combining the visual orbit and the period changes

3.1 Visual doubles

As was mentioned earlier in section 1, the visual double stars are the oldest binaries known. With its more than three-hundred-years history we can harvest a huge collection of old observations when estimating also rather long orbital periods. Now The Washington Double Star Catalog (WDS, Mason et al. 2001)[1] contains more than 1 000 000 observations of more than 120 000 visual binaries. The catalogue of orbits of visual binary stars[2] now contains more than 2500 orbits.

Thanks to the modern technique such as adaptive optics or interferometry one can get a reasonable results even down to the angular separation of mili-arcseconds. On the other hand, the most limiting factor now seems to be the magnitude. One issue is the magnitude of the source (only bright enough targets can be used due to high level of light needed for these techniques), but also the magnitude difference between the two stars. Most of the new observations are nowadays available only for the pairs with magnitude differences lower than 5 or 6 magnitudes (Tokovinin et al. 2015). The fainter companions are very hard to detect. All of these limitations plays a significant role and constrain some selection effects.

One can ask how many visual doubles comprise the eclipsing binary as one of its components? Are these objects rare, or do we know hundreds of them? There exists a special subset of eclipsing binaries, where both its eclipsing components were resolved and the eclipsing double became a visual double in fact (e.g. β Aur). However, how many visual doubles contain the eclipsing binary as one (unresolved) component? We compiled a catalogue of eclipsing-visual doubles (with more than three astrometric measurements) and found only about 340 such systems. I.e. this number is about 5 times lower than predicted from the number of visual doubles and the occurrence rate of the eclipsing binaries.

3.2 Period changes

On the other hand, the eclipsing binaries profited from the large photometric surveys covering the whole sky and the long-lasting photometric monitoring. Nowadays the observation of particular eclipsing binary presents usually quite a simple task, also for the non-professional astronomers using the smaller telescopes. Thanks to this availability of observing time and quite a minimal effort, the number of minima observations (i.e. only very small part of the light curve near the eclipses) for the eclipsing binaries grows rapidly during the last decade(s). An example of such a database is for instance the "O-C gateway"[3](Paschke & Brát 2006).

The eclipsing binary can serve as a ideal stopwatch for deriving the orbital motion of the eclipsing pair around a common barycenter in a multiple system. A similar method was in fact firstly used to derive the finite speed of light by Ole Rømer observing the Jupiter's moons eclipses. This method was modified for the use in eclipsing binary research, see e.g. Irwin (1959) and Mayer (1990). The time delay $\Delta\tau$ of time of minimum for a particular binary with respect to its linear ephemerides then resulted in

$$\Delta\tau = \frac{A}{\sqrt{1-e^2\cos^2\omega_{12}}} \cdot \left[\frac{1-e^2}{1+e\cos\nu} \sin(\nu+\omega_{12}) + e\sin\omega_{12} \right],$$

where A, e, and ω_{12} are the parameters of the third body orbit.

The longer the time span covered with the minima observations, the longer periods can be detected (up to a few decades or even centuries). On the other hand, the shorter periods are usually problematic to detect due to the physical and instrumental limitations. The shorter the

[1] http://ad.usno.navy.mil/wds/
[2] http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/orb6
[3] http://var.astro.cz/ocgate/

third body period, the lower its amplitude and hence also worse detectability. Nevertheless, also quite short periods can be found with rather large amplitudes because the third body is dominating and is very massive. Here comes the second limitation, because if the third component dominates the system (not only its mass, but also its luminosity), then the depths of eclipses are only very shallow, so the observations are more difficult (and the precision is worse).

3.3 Combination

In our paper (Zasche & Wolf 2007) (see the attached publication in section 7) we introduced a method how to combine the two above-mentioned methods together: the visual orbit and the period changes into one joint approach. It is not an easy task, and we know only several suitable systems for such an analysis nowadays. It is an alternative and independent method, whose main advantage is that it needs no spectroscopy on the long orbit and one is able to derive some basic physical parameters of the orbiting bodies and their relative orbit.

For its use one needs to choose only such systems, where we have the third body orbit covered with the astrometric observations (at least its significant part) as well as the period changes of the inner eclipsing pair. From the time delays as introduced above in equation in section 3.2 there can be computed a so-called mass function of the third body $f(m_3)$, which can be used to derive the mass of the third body. And the masses of the individual components are connected with their semimajor axes via a system's distance (see Zasche & Wolf (2007) for details).

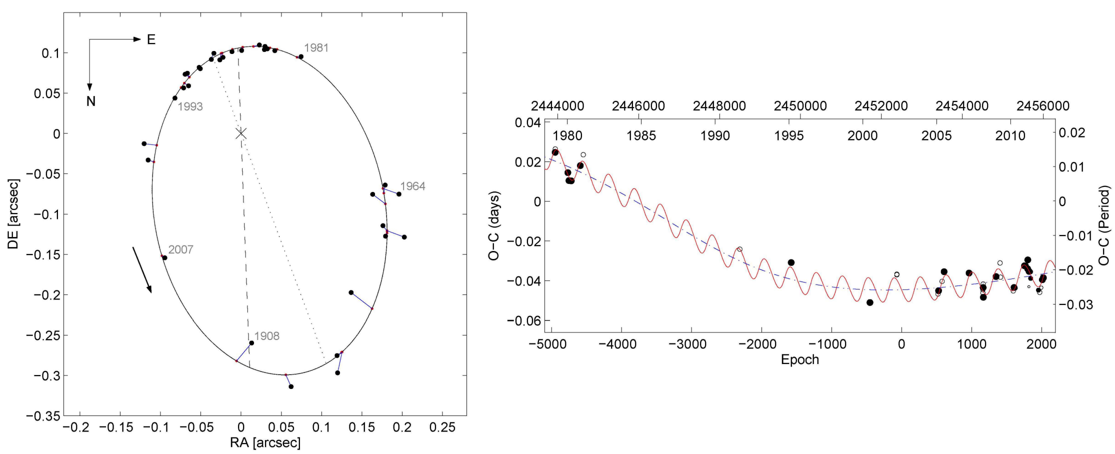

Figure 3: The plots of DN UMa as resulted from our analysis, the left figure for the orbit of the visual pair, the right one for the period changes of the inner eclipsing binary. (Zasche et al. 2012c)

The most problematic issue was found the selection process itself. There were found only a few suitable systems for such an analysis. In total, the number of visual doubles with known orbits (and which contain an eclipsing binary as one of its components) is of about 30 only. From this number only about 14 systems also show detectable period variation of times of minima of the inner eclipsing pair. All of these selection criteria were discussed when constructing a catalog of visual-eclipsing multiple systems published in Zasche et al. (2009)[4] (see the attached publication below).

This combined approach was used for several systems, whose studies were published in different publications: the studies of KR Com (Zasche & Uhlář 2010), V2083 Cyg (Zasche et al. 2012b), DN UMa (Zasche et al. 2012c), V819 Her, V2388 Oph, and V1031 Ori (Zasche et al. 2014a) – all of them are attached below in section 7. From these stars definitely the most interesting seems to

[4]For the up-to-date version of the catalogue, see http://sirrah.troja.mff.cuni.cz/∼zasche/Catalog.html

be the system DN UMa, which we found is a rare sextuple one. The 1.73-days eclipsing binary is orbiting around a barycenter with the third component on a 641-days orbit, while all these three bodies are revolving around a barycenter on a visual orbit with a period of about 118 years. We plot the orbit of the visual pair together with the period changes of the eclipsing inner pair in Fig. 3.

3.4 Limitations of the method

We have to mention also several limitations of the introduced technique. Some of them were already given above (the magnitude limits for the interferometric detection), but some others are also important. As one can see from the catalogue of eclipsing-visual systems, all of the multiples suitable for this method are bright targets (magnitude < 10), all of them have rather short orbital periods of the eclipsing pair (below 10 days), as well as relatively short orbital periods of the visual orbits. However, all these limitations are purely selection effects (e.g. longer periods are harder to cover with data).

Another limitation comes from the fact that only these stars with low magnitude difference between the components are resolved via interferometry. This yields the selection effect of the third components to be rather similar to the components of the eclipsing pair. The catalogue of eclipsing-visual pairs (Zasche et al. 2009) is full of such examples.

And moreover, also most of the suitable systems for such an analysis are relatively close (maximum a few hundreds of parsecs from the Sun). This also comes from the fact that only bright stars should be used, as well as from the need of resolving the system into a double.

Another kind of limitation comes from the inclination angle between the orbits and also the plane of the sky. If the orbits are perpendicular to each other, no period variation should be visible for the eclipsing pair. On the other hand, if the visual orbit is face on and both orbits are coplanar, we can see no eclipses. One can ask whether there is some preference for the mutual inclinations between both orbits. It would give us some clue of origin of the system (Zakirov 2008). However, the number of such systems with both orbits and their mutual inclination known is still only very limited.

3.5 Distance estimation

However, one important consequence this method has on the distance derivation. It can also serve as an independent distance estimation for the binaries where both methods (visual orbit as well as period changes) are adequately well covered with data points.

We used this method for deriving the distance to DN UMa (Zasche et al. 2012c) as well as for KR Com (Zasche & Uhlář 2010), V819 Her, and V2388 Oph (Zasche et al. 2014a). For all these systems the new value of distance as derived from our method presents the values comparable with the previous data, sometimes even much more precise than the Hipparcos (van Leeuwen 2007) published values.

4 Mining the databases

Another approach for the eclipsing binary research nowadays is the use of huge databases of photometric observations from the automatic or semiautomatic surveys. Some of these surveys were already mentioned above in section 2.2, however many others exist and their impact on current astrophysics is undisputable. As was already mentioned, most of the currently known eclipsing binaries come from these databases.

With a huge number of data points for each target there arises a problem with the reduction and the data pipelines used for these surveys. Sometimes the algorithms produce rather doubtful results, sometimes on the contrary the detection was not done.

4.1 In our Galaxy

From this reason we decided to use some of the surveys for our own analysis. At first, we used the photometric data from the OMC camera onboard the INTEGRAL satellite (Mas-Hesse et al. 2004) of selected Algol-type binaries. Such observations were analysed and the light curve fits were presented for these systems, which were never been analysed before (see Zasche 2010, and Zasche 2011). A sample of such fits is presented in Fig. 4. Here the selection process was rather straightforward: only those systems with the largest dataset from the OMC was chosen for such systems, which are of Algol type and were not studied before. The most interesting result from our analysis of 77 such systems is that in more than 42 % of them a significant level of the third light was detected. Such a result implies that a large fraction of multiples among the binaries in

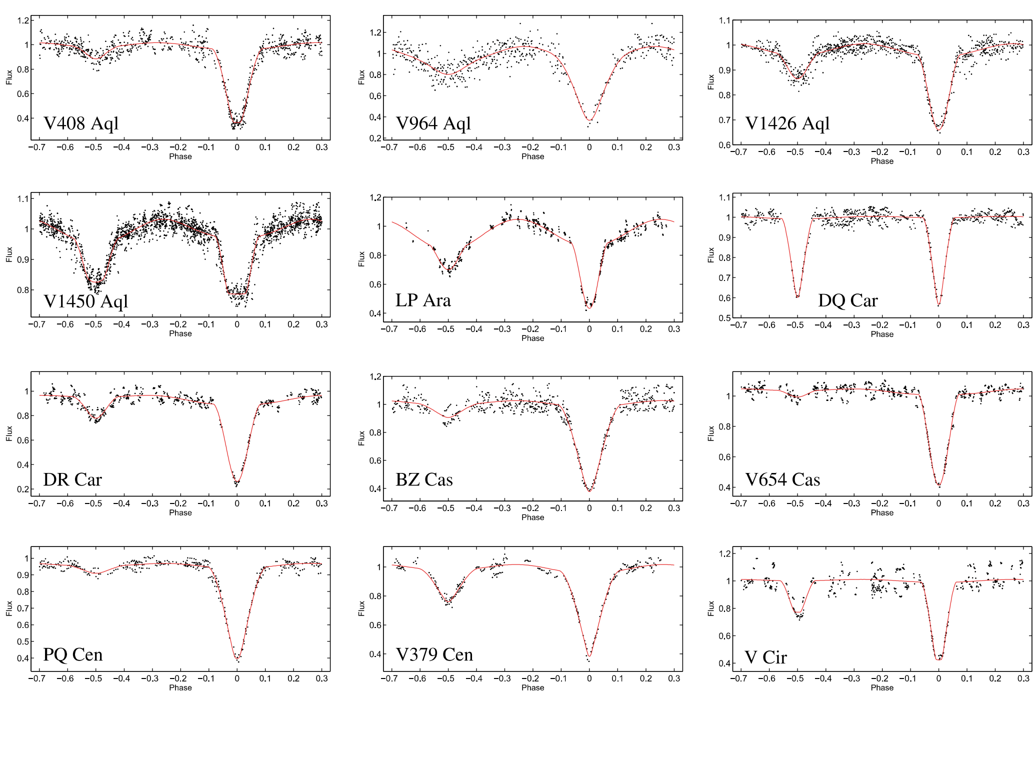

Figure 4: Sample of analysed light curves from the OMC data. (Zasche 2010)

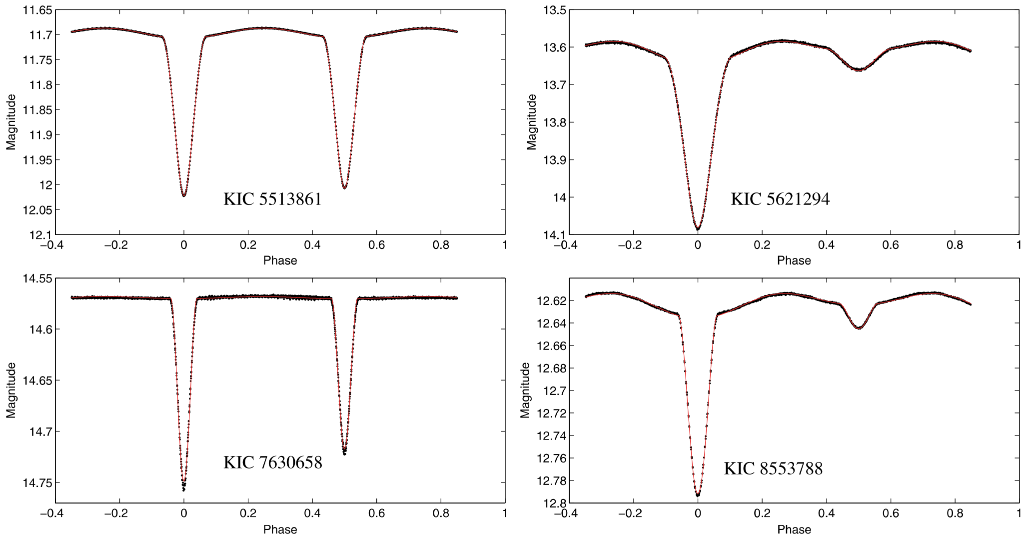

Figure 5: Sample of the light curve fits using the Kepler data. (Zasche et al. 2015a)

stellar population is in agreement with the previous studies, e.g. Duchêne & Kraus (2013).

However, a similar approach can be used also for some other surveys and projects and other groups of stars or variables. We also performed a "data mining" in databases from the SuperWASP project (Pollacco et al. 2006), ASAS (Pojmanski 1997), or Pi Of The Sky (Burd et al. 2005) to collect all available photometry for two low mass binaries GK Boo and AE For. For these two systems there were detected some period changes due to probable third distant components, see Zasche et al. (2012a). Such a result is also important due to the fact that only very low fraction of the low-mass binaries contain the third components (Duchêne & Kraus 2013). A similar study analysing the period changes for seven other eclipsing binaries was published, where we collected the photometry from different sources, discovering the third bodies in these systems with the orbital periods from 7 to 70 years (Zasche et al. 2014b).

The same approach of collecting the photometry from different sources was applied for our study of apsidal motion. At first, two eccentric systems V456 Oph and V490 Cyg were studied via an apsidal motion analysis (Zasche & Wolf 2011). Collecting the observations from the photometric surveys such as OMC, ASAS, or Pi Of The Sky and our new data we found out that these two systems are the ones with the shortest periods among the apsidal motion systems with the main sequence components. A similar study of 13 apsidal motion binaries using mainly the ASAS data was published elsewhere (Zasche 2012), with the resulting apsidal periods of several decades.

However, nowadays in the era of huge surveys and satellite data producing the ultra-precise observations continuously, one cannot even think of using such an old-fashioned approach of manually deriving the minima times and doing this kind of period analysis. This especially applies for the future satellite missions such as GAIA (de Bruijne 2012). Hence, we used the data from the satellite KEPLER (Borucki et al. 2010) as a testing example. There were found more than 2000 new eclipsing binaries in the field of Kepler satellite (Slawson et al. 2011) observed almost continuously during its 4-yr mission. Therefore, for ten selected eclipsing binaries we derived their times of eclipses automatically. Our new method of automatic minima derivation was using the light curve template as derived from the PHOEBE program. The new code fitted the observations with this template only by shifting the template in both axes. We found this method very fruitful for huge databases, which is the case for the Kepler data. Our approach was even better, because it uses better light curve fits (due to incorporating some new parameters) than the originally published

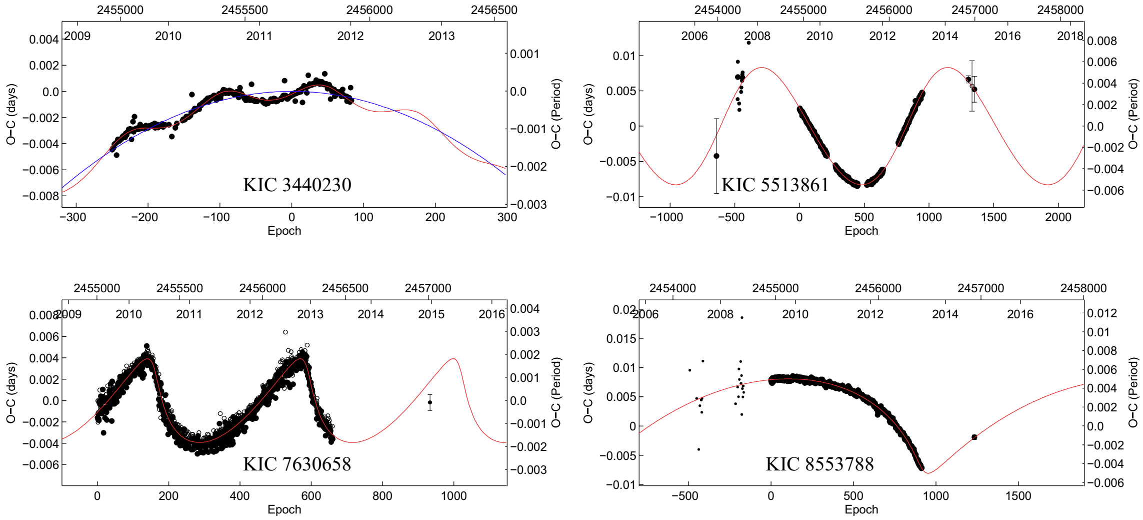

Figure 6: Plots with the period analysis based on the Kepler data for the selected binaries with potential third bodies. (Zasche et al. 2015a)

ones by the Kepler team (Slawson et al. 2011). With such data we carried out the period analysis of these ten eclipsing systems (and deriving more than 9000 times of minima) revealing the third body modulation in them, sometimes with surprisingly short orbital periods down to 1 yr (Zasche et al. 2015a). It should indicate that some dynamical effects can play a role in these systems on the timescale of decades only (see section 5 below).

4.2 Outside of our Galaxy

Similar large photometric surveys exist also for the stars out of our Galaxy. In the last two decades there were extensive monitoring programmes focused on both Magellanic clouds. These were especially the MACHO, OGLE II, and OGLE III projects. From these surveys there were also discovered many thousands of new eclipsing variable stars: see Faccioli et al. (2007) for the MACHO, Wyrzykowski et al. (2003) for OGLE II, and Graczyk et al. (2011) for OGLE III catalogues in the LMC.

Due to so large number of records in these databases, there were also discovered many new interesting variables. Therefore, we tried to identify some new eccentric eclipsing systems, where an analysis was still missing. We used the OGLE photometry for the light curve fitting, together with the OGLE II, III and MACHO photometry for the minima times derivation. These were used for the period analysis and the apsidal motion fitting. For several systems also the ESO spectra exist, and these were used to derive the radial velocities and to obtain masses and radii in absolute units. We applied such an approach for several systems, and published a study of five LMC eclipsing systems (Zasche & Wolf 2013a). There resulted that for these B-type stars the apsidal motion periods are of the order of decades, while the eccentricities are below 0.25. We also tried to plot all the known systemic velocities of eclipsing binaries located in the LMC and trying to identify a common motion how the LMC galaxy rotates. However, this was not successful at all because it is an irregular type of galaxy with no obvious rotation, but the plot of these radial velocities is included in Fig. 8. Another noteworthy result was the discovery of one potential triple system.

A similar study was also carried out for eighteen binaries located in the Small Magellanic Cloud

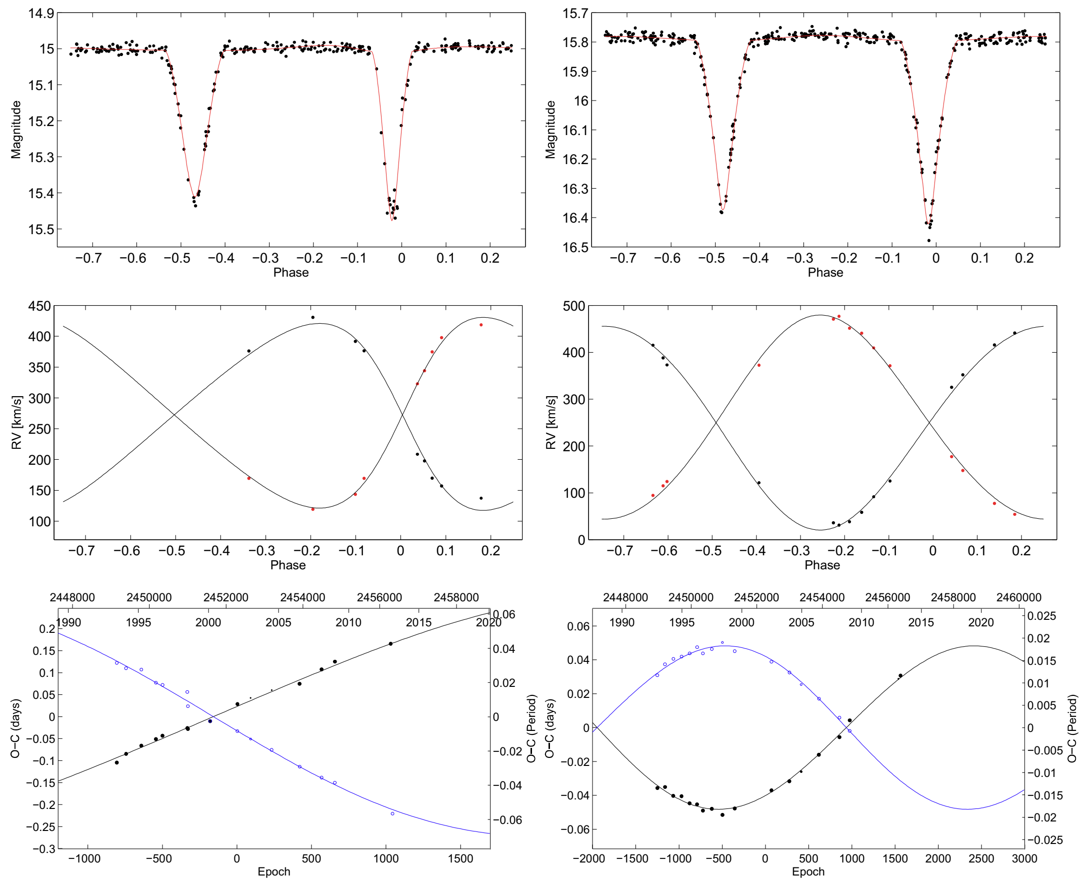

Figure 7: Fits for two eclipsing binaries located in the LMC, the left ones for MACHO 81.8881.47, the right ones for MACHO 79.5377.76. The top plots present the light curves, the middle ones are the radial velocity curves, while the bottom ones present the apsidal motion fits in the $O-C$ diagrams (Zasche & Wolf 2013a).

(SMC), published here: Zasche et al. (2014c). A similar approach as for the paper about five LMC systems was used here, finding out that the apsidal motion periods lie in between 19 and 142 years. Quite remarkable was also a discovery of one system with a probable third-body modulation of the minima times. What also should be mentioned is the inclusion of the description of a method how to proceed semiautomatically in such huge databases like OGLE. We presented a method how to derive the minima times for a period analysis with only very small effort using the light curve template as derived from the PHOEBE program. This method was then used for these eighteen eclipsing binaries from the SMC and we found out that such a method is adequately precise for the use here.

And finally our last paper on this topic was quite recent publication of thirteen LMC eccentric eclipsing systems (Zasche et al. 2015b). For all these B-type stars we derived their apsidal motion parameters as well as the light curve solutions, revealing that the apsidal periods are from 21 to 107 years. Moreover, for one system the third-body hypothesis (with its period of 22 yr) was presented and for another one also the spectra were analysed.

Generally, we can say that these huge surveys like OGLE and MACHO are very suitable for a similar kind of analysis, revealing that there exist many new interesting systems also out of our Galaxy. A typical example about potential of such surveys should be e.g. the comparison between the minimal apsidal motion periods for the main sequence stars in and outside of our Galaxy. The

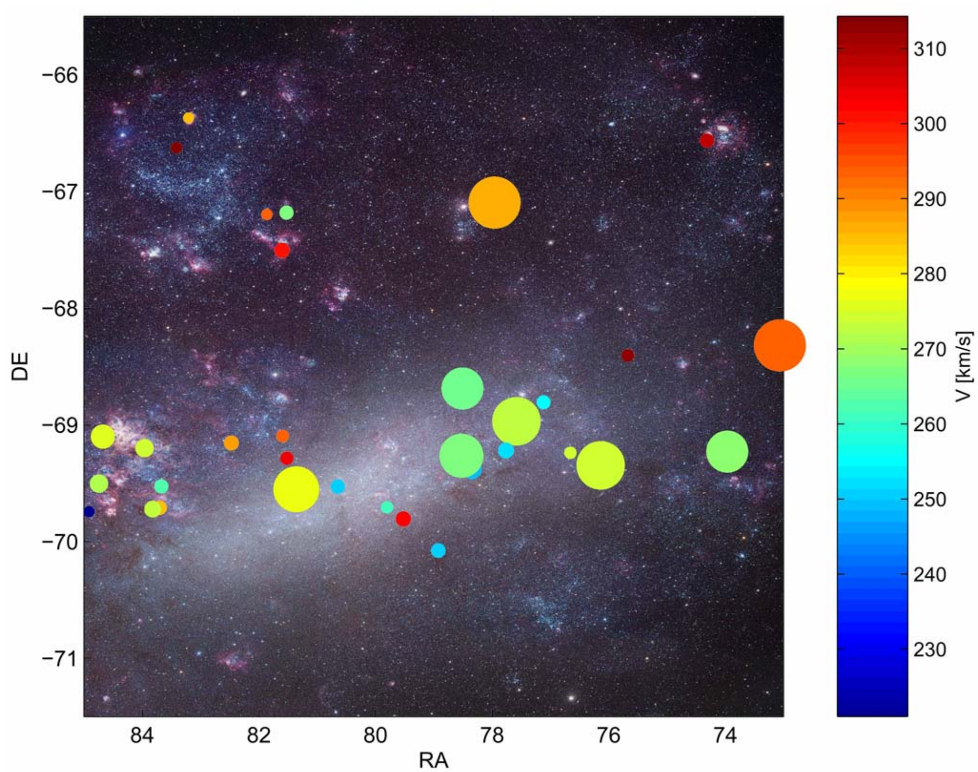

Figure 8: Position and systemic velocities of the eclipsing binaries located in the LMC and its vicinity. The larger the symbol, the higher the precision. (Zasche & Wolf 2013a)

shortest apsidal motion period in our Galaxy was detected for V490 Cyg with its 18.8 yr (Zasche & Wolf 2011), while the 7.6-yr period was detected for a SMC binary (North et al. 2010), and even more recently 7.1-yr binary exists in the SMC (Hong et al. 2015).

However, we have to be careful when interpreting the results of these surveys. They represent a small fraction of binaries and suffer from various selection effects. For example for the OGLE and MACHO surveys covering the Magellanic clouds - all of the binaries are definitely very luminous ones, hence mostly of early spectral type. For an early system, the probability of finding another component is much higher than for the late type one (Duchêne & Kraus 2013). Such an effect has to be taken into account when studying the statistical properties of the sample of stars discovered by these surveys.

5 Dynamical effects

Detecting so many triple and quadruple stars in the stellar population, one has to ask whether and how these bodies interact with each other, what is the dynamics of the systems and if we are able to detect also some dynamical interaction between these bodies. During the 20^{th} century there were discovered several eclipsing binaries, which show the change of their inclination angle as seen from the Earth. For the eclipsing binary such a slow precession of the orbit is easily detectable due to changing eclipse depth observed during different epochs. Such an effect has the easiest explanation via a three-body dynamics and the influence of the third component to the eclipsing pair. Its theory was presented e.g. in Söderhjelm (1975) for the case of Algol and λ Tauri systems. From this theory there results that the precession is more rapid if the third component has shorter orbital period and is closer to the eclipsing pair. On the other hand, there still exists a lower limit of period p_3 for the system to be stable, see section 2.5 above.

The equation of the nodal period from Söderhjelm (1975) can be written as:

$$P_{\rm nodal} = \frac{4}{3}\left(1+\frac{M_1+M_2}{M_3}\right)\frac{P_3^2}{P}(1-e_3^2)^{3/2}\left(\frac{C}{G_2}\cos j\right)^{-1},$$

where subscripts 1 and 2 stand for the two components of the eclipsing binary, while 3 stands for the third body. The term G_2 stands for the angular momentum of the wide orbit, and the C is the total angular momentum of the system. Typically the most problematic is the unknown value of the inclination of the wide orbit j.

Until a decade ago, there were known only about ten systems with the changing inclination angle, and for only three of them their nodal periods were known (see e.g. Zasche & Paschke 2012). This situation changed rapidly thanks to the OGLE and Kepler projects. These surveys discovered a few dozens of such interesting systems. Graczyk et al. (2011) called these stars "Transient Eclipsing Binaries (TEB)" because these are in general only binaries with rapid orbital precession but for some limited period of time also become eclipsing. The advantage of long-lasting photometric surveys is the fact that these systems are being monitored over many orbital cycles, hence the inclination change is sometimes visible even by a naked eye (see Fig. 9). Besides the 17

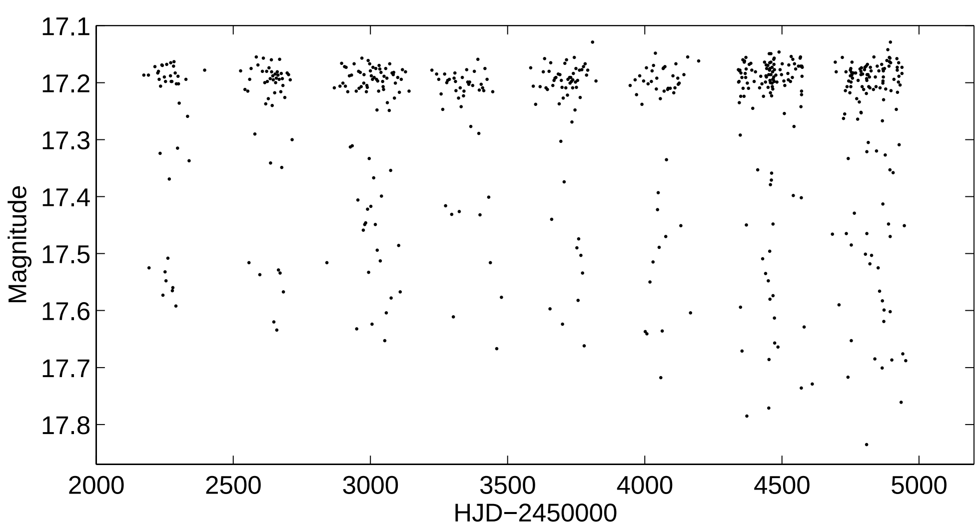

Figure 9: An example of suspicious eclipsing system with changing inclination discovered from the OGLE data. The increasing eclipse depth with respect to time is easily visible even by a naked eye (Graczyk et al. 2011).

such systems presented by Graczyk et al. (2011) we discovered also several others in the OGLE data and we continue monitoring of them nowadays.

However, the precession of the orbital plane of the eclipsing binary is not the only effect which can be detected via photometric monitoring. For example Rappaport et al. (2013) published a list of the triple-star candidates among the binaries observed by the KEPLER satellite and found there many other interesting objects. All of them show period changes due to the orbital motion around a common barycenter with the third component, some have eccentric orbits, and some show also the variable eclipse depths. For some more complicated systems, also much more complex variations in the minima timings were detected, see e.g. Borkovits et al. (2015b). For the most prominent cases there were also discovered the tertiary eclipses, which are in agreement with the predicted motion of the eclipsing pair from the period variation, see Conroy et al. (2014).

Generally we can say that such dynamical effects should be present in all triple systems in principle (the only exception should be the case of strictly co-planar orbits). However, the process of precession is usually too slow and the nodal periods are too long to be easily detected with the photometric data covering only a century.

5.1 HS Hya

Our first contribution to the topic of precessing eclipsing binaries was the study of classical and relatively bright system HS Hydrae (Zasche & Paschke 2012). The star is of about 8 magnitude bright and was discovered in 1960's. This star was studied several times on the basis of photometry and spectroscopy, Gyldenkerne et al. (1975), Popper (1971), and Torres et al. (1997). The only connection with the inclination change was the discovery of the third component of M0 type orbiting around the binary with a period of 190 days from radial velocities. Therefore, it is quite remarkable that nobody noticed its remarkable behavior and changing the inclination angle.

We collected all available photometry since 1960's and carried out a detailed analysis of the light curves from the ground as well as from the Hipparcos (van Leeuwen 2007) satellite. There was clearly shown that the inclination is changing quite rapidly (of about 15° during 47 years). Hence, we also decided to fit a model to the obtained data. For the inclination change we used a method presented by Drechsel et al. (1994):

$$\cos i = \cos I \cdot \cos i_1 - \sin I \cdot \sin i_1 \cdot \cos(2\pi(t - t_0)/P_{\rm nodal}),$$

where i is the inclination of the eclipsing binary, I is the inclination of the invariant plane against the observer's celestial plane, and i_1 is the inclination between the invariant plane and the orbital plane of the eclipsing binary.

Using this approach we derived the nodal period for HS Hya to be more than 600 years. However, only very small fraction of this period is covered with data, hence its uncertainty is rather large. Nowadays the system is almost non-eclipsing. Noteworthy is also the fact that the third component causing the orbital precession of the eclipsing pair is so small in comparison with both eclipsing stars (it represents only about 16% of the total mass of the system). Hence, its detection with other means is quite problematic.

Another remarkable consequence is the fact that the system was studied in detail spectroscopically by Torres et al. (1997) but using the older photometry and an assumption of constant inclination. Combining these data into one joint solution they found out e.g. the masses with a superb precision better than 0.01 $M_\odot$. However, the time gap of about 20 years between photometry and spectroscopy yields an inclination change of about 8°, which led to the difference between their predicted and true masses up to 0.06 $M_\odot$.

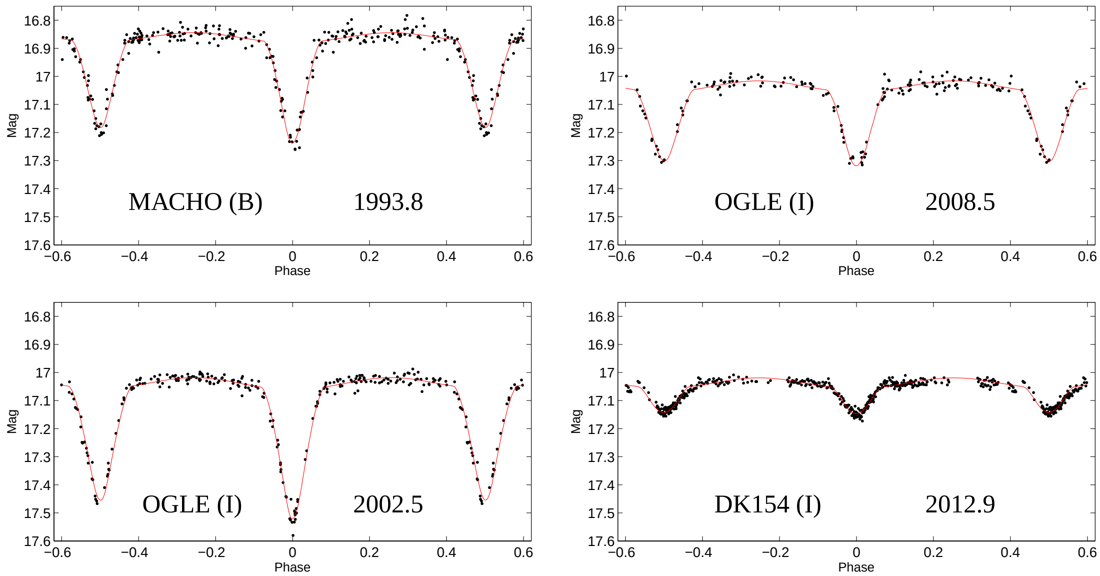

Figure 10: The light curves of MACHO 82.8043.171 as obtained during different epochs. (Zasche & Wolf 2013b)

5.2 MACHO 82.8043.171

Second published paper about the binary precession was the analysis of eclipsing binary out of our Galaxy, the system MACHO 82.8043.171 located in the Large Magellanic Cloud. This was for the very first time, when a study about orbital precession in eclipsing binary out of our Galaxy was published.

The star MACHO 82.8043.171 was discovered as a potential candidate for orbital precession by Graczyk et al. (2011) together with 16 other similar cases. It is a detached eclipsing binary of Algol type, having the orbital period of about 1.2565 days. We have chosen this one star due to its relatively short orbital period, detached configuration and relatively deep eclipses on the OGLE data. The other 16 systems are now also being monitored during our campaign.

For the detailed analysis we collected all available photometry for this system from the surveys MACHO and OGLE. We also observed the star with 1.54-meter telescope located at the La Silla observatory in Chile during the season 2012/13. All these data were analysed resulting in final light curve parameters and the fits revealed rather rapid inclination change (Zasche & Wolf 2013b). As one can see, the inclination has changed significantly during its 20 years of observations. Applying the same method as above for the system HS Hya there resulted that the period of the nodal precession is of about 77 years only. The results are shown in Figures 10 and 11. With such a short period this system is still nowadays the second fastest among known systems with precessing inclination angle (the only one more rapid is V907 Sco, Lacy et al. 1999).

We also tried to present some constraints on the perturbing star, but we lack of enough reliable information and detailed spectroscopy. This component is probably a low mass star orbiting around a common barycenter with the period from 6 to 15 days. Concerning that the two eclipsing components are rather similar to each other (having the type of about B2), the third component is of much later spectral type and having also much less mass. Hence, a spectroscopic confirmation should be possible only by using precise high-dispersion and high-S/N data from some of the ESO telescopes. Another method is to observe the star photometrically but with very high cadence and precision, which is quite problematic due to its brightness and also the fact that the photometric eclipses will stop as late as in 2017. Since that time only very mild ellipsoidal variations with an amplitude of about 0.03 magnitude in maximum will remain.

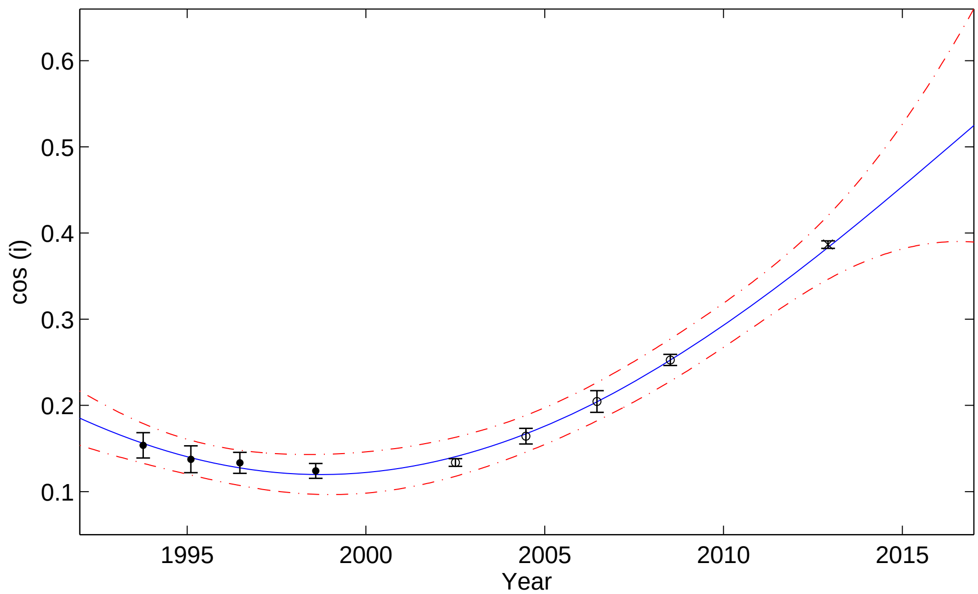

Figure 11: Inclination change of MACHO 82.8043.171 together with the fit. (Zasche & Wolf 2013b)

5.3 Quadruple system V994 Her

Definitely the most interesting multiple system under our study during the last years was the quadruple V994 Her. This was the very first system showing two sets of eclipses. Its nature was correctly identified as double eclipsing behaviour by Lee et al. (2008). In their study they found out that the quadruple consists of two detached eccentric eclipsing binaries located in one system. Both systems contain rather early type components (B and A stars) and their orbital periods are 2.08 and 1.42 days. The star was observed by several authors and the photometry of V994 Her is available since the Hipparcos satellite. However, since Lee et al. presented that the system is probably a quadruple one, they cannot prove that the two eclipsing pairs really orbit around each other.

We were aware of this handicap of their study, therefore we started to collect the photometry of V994 Her as early as in 2010. Due to limited time when the target can be observed from the Czech Republic we were able to collect data every year only during eight months in maximum. Due to the weather conditions and other limitations we collected only limited number of observations every year. With this data set we tried to perform an analysis of the period changes, which resulted in our study published in Zasche & Uhlář (2013). Quite unique method as presented in the study comes easily from the fact that if both the pairs are orbiting around each other, we should detect the times of eclipses of one pair behave in opposite to the other one. It means that when pair A is getting closer (and the minima times occur earlier), the pair B has to get farther (i.e. the minima are being delayed).

There resulted that the system is really quadruple (in fact quintuple together with the third distant component) and the two eclipsing binaries are gravitationally bounded with each other. Their mutual orbit has the period of about 6.3 yr and relatively high eccentricity of about 0.75. Moreover, both eclipsing pairs also show slow apsidal motion.

From this analysis we are even able to compute some other parameters of the relative orbit otherwise unreachable. This comes from the fact that using the individual masses as published by Lee et al. (2008) we can use our orbital solution to derive also the mutual inclination of the orbits. Using our computed values of parameters this angle resulted in about 37°. Such a result was quite surprising because one should expect that if both eclipsing pairs are almost perpendicular to the celestial plane, their relative orbit also should be.

However, this is a typical situation of observational limitations. In the Fig.12 we show the plots of the $O - C$ diagrams as presented in our study Zasche & Uhlář (2013). In these figures there are also shown the grey areas with lacking observations. Unfortunately, these epochs without any observations are located exactly in between the two periastron passages even for both eclipsing pairs A and B. Therefore, we continued our photometric observations also after the publication and thanks to the new data we found out that the whole picture of the system is a bit different.

In the next Fig.13 we plot the new updated $O - C$ diagrams for V994 Her with a new fit with its approximately half period and as one can see, the fit is much better. The χ^2 value resulted in about 1/3 of the original one. Moreover, some other implications of this result also differ a lot from the older solution. For example the mutual inclination of the orbits resulted in 0°, which means that the orbits are coplanar with each other. Such a configuration is much more probable one. The eccentricity of the orbit remained almost the same, being of about 0.75 and the orbital period is of about 2.9 yr. Also the predicted angular separation of the components resulted in different value of about 18 mas (instead of the original value of 28 mas).

As a by product of our analysis there also resulted that the masses of all components as derived

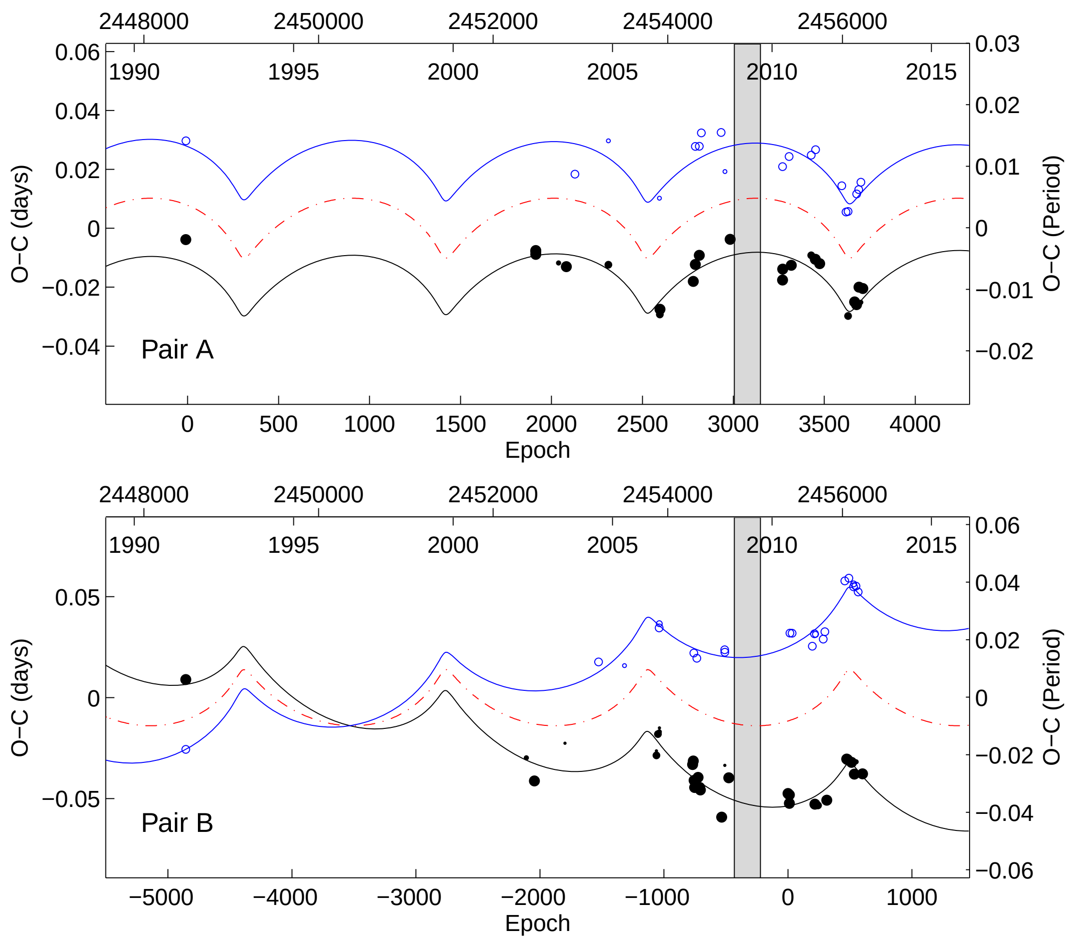

Figure 12: The $O - C$ diagrams for the system V994 Her as published in Zasche & Uhlář (2013). The grey areas show the time intervals without any data, located exactly in between the two periastron passages.

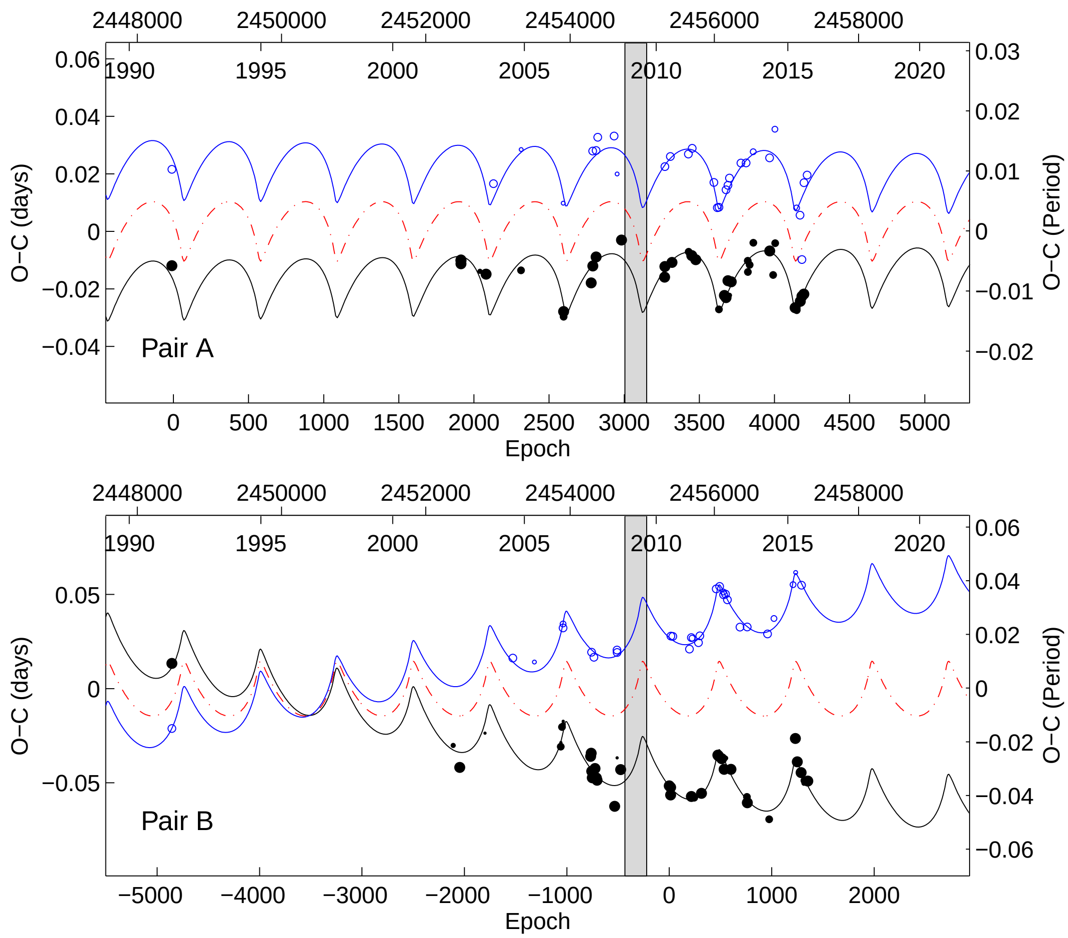

Figure 13: The new $O - C$ diagrams for the system V994 Her (unpublished yet). The grey areas show the same time interval as in the previous figure.

by Lee et al. (2008) are underestimated. The calculation of the masses of both pairs is using the fact that a so-called mass function of the third body can be computed using the orbital parameters, and moreover also the inclinations of the orbits are close to the 90°, i.e.

$$\frac{m_A \cdot A_A}{\sin i_A} = \frac{m_B \cdot A_B}{\sin i_B} \Longrightarrow m_A \cdot A_A \approx m_B \cdot A_B \doteq 0.0735,$$

where the masses of pairs are denoted as m_A, and m_B (in Solar masses), respectively and the amplitudes of the period variations in the $O - C$ diagrams for both pairs are labelled as A_A and A_B (in days). The correct values of masses are of about 1 $M_\odot$ higher for the components of pair A, while of about 0.5 $M_\odot$ higher for the stars orbiting in pair B than originally published by Lee et al. (2008). Such a result of deriving masses of components only on the basis of photometry is something unique in stellar astrophysics.

One can also ask, whether it is possible to detect some orbital precession when the two orbits are exactly coplanar and whether we can see a mutual eclipses of all components in the future. The orbits definitely precess in the space, however its movement is probably very slow. Only a dedicated spectroscopic, photometric, and interferometric monitoring is able to answer this question.

6 Conclusion and future prospects

In this thesis I tried to show how interesting objects the eclipsing binaries are and what also should be studied in them. Not only quite traditional modelling of the light and radial velocity curves, even in complex multiple systems with four or five components. But also studying the period changes, in combination with interferometry. Moreover, the precession of the eclipsing binary orbit can also be detected with quite modest technique.

One can ask why such multiple systems with the eclipsing components are so important. Is their role somehow crucial for our understanding of the Universe, evolution of the Galaxy and the stars, or the formation and stability of the planetary systems? Or is it just a remnant of the century-long intensive monitoring and studying history of the eclipsing binary research?

The usefulness of the eclipsing binary study was presented elsewhere (e.g. Guinan & Engle 2006). The eclipsing binaries were also the objects used for the statistical investigation of the triple and quadruple systems by Tokovinin (2008a), who (besides other results) concluded that the fragmentation and the orbit migration is the most promising scenario of the origin of multiple systems. The Kozai cycles and the tidal friction can effectively be studied in the case of the eclipsing binary in the multiple system. The deposition of the angular momentum when the two components are migrating closer is easily implemented via the third distant component. And the observations of the eclipsing binary over a longer time interval is a relatively easy task. We do not know yet, why we observe so many systems where the eclipsing pair is orbiting with so short orbital period and the third component is so distant. However, the Kozai mechanism seems to be one of the most likely explanations. Quite recently an evidence on this statement was published by Borkovits et al. (2015a) on the basis of detailed analysis of eclipsing binaries located in the Kepler field. They found that almost 10% of all eclipsing binaries show some period changes due to the orbital motion with the third components. Another interesting finding was the excess of systems with their mutual inclinations close to 40°, which is in agreement with the presence of Kozai cycles.

The selected published papers as presented in the thesis can also serve as useful lessons what should we be aware of and how we should be careful when interpreting the real data. From the analysis of the system HS Hya we have learned that the parameters of stellar components in the system cannot be taken seriously when using the data from different time epochs. One cannot be sure that the system is in the same configuration over a longer time interval and assuming the constant inclination would led to incorrect results (Zasche & Paschke 2012). Another implication is that there possibly should be much more such systems with precessing orbits among the known (and bright) systems observed over many decades. Only a dedicated analysis of historical data and their comparison with the new ones would be able to trace any other similar potential targets.

Another lesson coming from the published papers should be from the LMC and SMC surveys and our studies on the eclipsing binaries with apsidal motion and other phenomena. We have published four different papers on Magellanic Cloud's binaries and discovered several dozens of new interesting systems among the known eclipsing binary stars in LMC and SMC. Despite the fact that the OGLE and MACHO databases are freely available for the astronomical community, and only a very tiny fraction of the binaries were studied in detail, there are still only very few groups of researches digging these databases and carrying out the analyses. So, what is the conclusion? One has to take a look to the different direction when using the available databases and sometimes is able to find really interesting systems (see e.g. Zasche & Wolf 2013b). Among these several tens of thousands of known eclipsing binaries detected in the photometric surveys there definitely are many systems worth of study.

And finally, what also should be taken as a lesson coming from our published papers was the case of V994 Her. From that analysis there arises that when dealing with the incomplete data set, one has to be very critical when interpreting the results of the analysis. Sometimes the observable effects are too obvious and cannot be misinterpreted, however sometimes the data coverage is not sufficient enough for a final decision and choosing the right minimum in the χ^2 space. Unfortunately, the publication pressure force us to publish results which are sometimes not very well-justified with the data yet.

Hence, one can ask what should be the main goal when observing the eclipsing binaries or binaries in general in the next few decades. To reduce the statistical incompleteness of number of binaries within our Galaxy is only one particular result. To reduce the observed uncertainties of the stellar parameters to better calibrate the stellar evolution models is also important and can be carried out using the eclipsing binaries. However, to distinguish between different evolutionary scenarios and mechanisms of origin for the complex systems of multiplicity three and higher is one of the most important open questions of the nowadays stellar astrophysics. The role of magnetic activity cycles and the modulation of the brightness as well as the orbital period (as observed by Kepler satellite almost on every binary, see e.g. Borkovits et al. 2015a) also remains unclear. And obviously, the study of evolution, dynamics and stability of the multiple systems can set tight constraints also on the exoplanetary orbits and their possible suitability for abiogenesis.

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7 Reprints of published papers

Here is the list of the published papers included in this thesis:

- Zasche, P. & Wolf, M. 2007, Astronomische Nachrichten, 328, 928
- Zasche, P., Wolf, M., Hartkopf, W. I., et al. 2009, AJ, 138, 664
- Zasche, P. & Uhlář, R. 2010, A&A, 519, A78
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Combining astrometry with the light-time effect: The case of VW Cep, ζ Phe and HT Vir*

P. Zasche** and **M. Wolf**

Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic

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Three eclipsing binary systems with astrometric orbit have been studied. For a detailed analysis two circular-orbit binaries (VW Cep and HT Vir) and one binary with an eccentric orbit (ζ Phe) have been chosen. Merging together astrometry and the analysis of the times of minima, one is able to describe the orbit of such a system completely. The $O - C$ diagrams and the astrometric orbits of the third bodies were analysed simultaneously for these three systems by the least-squares method. The introduced algorithm is useful and powerful, but also time consuming, due to many parameters which one is trying to derive. The new orbits for the third bodies in these systems were found with periods 30, 221, and 261 yr, and eccentricities 0.63, 0.37, and 0.64 for VW Cep, ζ Phe, and HT Vir, respectively. Also an independent approach to compute the distances to these systems was used. The use of this algorithm to VW Cep gave the distance $d = (27.90 \pm 0.29)$ pc, which is in excellent agreement with the previous Hipparcos result.

1 Introduction

During the last century, many observations of close binary systems were collected, especially for eclipsing binaries. Most observations of these stars were made photometrically but in some cases also the spectroscopy was obtained. In a few cases, also astrometric observations were carried out and these systems, which were studied by several different techniques, are the most interesting, because one is able to find more relevant parameters of them. Especially, if it is possible to analyse the different measurements together (it means from different observational techniques in one least-squares fit) one is able to find the complete set of parameters describing the orbit of such a binary, which are not in contradiction. Such approach is potentially very powerful, especially in upcoming astrometric and photometric space missions.

There are a few well-known eclipsing binaries with astrometric measurements for which the light-time effect (hereafter LITE) was considered, or expected. However, the eclipsing binary (hereafter EB) nature and the astrometric orbit were usually studied separately.

For example, there are several published light-curve solutions for V505 Sgr with the third light included (see e.g. Lázaro et al. 2006; İbanoğlu et al. 2000; etc), and an analysis of its apparent orbital period changes interpreted as the LITE due to the third body (e.g. Rovithis-Livaniou et al. 1991). The only paper which compares the astrometry and a period analysis of $O - C$ deviations from the constant orbital period was published by Mayer (1997). Despite existing astrometric measurements, there were no attempts to combine these two methods together. The results from different approaches were just compared to each other.

Another systems are for instance QS Aql, 44i Boo, QZ Car, SZ Cam, GT Mus, or V2388 Oph. The coverage of the astrometric orbit is very poor for some of them. In the system QS Aql the LITE could be determined precisely, but the astrometric orbit is covered only very poorly, see e.g. Mayer (2004). The opposite case is V2388 Oph, where the astrometric-orbit parameters were computed very precisely, but there are only a few minimum-time measurements (see e.g. Yakut et al. 2004). For SZ Cam only a few usable astrometric observations were obtained, but the LITE is well-defined and also the third light in the light-curve solution was detected (Lorenz et al. 1998). QZ Car is a more complicated, probably quadruple system consisting of an eclipsing and a non-eclipsing binary, but there are also only a few usable astrometric measurements. Also GT Mus is a quadruple system, consisting of an eclipsing and RS CVn component. In many other cases, only measurements of the times of minima are available, without astrometry. For some others, astrometry without photometry, is only available. Other systems where the astrometric observations were obtained and the LITE is observable or expected are listed in Mayer (2004).

The only paper on combining these two different approaches into one joint solution is that by Ribas et al. (2002), where a similar method as described in this paper

* Based on observations secured at the South Africa Astronomical Observatory, Sutherland, South Africa.

** Corresponding author: zasche@sirrah.troja.mff.cuni.cz

was applied to the system R CMa, but where only a small arc of the astrometric orbit was available. Besides the astrometry and LITE also the proper motion on the long orbit was analyzed. On the other hand one has to note, that in Ribas et al. (2002) the complete astrometric parameters (with proper motions, parallax, etc.) were used, while in this paper only a relative astrometry of the distant body relative to the eclipsing pair was analysed.

2 Methods

2.1 Astrometry

The number of visual binaries with astrometric orbits has grown, but the whole orbit is covered with data points only in some cases. Thanks to precise interferometry the observable semimajor axes of astrometric binaries are still decreasing down to milli- and micro-arcseconds.On the other hand, one has to regret that no recent astrometric measurement of a wide pair of about $1''$ has been obtained for the systems mentioned below. All the astrometric observations were adopted from 'The Washington Double Star Catalogue' WDS[1] (Mason et al. 2001).

From astrometric data (N measurements of the position angle θ_i, separation ρ_i, the uncertainties σ_θ, and σ_ρ and the time of the observation t_i) one is trying to find out the parameters of the orbit for the distant component, defined by 7 parameters: period p_3, angular semimajor axis a, inclination i, eccentricity e, longitude of the periastron ω_3, the longitude of the ascending node Ω, and the time of the periastron passage T_0. One has to solve the inverse problem

$$\{(t_i, \theta_i, \rho_i, \sigma_{\theta,i}, \sigma_{\rho,i})\}_{i=1,N} \to (a, p_3, i, e, \omega_3, \Omega, T_0). \quad (1)$$

The least-squares method and the simplex algorithm was used (see e.g. Kallrath & Linnell 1987).

Comparing the theoretical position on the sky θ_0 and ρ_0 with the observed ones θ_i and ρ_i, one can calculate the sum of normalized residuals squared

$$\chi^2_{\rm astr} = \sum_{i=1}^{N} \left[\left(\frac{\theta_i - \theta_{0,i}}{\sigma_{\theta,i}} \right)^2 + \left(\frac{\rho_i - \rho_{0,i}}{\sigma_{\rho,i}} \right)^2 \right], \quad (2)$$

following Torres (2004). With this $\chi^2_{\rm astr}$ and using the simplex algorithm one can obtain a set of parameters (a, p_3, i, e, ω_3, Ω, T_0) describing the astrometric orbit.

The weighting is provided by the uncertainties σ_θ and σ_ρ. These values are obtained from the observations, or estimated as some typical uncertainty level for the certain kind of measurement provided by a specific instrument.

The efficiency and the computing time required by the algorithm strongly depends on the initial set of parameters and the chosen trial step in the parameter space. If nothing is known about the solution, one has to scan a wide range of parameters (eccentricity e from 0 to 1, and the angular parameters from $0°$ to $360°$).

[1] http://ad.usno.navy.mil/wds/

The efficiency of the algorithm could be improved if the simplex is used repeatedly. It can happen that the simplex converges into a local minimum while the global one is far away. It is therefore advisable to run the algorithm again, with as large initial steps as in the previous run, but keeping the values of the parameters corresponding to the previously found minimum as one vertex. Repeating this strategy several times over the whole parameter space, one can judge whether the global minimum was found by checking whether the sum of squares of the residuals is still changing or not.

To conclude, using this strategy and the combined method described in Sect. 2.3, one gets the satisfactory result after large number of iterations. This number and computing time is strongly depended on the input data set and the number of parameters fitted. For the case VW Cep with the largest data set (about 1600 data points, see below) and also with the most parameters to fit (14 in total) one reaches the solution, when the sum of squares is not changing significantly, after circa 100 000 simplex steps. This takes about one day on computer with 2 GHz processor.

2.2 Light-time effect

A different method to study eclipsing binaries in hierarchical triple systems is based on the eclipse timings. The light-time effect (or the 'light-travel time') causes apparent changes of the observed binary period with a period corresponding to the orbital period of the third body. This useful method is known for decades and its detailed description was presented by Irwin in 1959, while some comments on it and its limitations were discussed by Frieboes-Conde & Herczeg (1973) and by Mayer (1990).

From the numerical point of view the method is quite similar to the previous one, because it is also an inverse problem. One has M measurements of the times of minima of the system at certain constant JD_i with the individual uncertainties σ_m. The task is to find five parameters describing the orbit of the third body in the system: the period of the third body p_3, the semiamplitude of the LITE A, the eccentricity e, the time of the periastron passage T_0, and the longitude of periastron ω_{12}. One has to compute simultaneously also two (or three) parameters of the eclipsing binary itself, namely its linear (or quadratic) ephemeris JD_0 and period P (and q for the quadratic one). Altogether, one has 7 (or 8) parameters to derive from the model fit of the minimum-time measurements

$$\{(JD_i, \sigma_{m,i})\}_{i=1,M} \to (p_3, A, e, T_0, \omega_{12}, JD_0, P, q). \quad (3)$$

Similarly as in the astrometry case, the resultant sum of normalized square residuals is

$$\chi^2_{\rm LITE} = \sum_{i=1}^{M} \left(\frac{(O-C)_i}{\sigma_{m,i}} \right)^2, \quad (4)$$

where O and C stand for observed and computed time of minimum, respectively. The same remarks about the efficiency and the computing time required discussed for the astrometric solution also apply here.

At this place it is necessary to remark one useful comment. One has to distinguish between the two angles ω_3 and ω_{12}. The parameter used in LITE analysis is ω_{12}, but in astrometry the quantity $\omega_3 = \omega_{12} + \pi$ is employed. In this paper the angle ω stands for the longitude of the periastron for the eclipsing binary, i.e. $\omega = \omega_{12}$, and the subscripts will be omitted for clarity.

2.3 Combining the methods

The task is to combine the astrometry and the analysis of times of minima into one joint solution together. Having N astrometric and M minimum time measurements, one is able to merge them together and obtain a common set of parameters

$$(t_i, \theta_i, \rho_i, \sigma_{\theta,i}, \sigma_{\rho,i}, JD_i, \sigma_{m,i}) \rightarrow \rightarrow (a, p_3, i, e, \omega, \Omega, T_0, JD_0, P, q).$$

This set of 10 parameters fully describes the orbit of the eclipsing binary around the common centre of mass with the third unresolved component together with the ephemeris of the binary itself. It is necessary to solve one least-squares fit of these 10 parameters.

One is able to find out the mass of the third body and the semimajor axis of the wide orbit because the inclination is known and one can calculate the mass function of the wide orbit

$$f(M_3) = \frac{(a_{12}\sin i)^3}{p_3^2} = \frac{(M_3 \sin i)^3}{(M_1+M_2+M_3)^2} = = \frac{1}{p_3^2}\left[\frac{173.15\,A}{\sqrt{1-e^2\cos^2\omega}}\right]^3, \quad (5)$$

where a_{12} stands for the semimajor axis of the binary orbit around the common centre of mass and M_1, M_2, M_3 are the masses of the primary, secondary, and tertiary component, respectively. For more details see e.g. Mayer (1990).

The only difficulty which remains unclear is the connection between the angular semimajor axis a and the amplitude of LITE A. The quantity a_{12} could be derived from Eq. (5) and with the masses of the individual components one is able to calculate also the value a_3, i.e. the semimajor axis of the third component around the barycentre of the system

$$a_3 = a_{12}\,\frac{M_1+M_2}{M_3}. \quad (6)$$

The total mutual distance of the components is $a_{\rm total} = a_{12} + a_3$. Using the Hipparcos parallax π (Perryman & ESA 1997) one can obtain the distance d to the system. Now it is possible to enumerate the angular semimajor axis a as a function of d and $a_{\rm total}$:

$$a = \arcsin\left(\frac{a_{\rm total}}{d}\right). \quad (7)$$

The way how these two different approaches were putted together is following the similar approach by Torres (2004). From the mathematical point of view both methods are analogous and there is an overlap of the parameters in both methods. Our task is to minimize the combined χ^2,

$$\chi^2_{\rm comb} = \chi^2_{\rm astr} + \chi^2_{\rm LITE}, \quad (8)$$

where the values $\chi^2_{\rm astr}$ and χ^2_{LITE} are taken from the Eqs. (2) and (4).

Sometimes there arises a problem with the χ^2 values in both methods, which are incomparable. Especially when there are much more data points in one method against the other, also the resultant χ^2 would be much larger and as a consequence this method outweigh the other one. This problem could be eliminated using new uncertainties σ':

$$\sigma'_\theta = \sqrt{N}\cdot\sigma_\theta, \quad \sigma'_\rho = \sqrt{N}\cdot\sigma_\rho, \quad \sigma'_m = \sqrt{M}\cdot\sigma_m\,. \quad (9)$$

3 An application of the method to several particular systems

The method described above was tested on a few systems satisfying the following conditions: (i) More than 10 times of minima and more than 10 astrometric observations are available; (ii) the observed range of the position angle in the astrometric measurements is larger than 10°.

3.1 VW Cep

The eclipsing binary VW Cep (HD 197433, BD +75 752, HIP 101750, $V = 7.3$ mag, sp G5V + G8V) is a W UMa system and in fact it is one of the most often observed and analysed system. Both components are chromospherically active. VW Cep is rather atypical, because during the primary (the deeper one) eclipse is the less massive star (the hotter one) occulted by the larger companion (the more massive and the cooler one).

The first observations of its light variations were done by Schilt (1926). Since 1946, a large amount of photoelectric observations was obtained. However, the observed minima times did not fit the ephemeris due to the LITE and the mass transfer between components. There were many light-time effect studies of this system and Herczeg & Schmidt (1960) proposed the presence of a third body with an orbital period of 29 years and an angular distance of the third component between 0.5″ and 1.2″.

In 1974, the first successful visual observation of the third component was obtained and since then, there were 16 observations of it. Regrettably, the observations near the periastron passage are missing (the gap in data is from 1991 to 1999). The last two measurements ($\theta = 231.4°$, $\rho = 0.702''$ and $\theta = 232.6°$, $\rho = 0.695''$) were not published yet. These were obtained by a speckle camera in April 2007 and were kindly sent by E. Horch (priv. comm.).

The most complete set of times of minima is in the most recent period study of VW Cep by Pribulla (2000). The first times of minima are from the 1920's and altogether 1907 minima were collected. From this set of times of minima 313 measurements were neglected due to their large scatter

Table 1 The final results: parameters of the third bodies from combined astrometry and the light-time effect. The table is divided into three parts, in the first one are ten computed parameters, in the second one the values from the literature and in the last one the quantities computed from the previous parts. The values of parallax and distance were adopted from the Hipparcos measurements. In the row 'Data set', 'a' and 'm' denote the number of astrometric observations, and times of minima, respectively.

Parameter	Unit	VW Cep	ζ Phe	HT Vir
JD_0	HJD	2437001.4327 ± 0.0025	2441643.7382 ± 0.0008	2452722.5040 ± 0.0050
P	d	$0.278315349 \pm 0.00000012$	1.6697772 ± 0.0000013	0.4076696 ± 0.0000025
p_3	yr	29.79 ± 0.08	220.9 ± 3.5	260.7 ± 0.40
T_0	HJD	2450390.6 ± 37.3	2419908.9 ± 2465.6	2442832.3 ± 60.6
ω	deg	239.28 ± 2.88	97.1 ± 2.2	250.9 ± 0.6
e		0.633 ± 0.007	0.366 ± 0.082	0.640 ± 0.005
A	d	0.0131 ± 0.0004	0.0808 ± 0.0080	0.1274 ± 0.0024
a	mas	445.2 ± 33.0	859.5 ± 137.2	1023.5 ± 183.3
i	deg	33.6 ± 1.2	64.4 ± 3.0	45.4 ± 3.7
Ω	deg	17.7 ± 3.1	33.5 ± 4.9	180.8 ± 2.6
M_{12}	$M_\odot$	1.37	6.48	2.3
References		Kaszas et al. 1998	Andersen 1983	D'Angelo et al. 2006
π	mas	36.16 ± 0.97	11.66 ± 0.77	15.39 ± 2.72
d	pc	27.7 ± 0.7	85.8 ± 5.7	65.0 ± 11.5
a_{12}	AU	4.33 ± 0.20	15.52 ± 1.60	32.23 ± 0.74
$f(M_3)$	$M_\odot$	0.0154 ± 0.0016	0.0562 ± 0.0167	0.1692 ± 0.0098
M_3	$M_\odot$	0.74 ± 0.07	1.73 ± 0.26	2.10 ± 0.10
Data set		16a + 1594m	12a + 36m	275a + 31m

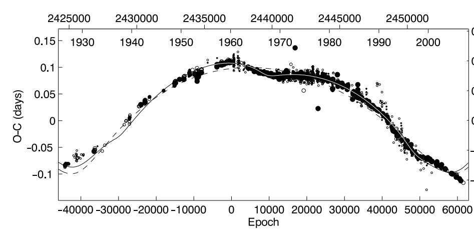

Fig. 1 An $O - C$ diagram of VW Cep. The individual observations are shown as dots (primary) and open circles (secondary), the small ones for visual and the large ones for CCD and photoelectric observations. The curves represent the predicted $LITE_3$ + $LITE_4$ (the solid one) and only $LITE_4$ (the dashed one).

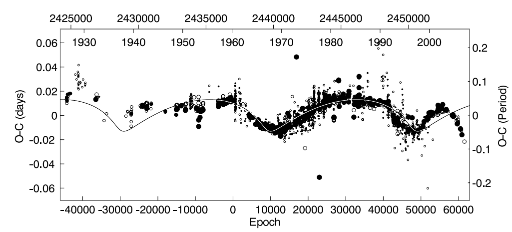

Fig. 2 An $O - C$ diagram of VW Cep after subtraction of the $LITE_4$. The description is the same as in the previous $O - C$ figure, and the solid line represents the LITE caused by the third component in the system.

(mostly the visual ones). This new minimum-time analysis is based on a larger data set (about 750 times of minima more than were used by Pribulla et al. 2000). Two new CCD observations of the minimum light of VW Cep were obtained in Ondřejov observatory with the 65-cm telescope and Apogee AP-7 CCD camera, 2 seconds exposure time in the R filter. These new times of heliocentric minima are 2454154.3094 ± 0.0001 and $2454195.49866 \pm 0.00012$.

The short-term variations with the period of about two years (see e.g. Kwee 1966; Hendry & Mochnacki 2000) are probably caused by the surface activity cycles on the primary component. Due to this activity an unique interpretation of the behaviour of period changes is still missing. Pribulla et al. proposed a mass transfer (the quadratic term) plus the third and the fourth body in the system (two periodic terms). Nevertheless, they were not able to explain the $O - C$ diagram in detail.

Another approach has been chosen in this paper. Especially due to only a few astrometric observations (16 measurements from 1974 to 2007) we have decided to explain only the most significant effects in the $O - C$ diagram. It means the astrometric variation with a period of about 30 years has been identified with the $O - C$ variation with the same period, but the long-term variation in the $O - C$ diagram (which has been interpreted by Pribulla et al. 2000 as a quadratic term) was explained as a variation due to the fourth body on its very long orbit. This approach was chosen especially because of the systemic-velocity variations, see below. It means during the computation process the value $\chi^2_{\rm comb}$ was minimized with respect to 14 parameters in total: $A, p_3, i, e, \omega, \Omega, T_0, JD_0, P, A_4, p_4, e_4, \omega_4, T_{0,4}$.

Table 2 VW Cep: parameters of the fourth-body orbit.

Parameter	Unit	Value ± Error
p_4	yr	77.46 ± 0.04
A_4	d	0.100 ± 0.002
ω_4	deg	283.42 ± 2.30
$T_{0,4}$	HJD	2453857.4 ± 13.6
e_4		0.543 ± 0.007

The combined approach of analysing the times of minima together with astrometry led to the parameters shown in Table 1 and 2. The $O-C$ diagram in Fig. 1 shows the times of minima together with the curve which represents the LITE_3 + LITE_4. If one subtracts only the LITE_4 variation and try to describe the behavior of the minimum times, one gets Fig. 2, where only the LITE_3 caused by the third component is displayed. The fit is not very satisfactory because of the presence of the chromospheric activity of the individual components, or due to a putative additional component (see e.g. Pribulla et al. 2000). In Fig. 3, the astrometric orbit of the binary with the individual measurements and their theoretical positions is shown. Regrettably, no observations near the periastron passage are available. The curve also represents the theoretical orbit according to the parameters given in Table 1 in agreement with the LITE analysis.

The parameters describing the LITE_3 and LITE_4 variations are in Table 1 and 2 and could be compared to the parameters derived during the previous analysis by Pribulla et al. (2000). Their values for the third-body orbit are: $p_3 = 31.4$ yr, $e = 0.77$, $\omega = 183°$, and $a_{\rm total} = 12.53$ AU. Our values are in Table 1 except for $a_{\rm total} = 12.35$ AU, and as we can see they differ significantly in several parameters. This is due to completely different approach describing the $O-C$ variations. Only the period and the amplitude of such variation are comparable, but these are the most important for our combined solution. One has also to disagree with the result by Pribulla et al. (2000), that the astrometric orbit could not be identified with the LITE_3 variation from the $O-C$ diagram. As one can see, our new results are in agreement with each other without any problems.

Also the astrometric orbit could be compared with the previously published one. Most recently Docobo & Ling (2005) published the following parameters of the astrometric orbit: $p_3 = 31.0$ yr, $a = 485$ mas, $i = 39.3°$, and $e = 0.68$. If one compares these values with the new ones (see Table 1), one can see that the differences are slightly beyond the limits of errors.

If we assume the mass of the eclipsing binary to be $M_{12} = 1.37\ \mathrm{M}_\odot$ (Kaszas et al. 1998) and the parallax $\pi = 36.16$ mas (from Perryman & ESA 1997), the distance to the system is only about 27.66 pc, which results in the third-body mass of $M_3 = 0.741\ \mathrm{M}_\odot$. The distant component is about 2.2 magnitudes fainter than the VW Cep itself, so its luminosity and also mass should be much smaller than the mass of the eclipsing components. The total bolometric magnitude of VW Cep is about 4.7 mag, so the magnitude of the third component is about 6.9 mag, which leads to the spectral type of about K3. The typical mass of this spectral type is about $0.75\ \mathrm{M}_\odot$ (according to Harmanec 1988), which is in good agreement with the new result and within its error limits.

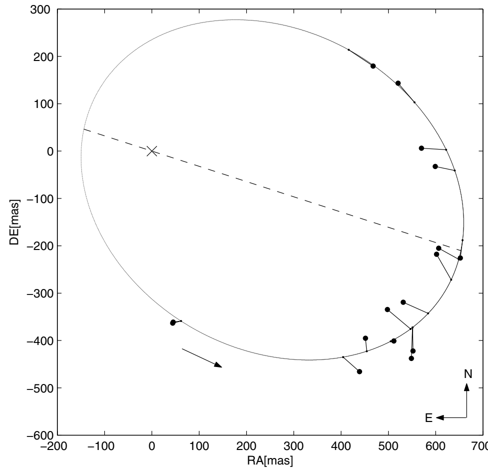

Fig. 3 Relative orbit of VW Cep on a plane of the sky. The points represent individual observations, while the solid curve corresponds to the solution described in the text. The straight lines connect individual observations with their expected positions on the fitted orbit. The cross indicates the position of the eclipsing binary on the sky and the arrow the direction of the orbit of the third body. The dashed-line represents the line of apsides.

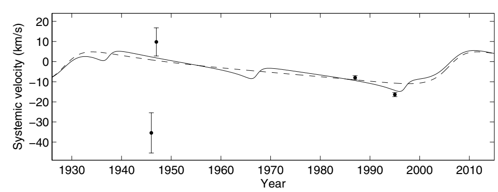

Fig. 4 Systemic velocity variations in VW Cep. The individual points represent computed systemic velocities (see details in text). The solid curve stands for the combined LITE_3 + LITE_4 variations, while the dashed one only for the LITE_4 variation.

Different systemic velocities v_γ were found at different epochs. These values are: $v_\gamma = (-35.4\ \pm 10)\ \mathrm{km\,s^{-1}}$ (Popper 1948), $(+9.8\ \pm 7)\ \mathrm{km\,s^{-1}}$ (Binnendijk 1966), $(-8\ \pm 1)\ \mathrm{km\,s^{-1}}$ (Hill 1989), and $(-16.4\ \pm 1)\ \mathrm{km\,s^{-1}}$ (Kaszas 1998). In the time plot (see Fig. 4) one can see the curve which represents the theoretical variation of v_γ caused by the orbital motion around the common barycentre. Except for the first one data point by Popper the systemic velocities are following the long-term variation and are almost within its errors near the theoretical values. The value of Popper is affected by a relatively large error. The scatter of the individual RV data points is much larger than that from Binnendijk, which could be caused by the combination of two different data sets from different instruments and obtained after more than 600 orbital revolutions (which could shift the ephemeris). Pribulla & Rucinski (2006) suggested that the scatter of the systemic velocity data points is instrumental, which seems unlikely for such a large amplitude. For the final confirmation of v_γ variations a more accurate and larger data set is necessary.

We also tried to derive the parallax of VW Cep using this combined approach. Leaving the parallax as another free parameter, it was calculated from the comparison of the angular and absolute semimajor axis. Using this approach, almost all of the relevant parameters remained nearly the same, only the inclination changed a bit, being about 1° lower and the angle Ω about 1.5° lower. The new parameters led to a higher third mass of $M_3 = 0.76\ \mathrm{M}_\odot$. The parallax decreased from (36.16 ± 0.97) mas (Hipparcos) to (35.85 ± 0.37) mas. This parallax would shift the distance from (27.7 ± 0.7) pc (Hipparcos) to (27.90 ± 0.29) pc. As one can see, the result of the parallax is more precise than any of the previously derived parallaxes (see Hendry & Mochnacki 2000 for a summary of the previous values).

One could conclude that the third body is probably of spectral type K3 with a mass around $0.74\ \mathrm{M}_\odot$. It is clear, however, that a more complicated model will be needed to describe the observed changes completely.

3.2 ζ Phe

The system ζ Phe is the brightest eclipsing binary with two components of early spectral types, exhibiting total and annular eclipses. This is the only binary with an eccentric orbit included in this study. ζ Phe (HD 6882, HR 338, HIP 5348, $V = 4.0$ mag, sp B6V + B9V) is an Algol-type eclipsing binary. It is a visual triple and SB2 spectroscopic binary.

The brightest component is the EB, while the most distant component is the faintest one (some $6''$away and with its apparent brightness of about 8 mag). The last known component is a 7^{th}-magnitude star at a distance of about 600 mas. This is the astrometric component and in our opinion also the one which causes the LITE. The depth of the primary minimum of the eclipsing pair is about 0.5 mag and the period is about 1.66 d.

The unfiltered light curve was observed in 1950's by Hogg (1951), after then by Dachs (1971) in UBV filters, and the best one by Clausen et al. (1976) in $uvby$ filters. In this latter paper all relevant parameters of the eclipsing system were derived and also the third light was computed. Its value changes from $3\%(u)$ to $8\%(y)$ and the distant component was classified as a spectral type A7 star.

Clausen et al. (1976) also collected the times of minima obtained before 1975. They concluded that no significant apsidal motion is observed. The first apsidal-motion study was published by Giménez et al. (1986). With an updated list of the times of minima one is able to conclude that the apsidal motion is definitely present. It is clearly visible in

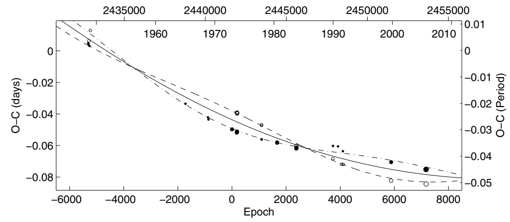

Fig. 5 The $O - C$ diagram of ζ Phe. The description is the same as in the previous $O - C$ figures. The apsidal motion curve (the dash-dotted one for the primary and the dashed for the secondary) is plotted around the LITE curve (solid).

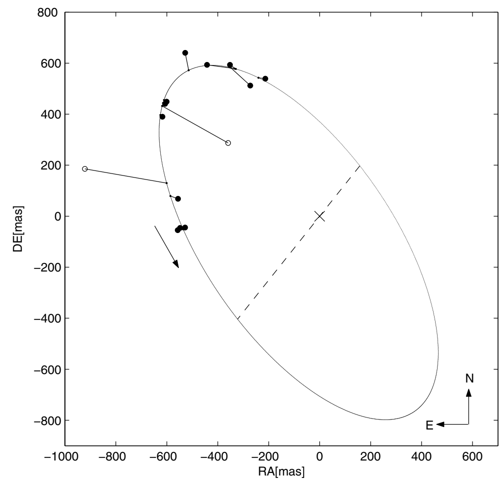

Fig. 6 Relative orbit of ζ Phe on a plane of the sky, for a detailed description see Fig. 3. Two measurements (the open circles) were neglected.

the $O - C$ diagram shown in Fig. 5. Altogether 36 times of minima used here came from the paper cited above and from Mallama (1981), Giménez et al. (1986), Kvíz et al. (1999). The most recent ones are in Table 3.

Our new photoelectric UBV observations were secured with the modular photometer utilizing Hamamatsu EA1516 photomultiplier on the 0.5-m telescope at the Sutherland site of the South African Astronomical Observatory (SAAO) during two weeks in September 2005. The Johnson UBV photoelectric measurements were secured with 10-second integration times. Each observation of ζ Phe was accompanied by an observation of the local comparison star η Phe (V = 4.36 mag). All measurements were carefully reduced to the Cousins E-region standard system (Menzies et al. 1989) and corrected for differential extinction using the reduction program HEC 22 rel. 14 (Harmanec & Horn 1998). The standard errors of these measurements were about 0.008, 0.006, and 0.005 magnitude in U, B, and V filters, respectively.

Table 3 The new minima timings of ζ Phe based on photoelectric observations.

HJD – 2400000	Error	Prim/Sec	Epoch	Ref.
47872.7742	0.005	Sec	3730.5	(1)
47873.6172	0.005	Prim	3731.0	(1)
48187.535	0.005	Prim	3919.0	(1)
48397.0807	0.005	Sec	4044.5	(1)
48484.7523	0.005	Prim	4097.0	(1)
48508.9557	0.005	Sec	4111.5	(1)
51466.9675	0.0005	Prim	5883.0	(2)
51467.7907	0.001	Sec	5883.5	(2)
53622.6453	0.0001	Prim	7174.0	(3)
53623.4710	0.0001	Sec	7174.5	(3)

(1) Perryman & ESA 1997; (2) Shobbrook 2004; (3) This paper.

The new times of primary and secondary minimum and their errors were derived using a least-squares fit to the data and by the bisecting-chord method. Only the bottom parts of the eclipses were used. The mean values and the errors for each individual filter are given. Six new times of minimum light were derived using the Hipparcos photometry (Perryman & ESA 1997) and fitting the published light curve. These new times of minima are also included in Table 3. In this Table, the epochs are calculated from the light elements given in Table 1, the other columns being self-explanatory.

ζ Phe has one of the shortest apsidal motions among the eclipsing binaries (see e.g. Claret & Giménez 1993). Due to a low eccentricity, the amplitude of the effect is small. For an accurate calculation of the apsidal motion rate the method described by Giménez & Garcia-Pelayo (1983) was routinely used. The eccentricity of the orbit in the eclipsing binary is $e' = 0.0107 \pm 0.0020$, the longitude of periastron $\omega_0 = 12.96^\circ \pm 5.96^\circ$, and the apsidal motion rate $\dot{\omega} = (0.028 \pm 0.001)^\circ/\mathrm{cycle} = (6.16 \pm 0.20)^\circ/\mathrm{yr}$, i.e. the apsidal motion period $U = 58.5$ yr. The most recent apsidal-motion analysis is more than 20 years old, made by Giménez et al. (1986), but with no LITE and with a smaller set of times of minima. The eccentricity derived by Giménez et al. was almost the same, but the apsidal motion rate $\dot{\omega}$ was $0.0373\,^\circ/\mathrm{cycle}$ and the angle $\omega_0 = 13^\circ$.

Our approach was a combination of the two different effects. The behaviour in the $O-C$ diagram was described as a sum of apsidal motion and LITE contribution $(O-C) = (O-C)_{\mathrm{apsid}} + (O-C)_{\mathrm{LITE}}$, distinguishing the primary and secondary minima. It means the least-squares algorithm was minimizing the χ^2_{comb} with respect to 12 parameters in total: $A, p_3, i, e, \omega, \Omega, T_0, JD_0, P, \dot{\omega}, \omega_0, e'$.

The astrometric solution based on the combined approach is satisfactory, while the older measurements have larger scatter than the recent ones (the old ones are visual, while the modern ones are speckle-interferometric). Two measurements were neglected, because of their large scatter (see Fig. 6). Our solution led to the parameters listed in Table 1, which could be compared to previously found values. Most recently Ling (2004) reported the parameters:

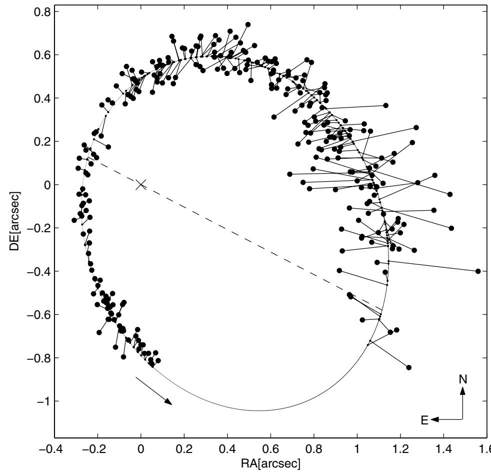

Fig. 7 Relative orbit of HT Vir on a plane of the sky, for a detailed description see Fig. 3.

$p_3 = 210.4$ yr, $e = 0.348$, $a = 804$ mas, $i = 61.9^\circ$, $\Omega = 33.5^\circ, \omega_3 = 271.7^\circ$. It is evident that the new parameters are in very good agreement with these ones. The new values imply the mass function of the distant body $f(M_3) = 0.056\ \mathrm{M}_\odot$. With the masses of the primary and secondary component of the eclipsing binary $M_1 = 3.93\ \mathrm{M}_\odot$ and $M_2 = 2.55\ \mathrm{M}_\odot$ (Andersen 1983), one could derive the mass of the astrometric third body $M_3 = 1.73\ \mathrm{M}_\odot$. This value corresponds to a spectral type around A7, which is in excellent agreement with the photometric analysis (Clausen et al. 1986).

3.3 HT Vir

One member of the visual binary STF 1781 is the eclipsing binary system HT Vir (ADS 9019, HD 119931, HIP 67186, BD+05 2794, $V = 7.2$ mag, sp F8V). HT Vir is a contact W UMa system, with a period of about 0.4 d and the depths of minima of about 0.4 mag. Both visual components have almost equal brightness. The third component of the system is brighter than the eclipsing binary HT Vir during its eclipses and fainter than it during its maxima.

According to Walker & Chambliss (1985) the distant astrometric component was discovered by Wilhelm Struve in 1830 at a separation of about $1.4''$ and position angle 240°. Since then, numerous astrometric observations were obtained (altogether 277, from which 275 were used in our analysis) and the orbit is almost completely covered by the observations.

Baize (1972) suggested that the star might be variable. After then, Walker & Chambliss (1985) obtained a complete light curve of HT Vir and did the first analysis. It indicated that both components of the eclipsing pair are almost identical and in contact. The temperatures of both components are about 6000 K and the spectral type is estimated as F8V for the primary and a little bit earlier for the secondary, the inclination is close to 90°. The total mass of the eclipsing pair is $M_{12} = 2.3\ \mathrm{M}_\odot$ (D'Angelo et al. 2006).

Lu et al. (2001) discovered that the distant component is also a binary. They have measured the spectra of the HT Vir eclipsing pair, and discovered also the lines from the third component in the spectra and their RV variations with a period of about 32.45 d. We therefore deal with a quadruple system.

Despite the spectral analysis and a large set of astrometric observations, there were only a few times of minima published during the last few decades. The main reason is relatively recent discovery of the photometric variability of HT Vir. The first times of minima come from 1979. Since then, there were only 31 observations obtained (see Fig. 8). Four new observations were obtained. The two of them were carried out in Ondřejov observatory with the 65-cm telescope and Apogee AP-7 CCD camera and 1 second exposure time in the R filter. This new times of heliocentric secondary minima are $2454175.58494 \pm 0.00011$ and $2454195.56170 \pm 0.00007$. The next one was observed by L. Brát (Private Observatory), using an 8-cm telescope with ST-8 CCD camera, 20 seconds exposure time in the R filter, resulting in $2454210.44154 \pm 0.00015$, and the last one by R. Dřevěný with ST-7 CCD camera, 60 seconds in the R filter, resulting in $2454213.49967 \pm 0.00012$. One unpublished observation by M. Zejda was also used and four times of minima by M. Zejda published in Zejda (2004) were recalculated, because the heliocentric correction was wrongly computed.

The final plot of the relative astrometric orbit of HT Vir is in Fig. 7. The results, parameters of the orbit around the common barycentre of the system, are given in Table 1. The values of these parameters, A, p_3, i, e, ω, Ω, T_0, JD_0, P, were obtained minimizing the χ^2_{comb}.

Walker & Chambliss (1985) published the first rough estimation of the proposed LITE from the astrometric orbit. Their value (0.18 d) is not too far from ours (0.13 d).

The new elements for the astrometric orbit can be compared to those of Heintz (1986), which are the following: $p_3 = 274.0$ yr, $e = 0.638$, $a = 1010$ mas, $i = 42.7°$, $\Omega = 176.4°$, $\omega_3 = 250.0°$. As one can see, the period of the new orbit is a bit shorter, but the main differences in these values are the angles ω and Ω. The same fit to the astrometric data points could be reached with simultaneously transformed values $\omega_3 \rightarrow \omega_3 + 180°$ and $\Omega \rightarrow \Omega + 180°$. This only means the interchange of the role of the two components. This result indicates the incorrect identification of the variable HT Vir in the system in our analysis (the variable was supposed to be the component A) and also in the WDS catalogue, see WDS notes[2]. While Pribulla & Rucinski (2006) correctly identified the variable HT Vir as the B component and A as a single-lined binary.

[2] http://ad.usno.navy.mil/wds/wdsnewnotes_main.txt

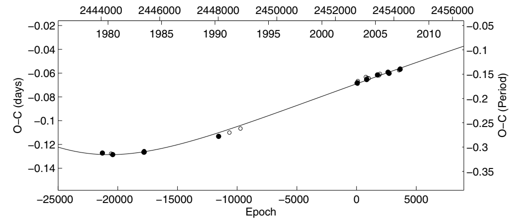

Fig. 8 An $O - C$ diagram of HT Vir. The description is the same as in the previous $O - C$ figures, all minimum times are photoelectric or CCD ones.

If we adopt these parameters to estimate the mass function of the distant pair (mass function of the whole pair, not the individual components), we obtain $f(M_3) = 0.17\,\mathrm{M}_\odot$. This is quite a high value, dictated by the large amplitude of the LITE. With the total mass of the primary and secondary $M_{12} = 2.3\ \mathrm{M}_\odot$ we get the third mass of $M_3 = 2.10\ \mathrm{M}_\odot$. The mass of the distant pair is quite high (D'Angelo et al. (2006) derived the mass for some 50 per cent lower, $M_3 = 1.15\ \mathrm{M}_\odot$), but note that also this object is a binary and we do not know the individual masses. From the spectroscopic observations (we remind that it is a SB1 type binary), we are only able to estimate the mass function of the components, or some upper limit for one of them (we do not know the inclination). Our resulting M_3 is the total mass of the SB1 pair $M_{3,1} + M_{3,2}$; the limit for the invisible-component mass $M_{3,2}\,\sin i = 0.075\,\mathrm{M}_\odot$. If we assume the coplanar orbit, high difference in masses would arise, one component should be much more luminous and also more luminous than the eclipsing pair itself, which is not the case. In fact the whole system is not coplanar (see e.g. $i = 315.5°$ and the inclination of the EB close to 90°). If we assume two approximately equal masses, there is a problem with the luminosity, because the distant pair has to be roughly as luminous as the eclipsing pair. This could only be satisfied if one component is underluminous or degenerate.

We have to take into consideration also the comment on the light-curve solution by Walker & Chambliss (1985). Using the Wood's model, they discovered that if the third light L_3 is fixed to be equal to the light from the distant visual component (it means $L_3 = 0.5$), the solution of the light curve is unrealistic. To conclude, the system could be much more complicated than the approach we have used here. Especially because of the resultant mass and luminosity of the distant pair, the body causing the astrometric variation is probably different from the one causing LITE, but this conclusion will be proven only if also the nonlinear part of the $O - C$ diagram is covered.

4 Discussions and conclusion

Although the number of systems where the astrometric orbit of the third component has been measured together with the presence of LITE is growing steadily, in the most cases only very limited coverage, both in astrometry and times of minima is available. Especially due to this reason the combined analysis of these systems is still difficult, the results are not very convincing and the resultant parameters are affected by relatively large errors.

During the last decade a few papers combining the approach of simultaneous solution of radial velocities, spectral analysis, astrometry, Hipparcos measurements or LITE were published. Besides the systems mentioned in the introduction (V505 Sgr, QS Aql, 44 Boo, QZ Car, SZ Cam, GT Mus, and V2388 Oph) there were also the analyses of V1061 Cyg (combining the light curve analysis, radial velocity analysis, light-time effect and Hipparcos measurements, see Torres et al. 2006), the papers where the radial velocity measurements and astrometry were combined (see Muterspaugh et al. 2006 for the solution of LITE system V819 Her, or Gudehus 2001 for μ Cas), the paper on HIP 50796 combining the radial velocities with the Hipparcos abscissa data (Torres 2006), or the paper on δ Lib comparing the results from the period analysis, light-curve analysis, spectral analysis, radio emission and astrometry, respectively (see Budding et al. 2005).

Three eclipsing binaries were studied in this paper. In the case of VW Cep, where the orbits in both methods have relatively best coverage, the distant body satisfies the limits for the luminosities, and also the systemic velocity variations coincide with our hypothesis. New results are comparable with the previous ones. An additional fourth body was introduced to describe the long-term variation in times of minima. The system is probably more complicated than we assumed (chromospheric activity cycles, stellar spots and flares), and we decided to explain only the most pronounced effects in the $O-C$ diagram. Using this combined approach it is possible to derive the parallax of VW Cep more precisely than in previous papers, resulting in $\pi = (35.85 \pm \pm\ 0.37)$ mas. The system ζ Phe displays an apsidal motion together with LITE and this explanation fits the $O-C$ residuals quite well. The quality of the astrometry is worse, but the main result about the masses and the spectral type of the third body is in an excellent agreement with the previous photometric analysis. The last system HT Vir is the case where the new resultant parameters of the distant body are about 2 times larger than one would expect. This could be due to the fact that only a few times of minima were observed in the linear part of the $O-C$ diagram, new minima are needed in the next decades.

The final result is that the method itself is potentially very powerful but it is also very sensitive to the quality of the input data, especially if the method is used for determining the distances of these binaries. It can only be applied successfully in those cases where the astrometric orbit and the LITE in the $O-C$ diagram are well defined by existing observations.

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A CATALOG OF VISUAL DOUBLE AND MULTIPLE STARS WITH ECLIPSING COMPONENTS

P. Zasche[1,2], M. Wolf[1], W. I. Hartkopf[3], P. Svoboda[4], R. Uhlař[5], A. Liakos[6], and K. Gazeas[6]
[1] Astronomical Institute, Faculty of Mathematics and Physics, Charles University of Prague, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic
[2] Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, México, DF 04510, Mexico
[3] U.S. Naval Observatory, 3450 Massachusetts Avenue, Washington, DC 20392, USA
[4] Private Observatory, CZ-614 00 Brno, Výpustky 5, Czech Republic
[5] Private Observatory, Pohoří 71, CZ-25401, Jílové u Prahy, Czech Republic
[6] Department of Astrophysics, Astronomy and Mechanics, Faculty of Physics, University of Athens, GR-15784 Zografos, Athens, Greece
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ABSTRACT

A new catalog of visual double systems containing eclipsing binaries as one component is presented. The main purpose of this catalog is to compile a complete list of all known multiples of this variety, both for current analysis and to highlight those in need of additional observations. All available photometric and astrometric data were analyzed, resulting in new orbits for eight systems and new times of minimum light for a number of the eclipsing binaries. Some of the systems in the catalog have acceptable solutions for their visual orbits, although in most cases their orbital periods are too long for simultaneous analysis. Also included, however, are a number of systems which currently lack an orbital solution but which may be suitable for simultaneous analysis in the future.

Key words: binaries: close – binaries: eclipsing – binaries: visual – catalogs – stars: fundamental parameters

1. INTRODUCTION

Binary stars are essential objects for determining precise physical properties of stars, especially masses, through a combined analysis of photometric, astrometric, and spectroscopic data. If the stars comprise an eclipsing binary (hereafter EB), radii, distance and, in favorable cases, effective temperatures also may be determined from a combined analysis of light and radial velocity (hereafter RV) curves. Moreover, masses and distances for visual binaries may be determined from a combined analysis of astrometric and RV measurements. Additional components often may be revealed through these analyses; one especially productive source is the study of the long-time behavior of the period of an EB. As might be expected, the longer the time span of conjunction time measurements, or times of minimum light, the greater the chance of detecting a long-period orbit due to an additional member of the system under study.

There are currently more than 2000 systems with known visual orbits (see the USNO Sixth Orbit Catalog[7]). Among these systems, at least 34 have been found to include an EB as one of their components. About 100 other EBs were found to be members of visual pairs or multiples, the orbit of which has not been computed yet. Collecting and investigating this fraction of the visual doubles is the purpose of this catalog.

The systems presented here were found through searches in the "Washington Double Star Catalog"[8] (WDS; Mason et al. 2001), identifying systems with EBs amongst their components. This catalog differs slightly from the one published by Chambliss (1992), where all of the multiple-star systems containing EBs known by the author were collected. Chambliss mentioned that 80 EBs were known to be components of multiple-star systems and presented 37 of them in detail. The present catalog is restricted to reasonably well observed visual binaries which contain EBs as a component (the qualifier "reasonably well observed" being described below). The number of known EBs amongst visual pairs is growing rapidly; we felt this justified collecting them into a separate catalog.

The $O - C$ diagrams constructed against the EBs linear ephemeris frequently display variations in their orbital periods (see, for example, a catalog of $O - C$ diagrams of such systems by Kreiner et al. 2001). For a discussion of the details and limitations of $O - C$ diagram analysis, see Sterken (2005). A periodic oscillation in an $O - C$ diagram may be explained as a light–time effect (hereafter LITE) caused by a distant companion orbiting around a common center of mass with the EB; see Irwin (1959), or Mayer (1990) for details. In favorable cases, this component may be identified as a distant member of the system, directly detectable astrometrically as a visual or interferometric companion. Despite the large number of EBs in our Galaxy (estimated at about 10^8, according to Kopal 1978 and Cooper & Hughes 1994), there are still only a few dozen systems known where the EBs are members of spatially resolvable pairs. A few of the most well known systems are V505 Sgr (see Mayer 1997), V819 Her (Muterspaugh et al. 2006), and VW Cep (Zasche & Wolf 2007, hereafter ZW, and Zasche 2008). Decades' worth of data are available for all these systems, making possible an analysis of period variations and also a solution of the visual orbits (fortunately the visual orbital periods in these examples are rather short). Despite this fact, until now the results from different techniques have been in contradiction with each other. A typical example of such a discrepancy is the system V505 Sgr, where Chochol et al. (2006) presented the period of the third body about 44.6 or 38.6 yr from period analysis, while Cvetković et al. (2008) derived the third-body period about 60.1 yr from the visual orbit. To the best of our knowledge, the system VW Cep is presently the most suitable for a combined analysis of variation of minima timings; the combination of available photometric and interferometric data can even be used to determine the distance to the system. The distance derived by this method is more precise than any previously derived value; see ZW for details. Such a combined approach is potentially very powerful, especially anticipating the high-quality data expected to come from planned astrometric and photometric space missions. The most serious weakness in this combined method seems to be due to the period of the distant component, which in most cases is

[7] http://ad.usno.navy.mil/wds/orb6.html
[8] http://ad.usno.navy.mil/wds/

extremely long (typically decades to centuries or longer). As a result, the data frequently cover only a small arc of the orbit, and this very incomplete coverage obviously degrades the precision of the results. For a detailed description of the method, including algorithms, limitations, and results, see ZW and Zasche (2008).

2. THE CATALOG

The selection criteria used during the compilation of this catalog were (1) the existence of more than 10 astrometric measurements, (2) a variation of position angles of the astrometric observations of more than 10°, and (3) the presence of an EB as one of its components.

A total of 44 systems which met these criteria were found; these are presented in Table 1 and commented upon in more detail in the following subsections. In a few cases, it was rather difficult to identify which component in the wide system comprised the EB. Other interesting systems, which contain an EB as one component but which do not satisfy the other selection criteria, were also included in Section 2.45. In Section 2.46, we discuss those systems which were difficult to classify. These include, for example, systems where the eclipsing nature is questionable, etc. In many systems, the only information about their distance is that by *Hipparcos* (Perryman & ESA 1997; see Column 9 in Table 1). However, the value of *Hipparcos* distance could be affected by a relatively large error due to the fact that the star is not a single target, but a binary.

The entire catalog is also available online.[9] This web site will be updated as new observations become available and as new systems meeting our selection criteria are discovered.

Notes on individual systems follow.

2.1. V640 Cas

V640 Cas (HD 123, HR 5, HIP 518, STF 3062AB) is listed as an EB. Only two photometric decreases were observed (Brettman et al. 1983), and no photometric analysis has been published. This system was observed over 16 nights from 2007 July to 2008 November in *B*, *V*, and *R* filters, but no minima were observed. From our new photometric observations, we can conclude that there is no variability above a level of 0.02 mag with periods in interval 1.02–1.1 days. Griffin (1999) discussed the plausibility of the photometric variations observed by Brettman et al. (1983), and also noted that no such variability is observable from the *Hipparcos* satellite (see Perryman & ESA 1997), concluding that the system is not variable at all. Therefore, the classification of V640 Cas as an eclipsing system is questionable. However, the system could be more complicated, and due to the presence of the third body the eclipses could turn on and off, similarly to V907 Sco (Lacy et al. 1999), SS Lac (Torres 2001), or V699 Cyg (Lippky & Marx 1994). The visual orbit is well observed, with some 572 data points obtained over 170 yr. Söderhjelm (1999) computed the most recently published orbital parameters, finding a period of about 107 yr and an angular semimajor axis of about 1.″4.

2.2. V348 And

V348 And (HD 1082, HIP 1233, A 1256AB) is an Algol-type EB. Its situation is similar to that of V640 Cas, as neither times of minima nor a photometric analysis have been found in the literature. The single available time of minimum was based on *Hipparcos* measurements, but is only poorly covered. Our new observations of the system, obtained during 19 nights, were summarized in Zasche & Svoboda (2008). The visual orbit is defined by data obtained over 93 yr and covering the range from 4° to 223° in position angle. Two rather different orbital solutions have been published: Olević (2002) derived values $p_3 = 138$ yr and $a = 150$ mas, while Seymour et al. (2002) found a period of about 330 yr and a semimajor axis 290 mas. Both solutions appear to fit the limited arc of observations equally well. The mass sums derived from these two different fits are not able to decide which solution is the more plausible, because the light-curve analysis has not yet been performed and the individual spectral types are not known. If we assume the spectral types of each of the components to be the same as the spectrum of the system as a whole (B9IV), the resulting mass sum should be much higher than predicted by either orbital solution—2.8 $M_\odot$ for Olević (2002) and 3.4 $M_\odot$ for Seymour et al. (2002).

2.3. V355 And

V355 And (HD 4134, HIP 3454, STF 52AB) is also an Algol-type EB, with a spectral classification of the whole system as F6V. The only published complete light curve is that of Tikkanen (2002), who also determined nine times of minima (unpublished, see the author's Web site).[10] Observations of the visual pair have been obtained during the past 170 yr, but cover a range in position angles of only about 20°. No visual orbit has yet been computed, but the orbital coverage to date suggests a period of order 3000 yr.

2.4. ζ Phe

ζ Phe (HD 6882, HR 338, HIP 5348) is an eccentric EB of Algol type, its spectral types were determined as B6V + B8V (according to Andersen 1983). It is a visual triple and double-lined spectroscopic binary. A detailed analysis using a combined solution of astrometry and times of minima was presented by ZW. This analysis yields a period for the visual orbit of about 221 yr. The mass of the predicted third body was derived to be $M_3 = 1.73\ M_\odot$, which is in excellent agreement with earlier photometric analyses by Clausen et al. (1976) and Andersen (1983). In addition to the long-term variation seen in the $O - C$ diagram caused by the LITE, apsidal motion is also detectable, with a period of ∼60 yr.

2.5. BB Scl

BB Scl (HD 9770, HIP 7372, GJ 60) is an EB and also the B component of a visual triple; we therefore deal with a quadruple system. Orbits of both the visual pairs have been derived. The wider AB–C pair (1.″42) revolves on its 112 year orbit (Newburg 1969), while the closer AB pair (0.″17) with period of 4.6 years was derived by Mason & Hartkopf (1999). The most detailed analysis is that by Watson et al. (2001), who analyzed this chromospherically active EB using spectroscopic and photometric techniques.

2.6. V773 Cas

V773 Cas (HD 10543, HR 499, HIP 8115, BU 870AB) is an Algol-type EB. One time of minimum light was derived from the *Hipparcos* observations, and three new minima were observed by the authors (see Table 2). The astrometry covers about 80° in position angle, from observations obtained during the last

9 http://sirrah.troja.mff.cuni.cz/∼zasche/Catalog.html

10 http://www.student.oulu.fi/∼ktikkane/AST/V355AND.html

Table 1
The Catalog

HD	Star	Spectral Types			V	P	p_3	π	Comp	Min	Min	M	Depth	Depth	Orbit	References
(1)	Designation (2)	1 (3)	2 (4)	3 (5)	(mag) (6)	(days) (7)	(yr) (8)	(mas) (9)	(10)	Pri (11)	Sec (12)	Astr. (13)	MinP (14)	MinS (15)	(16)	(17)
123	V640 Cas	G3V	M2-3	G9V	5.93	1.026	106.7	49.30 ± 1.05	3	2	0	572	0.066 V		y	1,2,3,4,5
1082	V348 And		B9IV		6.76	5.539	137.9/330	4.05 ± 0.76	3	1	0	61	0.150 Hp		y	1,2,6,7,8
4134	V355 And		F6V		7.69	4.7184	⋯	8.22 ± 1.74	3	7	2	51	0.310 V	0.21 V	n	1,2,9
6882	ζ Phe	B6V	B8V	A7V	3.97	1.66978	220.9	11.66 ± 0.77	3	25	17	11	0.510 V	0.31 V	y	1,2,11,12,13
9770	BB Scl	K3-4V	K4-5V	K1-2V+M2V	7.14	0.47653	4.56+111.8	42.29 ± 1.47	4	2	0	88+44	0.220 Hp	0.22 Hp	y	1,2,14,15,16,17
10543	V773 Cas	A3V		F0-5	6.21	1.29367	304.04	12.63 ± 0.77	3	4	0	79	0.090 Hp		y	1,2,18,19,20
12180	AA Cet	F2V	F2V	F5	7.22	0.53617	⋯	4.63 ± 2.36	4	160	80	33	0.500 p	0.50 p	n	1,2,21,76
14817	V559 Cas	B9V	B9V	B9V	7.02	1.5806	836	4.43 ± 1.51	3	9	6	101	0.220 V	0.20 V	y	1,2,22,21
19356	β Per	B8V	G8IV	A7m	2.12	2.86731	1.862	35.14 ± 0.90	3	≈1400	9	37	1.270 V	0.05 V	y	1,2,23,24
25833	AG Per	B3Vn	B3	B	6.69	2.02873	⋯	3.89 ± 1.31	3	51	52	39	0.310 V	0.31 V	n	1,2,25
29911	V592 Per	F2IV		G0V	8.37	0.71572	115.32	5.12 ± 1.55	3	11	15	19	0.350 Hp	0.27 Hp	Y	1,2,26,27
35411	η Ori	B1V	B3V	B2V	3.38	7.9904	9.44	3.62 ± 0.88	4	1	0	19	0.290 V	0.26 V	y	1,2,21,28
36486	δ Ori A	09.5II	B0.5III	B	2.23	5.73248	704.8	3.56 ± 0.83	3	6	3	38	0.120 V	0.06 V	Y	1,2,29
38735	V1031 Ori	A8III-IV	A5IV-V	A6IV-V	6.06	3.40556	92.66	4.99 ± 1.04	3	8	5	20	0.410 V	0.30 V	Y	1,2,21,30
57061	τ CMa	O9II		O	4.39	1.28212	⋯	1.02 ± 0.71	4	2	0	32	0.050 Hp	0.04 Hp	n	1,2,31
60179	YY Gem	dM1e	dM1e	A1V	9.07	0.81428	⋯	63.27 ± 1.23	6	97	85	140	0.690 V	0.68 V	n	1,2,32
66094	V635 Mon	G9III-IV	A2.5	F5	7.31	1.80781	257	3.06 ± 1.04	3	113	2	24	0.500 p		y	1,2,33,34,35
71487	NO Pup	B9V	A7V	A3V+A3V	6.7	1.25688	⋯	5.32 ± 0.87	5	10	5	29	0.450 V	0.13 V	n	1,2,21,36
71581	VV Pyx	A1V		A5-A7	6.58	4.59618	⋯	4.51 ± 1.00	3	6	5	11	0.520 V	0.50 V	n	1,2,37
71663	LO Hya	F0V	G0V	A5V+F5V	6.42	2.49963	54.70	11.73 ± 0.94	5	3	3	69	0.240 V	0.10 V	y	1,2,21,38
74956	δ Vel	A0V	A1V	F	1.95	45.150	142.00	40.90 ± 0.38	3	5	5	38	0.400 V		y	1,2,39,40
⋯	AC UMa	A2		G0	10.3	6.85469	1199.2		3	80	0	10	3.700 V		Y	1,41
82780	DI Lyn	F2V	F3V	G3V	6.76	1.68154	64.257	11.80 ± 2.50	5	3	2	12	0.080 V	0.05 V	y	1,2,42,43,44
91636	TX Leo	A2V		B	5.67	2.44507	⋯	7.05 ± 0.99	3	8	0	140	0.090 V	0.03 V	n	1,2,45,46
101205	V871 Cen		O7IIIn		6.49	2.0842	1715.8	−1.44 ± 1.42	5	1	0	17	0.080 V	0.08 V	Y	1,2,47
101379	GT Mus	A0V	A2V	K4III+dF/G	5.17	2.7546	90.7	5.81 ± 0.64	4	0	0	13	0.130 V		y	1,2,48,49
103483	DN UMa	A3V	A3V	A8-9	6.54	1.73043	136.538	4.07 ± 1.24	5	11	8	34	0.100 B	0.10 B	y	1,2,50,51
110317	VV Crv		F5IV		5.27	3.145	⋯	11.72 ± 1.90	5	1	0	156	0.150 Hp		n	1,2,52,53
114529	V831 Cen	B8V		B9V	4.58	0.64252	27.0	9.42 ± 1.52	5	1	0	40	0.170 V	0.15 V	y	1,2,54,55
119931	HT Vir	F8V	F8V	F	7.16	0.40764	260.7	15.39 ± 2.72	4	21	22	277	0.420 V	0.42 V	y	1,2,13,56,57
⋯	ET Boo		F8		9.09	0.64504	113.32	5.85 ± 1.40	4	18	13	20	0.300 Hp	0.20 Hp	y	1,2,58,59
133640	i Boo	K0V	K4V	G2V	4.76	0.26782	206	78.39 ± 1.03	3	358	241	753	0.600 V	0.49 V	y	1,2,5,60
148121	V1055 Sco		G3V		8.64	0.36367	⋯	11.45 ± 1.25	3	4	3	12	0.250 V	0.25 V	n	1,2,61
157482	V819 Her	F2V	F8V	G7III-IV	5.57	2.22964	5.530	15.53 ± 1.16	3	63	34	34	0.085 V	0.05 V	y	1,2,62,63
162724	V906 Sco	B9V	B9V	B9	5.96	2.78595	34.71	3.23 ± 0.83	3	6	1	14	0.270 V	0.25 V	Y	1,2,64
163151	V2388 Oph	F3V		F	6.26	0.80230	8.925	14.72 ± 0.81	3	21	10	35	0.280 Hp	0.23 Hp	y	1,2,65,66
163708	V1647 Sgr	A1V	A2V	F0-1V	6.8	3.28279	1219.7	8.70 ± 1.40	3	9	11	15	0.630 V	0.49 V	Y	1,2,67
165590	V772 Her	G1V	K6V	K7V+M0V	7.10	0.87950	20.08	26.51 ± 1.35	5	29	0	256	0.100 V		y	1,2,68,69
184242	V2083 Cyg		A3		6.88	1.86749	372	3.98 ± 0.79	3	5	2	58	0.240 Hp	0.24 Hp	y	1,2,7,9

Table 1
(Continued)

HD	Star	Spectral Types			V	P	p_3	π	Comp	Min	Min	M	Depth	Depth	Orbit	References
(1)	Designation (2)	1 (3)	2 (4)	3 (5)	(mag) (6)	(days) (7)	(yr) (8)	(mas) (9)	(10)	Pri (11)	Sec (12)	Astr. (13)	MinP (14)	MinS (15)	(16)	(17)
185936	QS Aql	B5V	F3	B4	5.99	2.51331	61.72	1.98 ± 0.82	3	21	3	76	0.130 V	0.04 V	y	1,2,70,71
187949	V505 Sgr	A2V	G5IV	F7-8V	6.49	1.18287	60.14	8.58 ± 1.38	3	316	6	17	1.050 V	0.17 V	y	1,2,72,73
195434	MR Del	K2	K6	K2	11.01	0.52169	1996.6	22.53 ± 5.13	3	16	11	37	0.310 V	0.17 V	Y	1,2,17
197433	VW Cep	K1	G5	K3	7.3	0.27832	29.79	36.16 ± 0.97	3	1093	821	17	0.450 V	0.33 V	y	1,2,13,74
201427	BR Ind		F8V		7.1	0.89277	167	20.47 ± 2.08	3	1	0	37	0.140 Hp		y	1,2,69

Notes. Columns 3–5 give the individual spectral types of primary, secondary, and tertiary components, V denotes the magnitude in V filter, P stands for the orbital period of the eclipsing pair, p_3 gives the period of the third body, π quotes the *Hipparcos* parallax, Column 10 gives the total number of known components in the system, Columns 11 and 12 stand for the number of times of primary and secondary minima observed (including our new ones), M denotes the number of astrometric observations, Columns 14 and 15 give the depths of primary and secondary minima. In Column 16 "y/n" indicates if there is (or not) an orbital solution for the system. The upper case "Y" denotes the orbital solution presented here for the first time. Column 17 lists the references for the particular system, respectively. The orbital periods p_3 are adopted from the published papers, or as determined in the present analysis., References: (1) Samus et al. 2004; (2) Perryman & ESA 1997; (3) Brettman et al. 1983; (4) Griffin 1999; (5) Söderhjelm 1999; (6) Olević 2002; (7) Seymour et al. 2002; (8) Abt 1981; (9) Abt 1985; (10) Tikkanen 2002; (11) Andersen 1983; (12) Clausen et al. 1976; (13) Zasche & Wolf 2007; (14) Newburg 1969; (15) Mason & Hartkopf 1999; (16) Watson et al. 2001; (17) Cutispoto et al. 1997; (18) Appenzeller 1967; (19) Schröder & Schmitt 2007; (20) Popović & Pavlović 1995; (21) Chambliss 1992; (22) Zaera 1985; (23) Pan et al. 1993; (24) Lestrade et al. 1993; (25) Gimenez & Clausen 1994; (26) Rucinski et al. 2007; (27) Grenier et al. 1999; (28) Balega et al. 1999; (29) Harvin et al. 2002; (30) Andersen et al. 1990; (31) van Leeuwen & van Genderen 1997; (32) Leung & Schneider 1978; (33) Docobo & Ling 2008; (34) Ginestet & Carquillat 2002; (35) Malkov et al. 2006; (36) Wolf et al. 2008; (37) Andersen et al. 1984; (38) Docobo & Ling 2007; (39) Otero et al. 2000; (40) Argyle et al. 2002; (41) Strohmeier 1959; (42) Wolf & Caffey 1998; (43) Tokovinin et al. 2006; (44) Tokovinin 1998; (45) Chamberlin & McNamara 1957; (46) Roberts et al. 2005; (47) Walborn 1973a; (48) Murdoch et al. 1995; (49) Parsons 2004; (50) Popper 1986; (51) Aristidi et al. 1999; (52) Massarotti et al. 2008; (53) Malaroda 1975; (54) Finsen 1964; (55) Edwards 1976; (56) Walker & Chambliss 1985; (57) Lu et al. 2001; (58) Seymour 2001; (59) Bartkevičius & Gudas 2002; (60) Docobo & Andrade 2006; (61) Houk 1982; (62) van Hamme et al. 1994; (63) Muterspaugh et al. 2006; (64) Alencar et al. 1997; (65) Yakut et al. 2004; (66) Hartkopf et al. 1996; (67) Andersen & Gimenez 1985; (68) Reglero et al. 1991; (69) Fekel et al. 1994; (70) Holmgren 1987; (71) Zasche 2008; (72) Tomkin 1992; (73) Cvetković et al. 2008; (74) Kaszas et al. 1998; (75) Houk 1978; (76) Duerbeck & Rucinski 2007.

Table 2
New Minima Timings of Selected Systems Based on CCD and Photoelectric Observations, the Kwee-van Woerden (1956) Method was Used

Star	HJD-2400000	Error	Type	Filter	Obs.
V773 Cas	54507.4103	0.0005	Pri	R	[1]
V773 Cas	54533.2864	0.0007	Pri	R	[1]
V773 Cas	54776.4933	0.0003	Pri	I	[4]
AA Cet	53687.4389	0.0002	Pri	R	[2]
V559 Cas	54433.3446	0.0004	Sec	BVR	[1]
V559 Cas	54505.2635	0.0004	Pri	R	[1]
V559 Cas	54535.2957	0.0007	Pri	R	[1]
V559 Cas	54738.4053	0.0009	Sec	BVRI	[4]
V559 Cas	54810.3245	0.0025	Pri	BVRI	[4]
V592 Per	54432.4787	0.0003	Sec	R	[1]
V592 Per	54491.5237	0.0003	Pri	R	[1]
V592 Per	54517.2911	0.0003	Pri	R	[1]
V592 Per	54523.3741	0.0005	Sec	R	[1]
V592 Per	54774.5904	0.0003	Sec	R	[4]
V592 Per	54798.5679	0.0003	Pri	R	[4]
V592 Per	54826.4795	0.0005	Pri	R	[4]
V1031 Ori	54831.3964	0.0003	Sec	R	[4]
V1031 Ori	54860.3377	0.0004	Pri	R	[4]
V635 Mon	54539.2564	0.0014	Pri	BV	[2]
V635 Mon	54857.4412	0.0019	Pri	R	[4]
AC UMa	54620.4612	0.0003	Pri	R	[3]
DI Lyn	54585.3703	0.0015	Sec	R	[1]
DI Lyn	54591.2478	0.0020	Pri	R	[1]
DI Lyn	54912.4254	0.0017	Pri	VRI	[4]
DI Lyn	54933.4489	0.0025	Sec	BVR	[1]
TX Leo	54595.4140	0.0021	Pri	R	[4]
DN UMa	52381.7956	0.0003	Sec	BV	[5]
DN UMa	54508.4873	0.0012	Sec	R	[1]
DN UMa	54521.4630	0.0009	Pri	R	[1]
DN UMa	54834.6816	0.0012	Pri	R	[1]
HT Vir	54539.4315	0.0003	Pri	VR	[2]
HT Vir	54539.6368	0.0005	Sec	VR	[2]
ET Boo	54524.4746	0.0002	Pri	VRI	[3]
i Boo	54499.4495	0.0003	Pri	R	[1]
i Boo	54499.5855	0.0001	Sec	R	[1]
i Boo	54499.7179	0.0001	Pri	R	[1]
V1055 Sco	53090.1272	0.0025	Pri	V	[6]
V1055 Sco	53090.3076	0.0031	Sec	V	[6]
V819 Her	54564.3794	0.0040	Pri	R	[1]
V819 Her	54585.5559	0.0020	Sec	R	[1]
V819 Her	54594.4766	0.0010	Sec	R	[4]
V819 Her	54623.4631	0.0010	Sec	BVR	[1]
V819 Her	54642.4133	0.0030	Pri	BVR	[4]
V819 Her	54738.2917	0.0021	Pri	R	[1]
V2388 Oph	54534.6075	0.0030	Sec	R	[2]
V2388 Oph	54583.5470	0.0003	Sec	R	[4]
V2388 Oph	54593.5738	0.0002	Pri	R	[4]
V2388 Oph	54614.4372	0.0006	Pri	R	[4]
V2388 Oph	54620.4524	0.0005	Sec	R	[4]
V2388 Oph	54675.4117	0.0004	Pri	R	[1]
V2388 Oph	54718.3351	0.0004	Sec	R	[1]
V772 Her	54540.5504	0.0021	Pri	R	[4]
V772 Her	54584.5230	0.0008	Pri	R	[4]
V772 Her	54628.5031	0.0009	Pri	R	[1]
V772 Her	54713.8093	0.0010	Pri	R	[1]
V2083 Cyg	54583.5507	0.0003	Pri	R	[1]
V2083 Cyg	54598.4903	0.0007	Pri	BVR	[1]
V2083 Cyg	54683.4603	0.0008	Sec	BVR	[1]
V2083 Cyg	54684.3951	0.0006	Pri	BVR	[1]
V2083 Cyg	54698.4014	0.0005	Sec	BVR	[1]
V2083 Cyg	54712.4065	0.0005	Pri	BVR	[1]
QS Aql	54309.4160	0.0030	Pri	R	[1]
QS Aql	54383.5446	0.0005	Sec	R	[1]
QS Aql	54696.4583	0.0020	Pri	R	[4]
QS Aql	54726.6177	0.0005	Pri	R	[1]

Table 2
(Continued)

Star	HJD-2400000	Error	Type	Filter	Obs.
QS Aql	54726.6177	0.0006	Pri	R	[1]
V505 Sgr	52837.4766	0.0030	Pri	BVRI	[2]
V505 Sgr	52843.3892	0.0029	Pri	VRI	[2]
V505 Sgr	53263.3029	0.0002	Pri	R	[2]
V505 Sgr	54267.5470	0.0002	Pri	VI	[2]
V505 Sgr	54270.5016	0.0040	Sec	I	[2]
V505 Sgr	54648.4260	0.0005	Pri	R	[4]
V505 Sgr	54655.5233	0.0003	Pri	R	[4]
V505 Sgr	54658.4817	0.0005	Sec	R	[4]
V505 Sgr	54706.3869	0.0002	Pri	R	[4]
MR Del	54278.4913	0.0005	Sec	R	[3]
MR Del	54676.5415	0.0010	Sec	R	[4]
MR Del	54682.5395	0.0010	Pri	BVR	[4]
MR Del	54706.5374	0.0003	Pri	R	[4]
VW Cep	54521.2597	0.0002	Sec	R	[1]
VW Cep	54522.3723	0.0003	Sec	R	[1]
VW Cep	54522.5128	0.0003	Pri	R	[1]
VW Cep	54536.2892	0.0003	Sec	R	[1]
VW Cep	54536.4282	0.0002	Pri	R	[1]
VW Cep	54536.5670	0.0002	Sec	R	[1]

Note. [Obs.]: [1] P. Svoboda, Brno; [2] Athens Observatory; [3] Ondřejov Observatory; [4] R.Uhlař, Jílové u Prahy; [5] San Pedro Mártir Observatory; [6] OMC *INTEGRAL* satellite.

120 years. The most recent preliminary visual orbit calculation by Popović & Pavlović (1995) derives a period of about 304 yr and a semimajor axis about 1″.

2.7. AA Cet

AA Cet (HD 12180, HIP 9258, ADS 1581 A) is a W UMa-type EB. There have been more than 200 times of minima obtained during the last 40 years, but no significant LITE variation has been detected. Astrometric observations of the visual pair have shown no significant change since its discovery by William Herschel in 1782; hence no orbital solution has been attempted. One new minimum of light was observed at Athens Observatory (see Table 2). Recently, Duerbeck & Rucinski (2007) discovered the visual component to be also a binary.

2.8. V559 Cas

V559 Cas (HD 14817, HIP 11318, STF 257AB) is an Algol-type eclipsing and spectroscopic binary. There have been only 14 observed times of minima since 1971, including our latest ones (see Table 2). Due to its very long orbital period (about 836 years, according to Zaera 1985), only about 100° of the orbit has been observed since 1830. Periastron passage occurred in 1932 and was well covered; regrettably, no minima times were determined during that era.

2.9. β Per

Algol (β Per, HD 19356, HR 936, HIP 14576, LAB 2Aa,Ab) is the well known prototype of this class of binaries. With its 2.12 mag in *V*, it is the second brightest system in the catalog. The time of minimum brightness was first measured by Montanari on 1670 November 8 (although the variability of the "Demon star" had been known from much earlier times). The current set of times of minima is very large, with about 1400 observations covering the past three centuries, and photoelectric measurements dating as far back as 1910 (Stebbins 1910). In spite of this, a detailed description of period variations in the $O-C$ diagram is still missing. The system is rather complicated, but the distant component (orbital period ∼1.8 yr) originally discovered on the basis of RV variations, was first resolved by speckle interferometry in 1973 (Labeyrie et al. 1974). The orbit of this component is now well established ($a = 94.6$ mas and $e = 0.23$, according to Pan et al. 1993). Several distant companions are listed in the WDS, but these are probably optical.

2.10. AG Per

AG Per (HD 25833, HIP 19201, STT 71AB) is an Algol-type EB. Over 100 times of minima, obtained from the 1920s up to the present, have been collected from the published literature. AG Per is one of the most typical apsidal-motion systems, and has been analyzed several times (see, e.g., Wolf et al. 2006). Data are sufficient for combining the apsidal motion and LITE into one joint solution (similar to the ζ Phe case). Precise light curves have also been measured and analyzed (see Woodward & Koch 1987). On the other hand, although astrometric observations have been obtained 39 times since 1846, the change in position angle has been too small to permit an orbital solution.

2.11. V592 Per

V592 Per (HD 29911, HIP 22050, COU 1524) is a β-Lyrae EB system. There have been 25 times of minima published to date, six of them observed for this paper (see Table 2). Astrometric data cover only about 20°, with 19 data points obtained over 28 years. A preliminary orbit has been computed (using standard methods, see, e.g., Batten 1973), yielding a period of about 115 years and a semimajor axis of about 220 mas. The derived elements are given in Table 3 and plotted in Figure 1, together with all observations used in the solution. Due to the fact that the orbit is only a preliminary one, the resulting derived mass of the system is unreliable. In this case, the mass derived from the visual orbit (about 6 $M_\odot$) is considerably higher than would be expected according to the estimated spectral types. New observations are needed.

Table 3
Orbital Elements for the Newly Derived Solutions and the Total Masses of the Systems According to These Orbital Solutions

WDS Designation $\alpha\delta$(2000)	Variable Star Designation	Period p_3 (yr)	Epoch of Periastron T_0 (yr)	Semimajor Axis a ($''$)	Inclination i (deg)	Longitude of Periastron ω (deg)	Eccentricity e	Longitude of Node Ω (deg)	Total Mass ($M_\odot$)
04445+3953	V592 Per	115.3	1903.9	0.223	79.1	98.5	0.498	210.0	6.21
		±7.1	±6.4	±0.030	±8.4	±9.7	±0.006	±9.0	±4.08
05320-0018	δ Ori A	704.8	1972.8	0.970	96.9	95.2	0.914	325.3	40.7
		±127.7	±145.2	±0.331	±13.8	±9.6	±0.165	±17.3 :	±32.2
05474-1032	V1031 Ori	92.66	1942.6	0.176	76.3	0.3	0.001	111.9	5.11
		±6.61	±7.8	±0.007	±8.2	±28.5 :	±0.001	±9.4	±1.13
08558+6458	AC UMa	1199.2	1349.0	30.15	106.5	102.7	0.790	62.9	$5\cdot10^6$
		±341.8	±280.5	±0.52	±7.8	±8.9	±0.047	±6.8	$\pm4\cdot10^6$
11383-6322	V871 Cen	1715.8	909.2	1.316	81.9	73.8	0.730	234.8	3390
		±285.4	±230.1	±0.445	±13.0	±14.8 :	±0.106	±8.8	±2860
17539-3445	V906 Sco	34.71	1974.1	0.172	80.5	183.0	0.001	103.0	125.2
		±1.13	±1.2	±0.015	±6.8	±9.7	±0.002	±9.7	±46.7
17592-3656	V1647 Sgr	1219.7	1778.4	14.36	94.7	269.4	0.841	113.8	3021
		± 83.4	±76.2	±6.08	±8.5	±21.2	±0.027	±12.7	±468
20312+0513	MR Del	1996.6	1945.9	3.763	74.2	0.0	0.493	61.2	1.17
		±170.5	±130.3	±0.156	±8.4	±7.4	±0.051	±8.0	±0.40

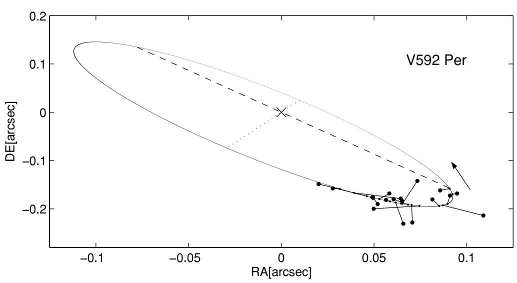

Figure 1. Relative orbit of V592 Per on the plane of the sky. Individual measurements are plotted as dots, and straight "$O - C$" lines connect the these observations to their predicted positions on the fitted orbit. The cross indicates the position of the eclipsing binary on the sky, the dotted line represents the line of apsides, and the dashed line the line of nodes.

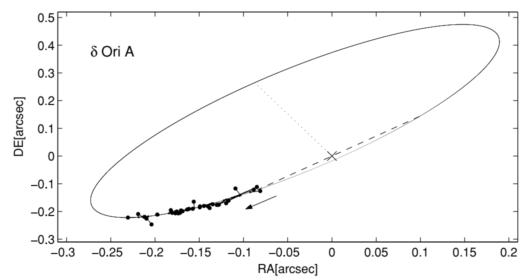

Figure 2. Relative orbit of δ Ori A on the plane of the sky.

2.12. *η Ori*

η Ori (HD 35411, HR 1788, HIP 25281, MCA 18Aa,Ab + DA 5AB) is a quadruple system with three resolvable components. The primary is an eclipsing and also a double-lined spectroscopic triple (periods 8 days and 9.2 years). One of the components also has a pulsation period of ~8 hr. There has been only one published time of minimum, derived from the *Hipparcos* observations. The orbit of the interferometric pair (MCA 18Aa,Ab) derived by Balega et al. (1999) finds an orbital period of about 9.44 yr, in reasonable agreement with the spectroscopic period.

2.13. *δ Ori A*

δ Ori A (HD 36486, HR 1852, HIP 25930, HEI 42Aa,Ab) is a massive EB with an orbital period 5.7 days. Only nine times of minima were found in the literature, and these minima do not show any significant LITE variation (more probably apsidal motion). On the other hand, there is a fair amount of motion on the plane of the sky seen in the 38 measurements obtained since the visual pair was first observed in 1978. The preliminary orbit listed in Table 3 and shown in Figure 2 predicts a period of about 705 years and a semimajor axis of 1$''$. From the orbital parameters, the total mass of the system is about 40 $M_\odot$. For a detailed discussion about the masses of the binary components, see Harvin et al. (2002). There appears to be a problem with the derived masses of primary and secondary, which are substantially below the expected masses for stars of their luminosity. On the other hand, the evolutionary tracks of stars with the measured values of [$\log T_{\rm eff}$, $\log L$] predict much higher masses for both components. If we accept the masses derived by Harvin et al., the mass of the third component should be about 20 $M_\odot$. Single stars of such a mass should be observable via a UV flux contribution, which has not happened. A plausible conclusion is that the distant component is probably also a binary.

2.14. *V1031 Ori*

V1031 Ori (HD 38735, HR 2001, HIP 27341, MCA 22) is an Algol-type detached system. Twelve times of minima have been found in the literature. A new circular orbit of the interferometric binary is shown in Figure 3. Based on only 20 observations obtained from 1980 to 1997, the solution is obviously very preliminary. The derived orbital period is about 93 yr and the semimajor axis about 0$''$.18 (see Table 3 for the parameters). From our new orbital solution, we derive a mass of $M_{123} = (5.1 \pm 1.1)\ M_\odot$ for all three components.

Based on the RV measurements and a few speckle observations, Andersen et al. (1990) concluded that the orbit

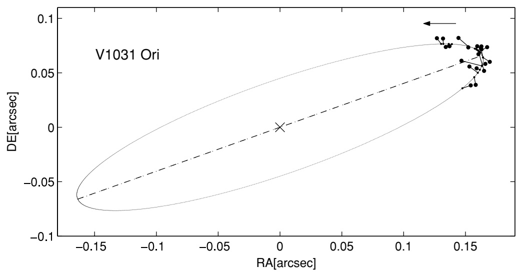

Figure 3. Relative orbit of V1031 Ori on the plane of the sky.

should be much larger, with a period of about 3700 years. Third-component lines were observed in the spectra of V1031 Ori and RVs for the 93 year orbit would be much larger than measured. Andersen et al. (1990) also derived the physical parameters of both eclipsing components, resulting in $M_{12} = (4.76 \pm 0.04)\, M_{\odot}$. However, they assumed that the wide orbit is coplanar with the EB orbit, which is not necessary true in multiple systems. Because the orbital coverage is so poor, only further interferometric observations, as well as precise RV investigation will reveal the true nature of the system. New times of minima are also needed.

2.15. τ CMa

τ CMa (HD 57061, HR 2782, HIP 35415, FIN 313Aa,Ab) is the brightest star in the open cluster NGC 2362. It is a β-Lyrae-type EB, with a period about 1.28 days. τ CMa is also a spectroscopic binary with an orbital period of about 154.9 days; the EB is probably the visual secondary (Stickland et al. 1998). This interesting system therefore contains both the longest period spectroscopic binary and the shortest period EB known among the O-type stars. The system was precisely analyzed by van Leeuwen & van Genderen (1997). This triple system is one member of the visual binary FIN 313Aa,Ab, which has been measured astrometrically 32 times since 1951. The change in position angle is still quite small, however, so no orbital solution has yet been attempted.

2.16. YY Gem

YY Gem (Castor C, α Gem C, HD 60178J, HIP 36850, STF 1110AB) is an EB and also the C component of the Castor multiple system. The three visual components are all doubles: A and B are spectroscopic binaries, while C is the EB YY Gem; we therefore are dealing with a sextuple system. (A fourth visual companion is also listed in the WDS; however, the D component shows a very different proper motion and is likely an optical rather than physical companion.) About 180 times of minima have been published for YY Gem. With 1341 observations covering nearly two centuries, the orbit of the AB pair ($p_3 = 467$ yr, $a = 6\overset{''}{.}8$) is well defined now. However, no significant change in position angle has been seen in the orbit of component C around the AB pair, despite data spanning 180 years.

2.17. V635 Mon

V635 Mon (HD 66094, HIP 39264, A 1580AB) is an Algol-type EB. It is well observed, with over 100 times of minima published to date; however, these data points follow the linear ephemeris without any indication of a LITE. A total of 24 astrometric measurements have been made over the past century, spanning about 150° (although phase coverage was very sparse through most of that time). The most recent analysis by Docobo & Ling (2008) gives a period of 257 years, with a semimajor axis of about 313 mas.

2.18. NO Pup

NO Pup (HD 71487, HR 3327, HIP 41361, B 1605Ba,Bb) is an eccentric EB of Algol type. There have been 15 times of minima observed and the apsidal motion of the system has been studied a few times, resulting in an apsidal period of about 37 years (Giménez et al. 1986). Altogether there are four visible components in this multiple system, with the eclipsing system probably comprising the primary. Chambliss (1992) has estimated that the close Ba,Bb pair orbit with a period of about 32 years, but no orbital analysis has yet been published. The relative separation and angle between A and the pair comprising B has remained essentially unchanged over the past 160 years. A fourth component was discovered in 1997, using adaptive optics, by Tokovinin et al. (1999), but has not yet been confirmed.

2.19. VV Pyx

VV Pyx (V596 Pup, HD 71581, HR 3335, HIP 41475, B 2179AB) is an Algol-type EB and also a double-lined spectroscopic binary. Andersen et al. (1984) analyzed the light curve and also the RV curves of the system, deriving a precise set of physical parameters. There were 11 times of minima found in the literature (1976–2005), but these data show very slow apsidal motion (on the order of centuries). The visual orbit is also covered only very poorly, with 11 observations obtained over the course of 38 years showing a change in position angle of about 13°; no orbital analysis is yet possible. Andersen et al. (1984) speculate that the visual companion could also be a binary; speckle interferometric observations have ruled out any companions with separations greater than ∼30 mas and magnitude difference less than about 3 mag, but only further precise observations could prove or disprove the existence of closer and/or fainter companions.

2.20. LO Hya

LO Hya (HD 71663, HR 3337, HIP 41564, A 551AB) is another Algol-type EB. A detailed analysis of this system was performed by Bakos (1985). Both the A and B components are spectroscopic binaries, while the distant C component also appears to be a physical companion. We therefore deal with at least a quintuple system. One spectroscopic component is also the EB LO Hya, with an orbital period of about 2.5 days. Six times of minima have been found in the literature. Some 69 astrometric measurements obtained during the last century reveal a visual orbit with a 55 year period (see Docobo & Ling 2007).

2.21. δ Vel

δ Vel (HD 74956, HR 3485, HIP 42913, I 10AB) is an Algol-type EB classified as A1V spectral type; at $V = 1.95$ mag it is the brightest system in the catalog. The star was discovered to be photometrically variable in 1997 (see Otero et al. 2000 for details); the period of such variation is about 45 days. Altogether 10 times of minima were obtained, but these observations indicate very slow apsidal motion (on the timescale of centuries). The visual A and B components orbit with a period of about 142 years and a semimajor axis of about 2″ (according

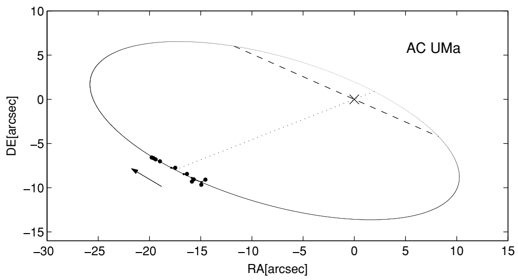

Figure 4. Relative orbit of AC UMa on the plane of the sky.

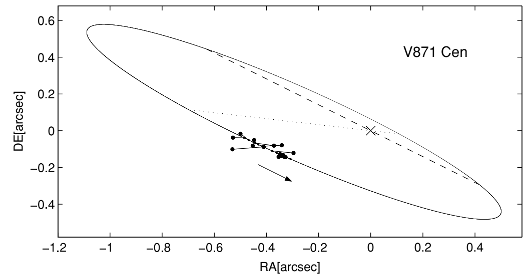

Figure 5. Relative orbit of V871 Cen on the plane of the sky.

to Alzner & Argyle 2000). The whole system is, however, more complicated, consisting of two proper-motion pairs (with separations of 2″ and 6″, respectively), separated in the sky by 72″. The primary component was additionally resolved into a 15 mas pair by long-baseline interferometry. We therefore appear to be dealing with a system of at least six components. However, thanks to the interferometric observations and detailed analysis by Kellerer et al. (2007), the picture of the system has been simplified somewhat. According to these authors, the two distant components C and D do not belong to the system. Furthermore, the 45 day period interferometric orbit appears to correspond to that of the eclipsing pair.

2.22. *AC UMa*

AC UMa (ARG 21AB) is an Algol-type EB, and at $V = 10.3$ mag is one of the faintest systems studied here. The orbital period is about 6.85 days. The 80 times of minima found in the literature suggest a possible variation in orbital period on the timescale of decades, but this finding is inconclusive and a larger data set is needed. The visual orbit shown in Figure 4 is based on only 10 observations obtained during the past 106 years. As one can see, only a short arc of the orbit is covered by data, so one cannot derive the parameters of the orbit precisely. This solution gives an extremely long period of about 1200 years, although this value could be even longer (see Table 3). Another possible explanation is that the distant component is only an optical companion and not physically associated with the EB system. The different proper motions of the two visual components suggest this latter interpretation to be the more probable one (see the Catalog of Rectilinear Elements[11] for details). Another argument that the component is probably not gravitationally bound with the EB is the fact that the total mass computed from the visual orbit is unacceptably high, see Table 3.

2.23. *DI Lyn*

DI Lyn (A Hya, HD 82780, HR 3811, HIP 47053, COU 2084Aa,Ab) is an Algol-type EB. There is only one time of minimum available in the literature, see Wolf & Caffey (1998); however, four additional minima were measured for this paper (see Table 2). This hierarchical system is rather complicated, and contains at least five physical components, see Tokovinin et al. (2006), component C seems to be only an optical one. Two components are spectroscopic binaries (periods 28 days and 1.7 days), one of them is also the EB DI Lyn. Tokovinin (1997) estimated the period of the close visual Aa,Ab pair at ∼64 yr. However, any orbital solution has been published, and this estimation of period was based only on the relative motion of these stars—only about 28° in 22 years—and the Kepler's third law, so this may be an underestimate.

2.24. *TX Leo*

TX Leo (HD 91636, HR 4148, HIP 51802, STF 1450AB) is an Algol-type EB and its apparent brightness is about $V = 5.67$ mag. There have been eight times of minima observed since 1930. The astrometric data set is much larger, about 140 measurements secured over the last 180 years, but the relative motion has been minimal.

2.25. *V871 Cen*

V871 Cen (HD 101205, HIP 56769, I 422AB) is a β-Lyrae-type EB. There is a brief paper on the photometric observations of V871 Cen, together with one minimum time derived (see Mayer et al. 1992). Confirmation of the period of its photometric variability is based on analysis of *Hipparcos* and ASAS data, see Otero (2007). The system includes four visual components; astrometric measurements of the closest pair secured during the last 104 years reveal a change in position angle of only about 20°, so our 1700 year period orbital solution is not very convincing (see Table 3 and Figure 5 for details). Also a derived total mass of the system more than 3000 $M_{\odot}$ indicates an unacceptable solution with the current data.

2.26. *GT Mus*

GT Mus (HD 101379, HR 4492, HIP 56862, B 1705AB) is one component of a quadruple system, as each member of this close visual pair is itself a close binary (see Murdoch et al. 1994). One of them is a spectroscopic binary with period about 61 days, which is also an RS CVn-type binary, while the other one is an EB with orbital period about 2.75 days. No minima have been published. Astrometric data obtained during 76 years and cover about 110° of the orbit. The estimated period of the AB pair is about 91 years (Parsons 2004). The visual pair has two faint wide companions; the physical/optical nature of these is unknown.

2.27. *DN UMa*

DN UMa (HD 103483, HR 4560, HIP 58112, A 1777AB) is another Algol-type EB, which comprises the primary component of the visual quadruple system ADS 8347. The D component of this system is over 1 arcmin in separation from the primary; however, the similarity in parallax indicates the wide pair is probably physical. A detailed light-curve analysis was published by Garcia & Gimenez (1986) and an RV curve analysis by Popper (1986). There have been 16 observed times of

[11] http://ad.usno.navy.mil/wds/lin1.html

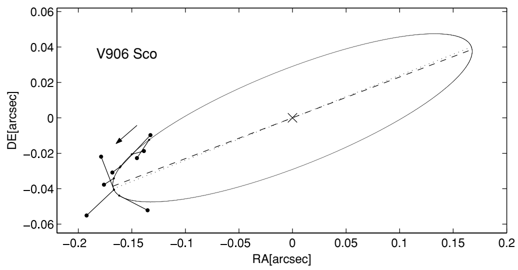

Figure 6. Relative orbit of V906 Sco on the plane of the sky.

minima from 1979 until our recent measurements (see Table 2). The visual orbit is defined reasonably well, with a century's worth of data covering nearly a full revolution. The most recent orbit was by Aristidi et al. (1999), who derived $p_3 = 136.5$ yr and $a = 230$ mas.

2.28. *VV Crv*

VV Crv (HD 110317, HIP 61910, STF 1669AB) is a system consisting of two spectroscopic binaries (periods 44.51 days and 1.46 days; see Massarotti et al. 2008). The eclipsing nature of one of its components was discovered from *Hipparcos* data (Perryman & ESA 1997); this gave an orbital period of about 3.14 days, suggesting that the system might be quintuple. *Hipparcos* data have also provided the only time of minimum found thus far in the literature. Astrometric data have been obtained over the past 180 years, but have described a change in position angle of about only 14°. Due to this short arc, no orbit has been calculated; however, Tokovinin et al. (2006) have estimated the period of AB pair to be about 4500 years.

2.29. *V831 Cen*

V831 Cen (HD 114529, HR 4975, HIP 64425, SEE 170AB) is a β-Lyrae system and also a spectroscopic binary, with an orbital period of about 0.64 days. The only published minimum is that measured by the *Hipparcos* satellite. The close AB pair of this visual quadruple system has been observed for over 100 years, with a single attempt at an orbital solution by Finsen (1964) yielding $p_3 = 27$ yr and $a = 185$ mas. $O - C$ errors are quite large, however; this is due primarily to the small separation of the AB pair, but perhaps also in part to the presence of the nearby C component (separation $< 2''$) further complicating the early measurements.

2.30. *HT Vir*

HT Vir (HD 119931, HIP 67186, STF 1781) is a contact W UMa system. Although only a visual binary, the system is in fact quadruple, with three components visible in the spectra. The spectroscopic single-lined binary (period 32.5 days) constitutes component A, while the EB (period 0.41 days) is the B component. Astrometric measurements have been made regularly since Struve's discovery of the visual pair in 1830, defining the orbit quite precisely. On the other hand, times of minima have been measured only a few times since discovery of the eclipsing variable. A detailed analysis of this system, combining the angular position measurements and period variation, was presented in ZW.

2.31. *ET Boo*

ET Boo (HIP 73346, COU 1760) is a ninth magnitude β-Lyrae EB. The system has been found to be quadruple, according to Pribulla et al. (2006). There have been 31 times of minima published to date, including one new value published here (see Table 2). It is also a close visual binary, discovered in 1978 (Couteau 1981). Astrometric measurements obtained between 1978 and 1999 have shown a change in position angle of about 40°; unfortunately it has not been observed in nearly a decade. A very preliminary orbit was derived by Seymour (2001), giving a period of about 113 years and an angular semimajor axis of 261 mas. Variation of the orbital period is hardly detectable with available data; therefore, new observations of minima and also astrometry are needed.

2.32. *i Boo*

i Boo (HD 133640, HR 5618, HIP 73695, STF 1909AB) is a well known EB of the W UMa type and, at a distance about 13 pc, also the nearest system in the catalog. Many times of minima have been observed over the last 90 years, including three new values listed in Table 2, but a satisfactory explanation of the period changes is still lacking. It is an X-ray binary and has also been found to exhibit flares. There is quite a large set of astrometric measurements of the visual binary, dating back to its discovery by William Herschel in 1781, and most phases of the orbit are quite well defined. The most recent orbital analysis finds a period of about 206 years and a semimajor axis of $3''.8$ (Söderhjelm 1999).

2.33. *V1055 Sco*

V1055 Sco (HD 148121, HIP 80603, B 872AB) is a β-Lyrae EB. There have been only seven times of minima published in the literature, two of them derived from photometric data obtained by the Optical Monitoring Camera (OMC) onboard the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL)* satellite (see Table 2). Astrometric measurements obtained during the last 70 years cover only about 15° in position angle, making it much too premature to attempt a solution to the visual orbit.

2.34. *V819 Her*

V819 Her (HD 157482, HR 6469, HIP 84949, MCA 47) is an Algol-type EB, orbiting about a common center of mass with a third component in a 5.5 year period orbit. Eccentricity is about 0.67, and LITE is evident. The wider pair was discovered by speckle interferometry in 1980 (McAlister et al. 1983) and has been extensively observed by this technique and also more recently with the Palomar Testbed Interferometer (Muterspaugh et al. 2008). In this system, LITE was analyzed together with the interferometry and RV data (see Muterspaugh et al. 2006).

2.35. *V906 Sco*

V906 Sco (HD 162724, HR 6662, HIP 87616, B 1871AB) is a detached triple-lined EB. A detailed photometric and spectroscopic analysis of this system was made by Alencar et al. (1997), who also included a discussion about possible apsidal motion. A new visual orbit has been derived (see Figure 6 and Table 3); in this solution only the more precise interferometric measurements from the astrometric data set were used, due to the much larger scatter in the earlier micrometry data. The last astrometric observations of any type were obtained more than

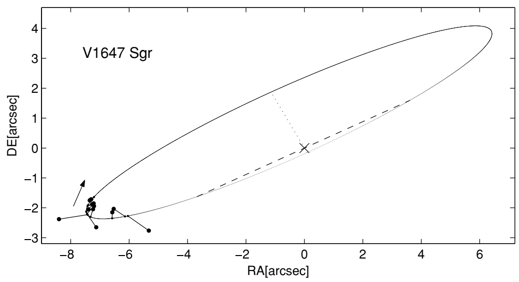

Figure 7. Relative orbit of V1647 Sgr on the plane of the sky.

15 years ago, so new measurements are needed to improve upon this solution. Also a total mass about 100 $M_\odot$ indicates this orbit to be a preliminary one.

2.36. V2388 Oph

V2388 Oph (HD 163151, HR 6676, HIP 87655, FIN 381) is a contact EB of W UMa type. A detailed analysis of *ubvy* light curves was performed by Yakut et al. (2004) and an RV analysis by Rucinski et al. (2002). A preliminary solution for the visual orbit was made by Hartkopf et al. (1996), finding a period of about 9 years. Unfortunately, there have been only a few observations published of times of minima; due to the poor sampling afforded by these data, no variation in the $O - C$ diagram for minima times is evident.

2.37. V1647 Sgr

V1647 Sgr (HD 163708, HIP 88069, HJ 5000) is an Algol-type EB. A few dozen times of minima are available; these data indicate a slow apsidal motion with a period about 530 years (see Wolf 2000). Andersen & Gimenez (1985) published the most detailed study of the whole system to date, including into their analysis also the visual component. Astrometric measurements of the visual pair obtained over the past 170 years cover only about 14° in position angle, as shown in Figure 7. A preliminary orbit was computed for the first time, but the results are not very convincing due to the limited phase coverage. The period derived here is about 1200 years (see Table 3 for the orbital parameters); the total mass which results in more than 3000 $M_\odot$ makes this solution unrealistic.

2.38. V772 Her

V772 Her (HD 165590, HIP 88637, STT 341AB) is an EB as well as an RS CVn variable star. This is the A component of a close visual triple and spectroscopic binary of very high eccentricity; Heintz (1982) derived values of $p_3 = 20$ yr and $e = 0.956$. See also Batten et al. (1979) for details on the spectroscopic orbit. The C component is physically connected to the system and was also found to be a spectroscopic variable (period is about 25 days, according to Fekel et al. 1994). We therefore deal with at least a quintuple system (the WDS lists four additional wide companions, but these are probably optical due to their fast relative motion; see Tokovinin 1997). There have been more than 20 times of minima published to date. Bruton et al. (1989) published an $O - C$ diagram with 16 minima times, fitted with a LITE curve based on parameters derived from the visual orbit.

2.39. V2083 Cyg

V2083 Cyg (HD 184242, HIP 96011, A 713) is an Algol-type EB. There has been only one time of minimum (based on *Hipparcos* data) published, our six new observations are in Table 2. Astrometry of the close visual pair during the last century covers about 70° of the orbit. A preliminary orbital solution by Seymour et al. (2002) gives a period of about 372 years and an angular semimajor axis about 498 mas.

2.40. QS Aql

QS Aql (HD 185936, HR 7486, HIP 96840, KUI 93) is an Algol-type eclipsing, and also spectroscopic, binary. The 24 available minima observations (four of which are new; see Table 2), allow the period variation to be clearly visible. The close visual binary has been observed for over 70 years; the recent orbit by Docobo & Ling (2007) finds an extremely large eccentricity ($e = 0.966$), but many of the observations show large residuals to this 62 year period solution. Combined analysis is still problematic (see Mayer 2004) due to poor coverage of the system by both methods.

2.41. V505 Sgr

V505 Sgr (HD 187949, HR 7571, HIP 97849, CHR 90) is an Algol-type eclipsing (and also spectroscopic) binary. Since its discovery as a variable, several light-curve measurements and analyses have been attempted, the latest by İbanoğlu et al. (2000). A detailed spectral analysis of the system was published by Tomkin (1992), who also noted discovery of a third component in the spectrum of the system, as well as a slow change in the RV of this component. Solution of the visual orbit is still uncertain: Tomkin (1992) estimated a period of about 100 years, while Mayer (1997) derived an orbit with a period of about 38 years; the recent orbit by Cvetković et al. (2008) found a period of 60 years. The problems of the visual orbit and the LITE solution were discussed in Zasche (2008). The set of times of minima is quite large (more than 300 observations), but a detailed explanation of the period changes is still lacking (see Chochol et al. 2006). Nine new minima observations were obtained, see Table 2.

2.42. MR Del

MR Del (HD 195434, HIP 101236, AG 257AB) is an Algol-type EB; at $V = 11.01$ it is the faintest object in the catalog. There have only been a few times of minima observed during the last 15 years; four additional new measurements are given in Table 2. Although the visual pair has been observed for a century, the position angle has changed by only about 15°. Such a small change suggests an orbital period of order 2000 years; our preliminary solution is given in Table 3 and illustrated in Figure 8. The resulting total mass results in about 1.2 $M_\odot$.

2.43. VW Cep

VW Cep (HD 197433, HIP 101750, HEI 7) is a W UMa-type system, whose primary and secondary are both chromospherically active. There have been numerous LITE studies made of this system; Herczeg & Schmidt (1960) proposed the presence of a third body with an orbital period of 29 years and an angular separation between 0.″5 and 1.″2. In 1974, the first successful visual observation of the third component was obtained by Heintz (1975). The visual orbit is fairly well defined, and the parameters of this orbit (see Docobo & Andrade 2005) are in agreement

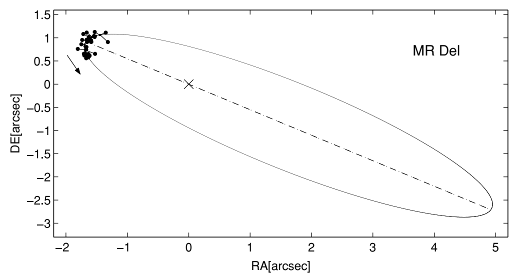

Figure 8. Relative orbit of MR Del on the plane of the sky.

with the LITE variation in the $O - C$ diagram of minima timings (see ZW for details). This system seems to be perhaps the most suitable one for simultaneous analysis of both the period variation and the visual orbit; this technique could also derive the distance to the system. Six new minima observations were obtained for this paper; see Table 2.

2.44. BR Ind

BR Ind (HD 201427, HIP 104604, HU 1626AB) is an Algol-type EB. The position angle of the visual binary changed by ∼80° between 1914 and 2001; this was sufficient to define a preliminary orbit of $p_3 = 167$ yr and $a = 894$ mas (Seymour et al. 2002). The only published time of minimum was derived from *Hipparcos* data.

2.45. Other Systems

There are also numerous other cases where the strict conditions introduced in the beginning of Section 2 are not satisfied. Some of the more interesting systems are presented in Table 4. Their visual orbits have not yet been derived, due to insufficient phase coverage. In most of these systems the change of position angle is too slow, or there are still only a few measurements available. One could expect that during the next decades some of these systems will move to that ones in chapter 2.

2.46. Special Cases

There are also a number of "special cases" which were not included in the catalog due to their more complicated or uncertain nature. A few examples are described below.

1. In all systems included in the catalog, the close EB comprises one component of a much wider visual interferometric pair. However, in a few rare cases the components of the EB also comprise the components of the visual pair. The systems β Aur, β Cap, γ Per, and V695 Cyg are eclipsing pairs which have also been resolved by interferometry (another possible example of such a system is α Com). The chances of an orbit being sufficiently edge-on to produce eclipses are of course greater for systems with smaller separations; it is therefore expected that the number of such "visual–eclipsing" binaries will increase as more EBs are observed by long-baseline interferometers. However, these systems do not meet the criteria for inclusion in this catalog.
2. Another class of objects not included in the catalog is that of the so-called ellipsoidal variables. Systems such as HD 178125 (18 Aql, Y Aql) or HD 22124 (IX Per) are also sometimes classified as EBs and a few "minima" have been published, as well.
3. The system HD 217675 (o And, 1 And) is sometimes classified as an EB. In fact, this quadruple system (Hill et al. 1988) is photometrically variable (Olsen 1972), but, according to (Pavlovski et al. 1997), it is not an EB.

3. DISCUSSIONS AND CONCLUSION

More than 13,000 systems in the WDS had sufficiently large astrometric data sets to allow potential analysis and were, therefore, checked for the presence of EB components. Many stars which were suspected to be variables were found in this large set, but only a very limited number of these systems had ever been given detailed spectroscopic or photometric analysis. Systems chosen for inclusion in this catalog were selected on the basis of EB designations in the SIMBAD database and notes in the WDS.[12] However, in many cases identification of a star as an eclipsing variable is a rather difficult task; because of this, many such systems are designated in SIMBAD only as "variable stars." Although the current number of known visual doubles containing eclipsing variables as components is still quite limited, this number is expected to increase substantially as the true nature of more of these "variable stars" is determined through further photometric observation.

A long-term goal is to increase the size of this catalog to the point where reliable statistical analysis of this class of systems may be attempted. The subset of visual multiple systems including EB components could be another area of potential interest. If one has information about the various orbits in these systems, the ratio of periods or the mutual inclinations of the long and the short orbits could prove an interesting probe into the mechanisms for formation of these objects. Also a frequency of quadruple or quintuple systems among multiples could be studied. The main catalog in the present paper includes seven quadruple systems, eight quintuples, and one sextuple. However, there are still many cases, where the membership of a star to the system is questionable, so this fraction of multiples is expected to increase.

Regrettably, many of the systems in the catalog lack recent observations. Ironically, this is due in part to the fact that many of these systems are too bright for modern photometric equipment. Some of the earliest known EBs are now neglected, since they can easily saturate a CCD detector mounted on even a modest telescope. Phase coverage of most visual binary orbits is insufficient, due largely to the exceedingly long orbital periods of these pairs. Astrometry of closer interferometric pairs is also lacking, as shifting priorities of telescope allocation committees has made it difficult for observers to get time on the large telescopes needed for obtained these data. As a result, analysis is complicated, and newly derived orbital elements are affected by relatively large errors due to small arcs of the orbit covered and/or sparse phase coverage.

In conclusion, although a few of the systems in the catalog presented here (e.g., V505 Sgr, QS Aql, V2388 Oph) are suitable for simultaneous analysis of period variation and astrometry, in most cases the time span of observations is still too short and more data are needed. The highest priority systems for which interferometric observations are desired include V1031 Ori, ET Boo, and V906 Sco. Systems especially in need of additional photometric observations for minima determinations are V1031 Ori, LO Hya, V906 Sco, and V2388 Oph.

[12] http://ad.usno.navy.mil/wds/wdsnewnotes_main.txt

Table 4
Other Eclipsing-Visual Systems

HD	Star	Spectral Types			EB Type	V	P	Min	Min	M	Depth	Depth	$\Delta\Theta/\Delta T$	References
	Designation	1	2	3		(mag)	(days)	Pri	Sec	Astr.	MinP	MinS	(°)/(yr)	
1061	UU Psc		F0IV		EW	6.01	0.84168	1	0	145	0.05 V	0.05 V	1/225	1,2,3
4161	YZ Cas	A2IV	F2V		EA	5.65	4.46722	32	3	11	0.41 B	0.07 B	0/103	4,5
4502	ζ And	K1III	F		EW	4.10	17.7695	3	2	4	0.22 V	0.10 V	40/91	4,6
5679	U Cep	B7V	G8III–IV	G8III	EA	6.92	2.49291	1268	1	8	2.49 V	0.18 V	1/119	4,7
8152	AQ Psc		F8V		EW	8.67	0.47561	11	11	4	0.36 V	0.36 V	6/81	1,8,9
	RS Tri		A5V		EA	10.26	1.90892	85	1	9	0.73 V	0.13 V	1/110	4,10
13078	BX And	F2V	K		EB	8.98	0.61011	257	42	22	0.67 b	0.25 b	2/176	4,11
	GZ And	G5V	G5V	M3V	EW	10.89	0.30502	99	118	9	0.78 V	0.75 V	4/170	4,12,13
	EX Per	A1			EA	12.00	8.47595	8	2	10	0.80 V	0.50 V	2/96	4
18541	ST Per	A3	K1-2IV		EA	9.61	2.64836	341	2	4	1.88 V	0.10 V	0/70	4,14
24909	IQ Per	B8V	A6V	A3	EA	7.73	1.74356	125	15	18	0.55 V	0.16 V	0/132	4,15,16
25638	SZ Cam	O9IV	B0.5V	B0	EB	6.93	2.69847	77	14	78	0.29 B	0.24 B	2/177	4,17
34335	CD Tau	F7V	F5IV	K2	EA	6.77	3.43514	51	40	29	0.57 V	0.54 V	1/178	4,18
35921	LY Aur	O9III	O9.5III	B0V	EB	6.85	4.00250	32	17	31	0.69 V	0.60 V	4/105	4,19
37020	θ Ori	B3V	A7IV	O7V	EA	7.96	6.47053	19	0	112	0.75 V	0.08 V	0/176	4,20
					+ EA	+ 6.73	+ 65.4329	+ 24	+0		0.93 V			4,20
62863	PV Pup	A8V	A8V	A2V	EA	6.93	1.66073	2	3	59	0.44 V	0.43 V	1/225	4,21
65818	V Pup	B1V	B3IV		EB	4.45	1.45449	16	4	6	0.57 V	0.47 V	1/119	4,22
74307	S Cnc	B9V	G8IV	G0V	EA	8.35	9.48454	234	0	5	1.96 V	0.10 V	0/120	4,16,23
75821	KX Vel		B0III		EA	5.09	26.30624	0	0	8	0.08 B		4/65	4,24
83950	W UMa	F8V	F8V		EA	7.96	0.33363	1176	284	4	0.73 V	0.68 V	7/80	4,25
89714	HP Car		B0.5III		EA	8.93	1.60045	1	0	4	0.45 V	0.45 V	18/59	4,26
93206	QZ Car	O9.7I	B0I	O9V	EB	6.24	5.9991	5	1	4	0.33 V	0.27 V	0/85	4,27,28
	AM Leo		F8V		EW	9.31	0.36580	194	139	41	0.58 V	0.58 V	0/175	4,29
99769	MN Cen		B2-3V		EA	8.8	3.48901	7	4	10	0.40 b	0.10 b	0/117	4,30
99946	AW UMa	A8Vn		G5	EW	6.92	0.43873	103	72	21	0.30 V	0.25 V	0/131	4,31
106400	AH Vir	G8V	G8V	K1V	EW	9.33	0.40753	261	169	7	0.60 V	0.53 V	2/93	4,32
114911	η Mus		B8V		EA	4.77	2.3963	2	0	17	0.05 V		3/176	4,33
117408	SS Hya	A0V		A0	EA	7.86	8.2	1	0	4	0.22 B		6/108	4,34
132742	δ Lib	A0V	K0IV	F	EA	4.95	2.32735	200	0	4	0.99 V		3/94	4,35
134646		F4III		G8	EA	6.82	2.44405	1	0	11	0.13 V	0.06 V	2/102	36,37
135421	BV Dra	F9V	F8V		EW	8.04	0.35007	53	61	39	0.60 V		1/167	4,38
	+ BW Dra	+G3V	+G0V		+EW	+ 8.74	+ 0.29217	+ 53	+ 42		+ 0.47 *V*	+ 0.41 *V*		4,38
138672	EI Lib	A3-7	F5-8	Am	EA	9.50	1.98691	4	0	7	1.00 b		3/79	4,16,34
139319	TW Dra	A5V	K0III		EA	7.43	2.80685	499	5	36	2.50 b		4/157	4,39
139966	HH Nor	F0		F0IV	EA	10.2	8.58313	1	0	9	1.20 b		0/164	4,30,40
149730	R Ara		B9IV		EA	6.65	4.42509	6	0	21	0.90 b	0.20 b	8/164	4,30
150708	WW Dra	G2IV	K0IV	F2V	EA	8.59	4.62972	84	10	23	0.65 V	0.08 V	1/175	4,20
153751	ϵ UMi	G1	A-F		EA	4.22	39.4809	1	0	6	0.04 V	0.02 V	4/80	4,41
155937	AK Her	F2V	F6V	K2V	EW	8.51	0.42152	460	161	14	0.48 V	0.35 V	0/104	4,12,20
156247	U Oph	B5V	B5V	B5	EA	5.90	1.67735	431	257	13	0.72 V	0.62 V	3/123	4,42
156633	u Her	B2IV	B8III	B	EB	4.80	2.05103	222	36	28	0.68 V	0.24 V	2/158	4,43
161321	V624 Her	A4	A7		EA	6.20	3.89498	3	1	7	0.18 V	0.17 V	0/98	4,44
161783	V539 Ara	B3V	B4V	A0-1V	EA	5.92	3.16913	17	12	16	0.52 V	0.43 V	2/166	4,45
163181	V453 Sco		B0I		EB	6.61	12.00597	4	1	5	0.37 V	0.34 V	3/89	4,33
165814	V3792 Sgr	B4IV		B9IV	EB	6.71	2.24808	2	0	10	0.45 V	0.38 V	1/130	4,34,46
166937	μ Sgr	B8I	B1.5V	B9III	EA	3.84	180.55	1	0	18	0.08 V		5/177	1,42,47
	TZ Lyr		F5V		EB	10.77	0.52883	400	5	5	0.98 V	0.18 V	6/74	4,29
167647	RS Sgr	B5V	A2V	A1V	EA	6.03	2.41568	36	8	8	0.96 V	0.27 V	2/108	4,48,49
174638	β Lyr	B8II	B6.5	B5V	EB	3.52	12.93763	1475	923	93	1.11 V	0.60 V	6/129	4,50,51
178001	BH Dra	A2V	A7	Am	EA	8.43	1.81724	193	0	20	0.89 V	0.20 V	2/103	4,10,33
180639	V342 Aql	A4II	K0IV	K2II	EA	8.68	3.39088	121	0	41	3.40 b		1/160	4,52,53
181987	Z Vul	B4V	A3III		EA	7.33	2.45493	425	17	5	1.65 V	0.33 V	0/101	4,54
183794	V822 Aql	B3	B9		EA	7.12	5.29495	16	6	24	0.57 V	0.20 V	5/126	4,73
185507	σ Aql	B3V	B3V	G8V	EB	5.18	1.95026	6	3	6	0.20 V	0.10 V	3/170	4,16,42
191515	V346 Aql	A0V	G4IV		EA	9.08	1.10636	702	0	19	1.10 b	0.10 b	3/69	4,10
192909	V1488 Cyg	K3I	B4-5	A	EA	4.02	1147.4	1	0	10	0.24 V		2/178	4,55
	V1191 Cyg		F6V		EW	10.8	0.31338	23	19	5	0.33 V	0.29 V	2/107	4,56
198287	V367 Cyg	A7	B6-7		EB	7.04	18.59773	88	32	7	0.93 V	0.49 V	115/56	4,57
199005	KZ Pav	F6V	K4IV	F2	EA	7.75	0.94988	86	11	21	1.59 V		1/165	4,58
203069	RY Aqr	A8V	K1	K2V	EA	8.86	1.96658	161	4	4	1.30 V		1/101	4,59
204215	KP Peg		A2V		EB	7.28	0.72721	8	0	91	0.21 V		5/177	4,60
206155	EE Peg	A3V	F5V	K5V	EA	6.98	2.62821	77	2	5	0.58 V	0.13 V	123/24	4,20
208392	EM Cep	B0.5V	B1V	B1V	EW	7.03	0.80619	27	24	26	0.15 V	0.14 V	0/175	4,10,61

Table 4
(Continued)

HD	Star Designation	Spectral Types 1	2	3	EB Type	V (mag)	P (days)	Min Pri	Min Sec	M Astr.	Depth MinP	Depth MinS	$\Delta\Theta/\Delta T$ (°)/(yr)	References
209278	DX Aqr	A2V	K0III		EA	6.37	0.94501	164	5	81	0.41 V		2/184	4,62
209943	V376 Cep	F5		F6IV-V	EA	7.43	1.166	2	0	150	0.07 V		9/182	1,63
211853	GP Cep	WN6o/WCE	O3-6	B0:I	EB	9.03	6.6884	1	0	12	0.11 V		0/94	4,64
				+ B1:V-III	+ EB		+ 3.4696	+ 1	+ 0					
215661	ZZ Cep	B7	F0V	A2	EA	9.00	2.14180	240	0	23	0.95 V	0.14 V	1/155	4,10,65
216309	SU Aqr		A2IV		EB	9.95	1.04470	44	0	9	0.60 b	0.30 b	1/99	4,34
219113	SZ Psc	F8V-IV	K1IV		EA	7.44	3.96579	60	0	5	0.54 V	0.20 V	1/91	4,66,67
221253	AR Cas	B4.2IV		A6V	EA	4.88	6.06633	9	1	11	0.14 V	0.04 V	2/119	4,68
232121	SX Cas	B7	K3III		EA	9.05	36.56375	82	1	6	0.87 V	0.36 V	1/95	4,69
256320	FI Ori	F5	K2IV	F7V	EA	10.3	4.44815	40	1	10	0.90 b		7/95	4,70,71
261025	AK Aur	A1	F5III	F5	EA	10.20	4.76314	8	1	10	0.50 B		0/179	4,10
349425	AD Her	A4V	K2		EA	9.68	9.76661	26	0	17	1.47 V	0.09 V	0/107	4,72

Notes. For the explanation of the individual columns, see Table 1. In the column, the "EB types" are the following abbreviations: "EW" for W UMa type, "EB" for β Lyrae type, and "EA" for Algol-type eclipsing binaries, respectively. The column $\Delta\Theta/\Delta T$ denotes the mean rate of the position angle variation with time, which has been derived only from the first and the last measurements of the system. θ Ori, BV+BW Dra, and GP Cep constitute multiple systems with two eclipsing binaries. The system GP Cep is more complicated, its light curve is rather "eclipsing like" (see Demers et al. 2002). References: (1) Samus et al. 2004; (2) Cowley & Fraquelli 1974; (3) Shobbrook 2005; (4) Malkov et al. 2006; (5) Celikel & Eryurt-Ezer 1989; (6) Kővári et al. 2007; (7) Plavec 1983; (8) Djurašević et al. 2006; (9) Sarma & Radharkrishnan 1982; (10) Brancewicz & Dworak 1980; (11) Samec et al. 1989; (12) Rucinski et al. 2007; (13) Tokovinin 1997; (14) Olson 1982; (15) Lacy & Frueh 1985; (16) Halbedel 1985; (17) Lorenz et al. 1998; (18) Ribas et al. 1999; (19) Drechsel et al. 1989; (20) Chambliss 1992; (21) Vaz & Andersen 1984; (22) Frieboes 1962; (23) Etzel & Olson 1985; (24) Morgan et al. 1955; (25) Rucinski et al. 1993; (26) Proust et al. 1981; (27) Walborn 1973b; (28) Leung et al. 1979; (29) Hill et al. 1975; (30) Houk & Cowley 1975; (31) Abt 2004; (32) Lu & Rucinski 1993; (33) Levato 1975; (34) Houk & Smith-Moore 1988; (35) Bakiş et al. 2006; (36) Pagel 1960; (37) Otero 2007; (38) Batten et al. 1989; (39) Zejda et al. 2008; (40) Budding 1984; (41) Hinderer 1957; (42) Lindroos 1985; (43) Hilditch 2005; (44) Petrie 1950; (45) Andersen 1983; (46) Gray et al. 2006; (47) Polidan & Plavec 1984; (48) Ferrer & Sahade 1986; (49) Lindroos 1986; (50) Guetter 1968; (51) Harmanec & Scholz 1993; (52) Stephenson 1960; (53) Erdem et al. 2007; (54) Popper 1957; (55) Ginestet & Carquillat 2002; (56) Rucinski et al. 2008; (57) Pavlovski et al. 1992; (58) Svechnikov & Kuznetsova 1990; (59) Helt 1987; (60) Pych et al. 2004; (61) Simonson 1968; (62) Hoffleit & Jaschek 1982; (63) Grosheva 2006; (64) Demers et al. 2002; (65) Carrier et al. 2002; (66) Zhang & Gu 2008; (67) Eaton & Henry 2007; (68) Krylov et al. 2003; (69) Plavec et al. 1982; (70) Fehrenbach 1961; (71) Budding et al. 2004; (72) Batten & Fletcher 1978; (73) Popper 1981.

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The triple system KR Comae Berenices★ *(Research Note)*

P. Zasche[1] and R. Uhlář[2]

[1] Astronomical Institute, Charles University, Prague, V Holešovičkách 2, 18000 Prague 8, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Private Observatory, Pohoří 71, 25401 Jílové u Prahy, Czech Republic

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ABSTRACT

Aims. We present the detailed analysis of triple system KR Com with different observational techniques – photometry, interferometry, and period variation.

Methods. The use of *BVR* photometry of the close-contact binary KR Com, which is the primary component of a triple system, helps us to better describe the properties of the components. The interferometric data obtained during the last 30 years sufficiently determine the visual orbit, but the use of minima timings of KR Com for the study of period variation together with the visual orbit is a novel approach in this system.

Results. Basic physical parameters resulting from the light curve analysis agree well with the previous results from spectroscopy. The temperatures for the primary and secondary component resulted in 5549 and 6072 K, respectively, and the amount of the third light in all filters is about 1/3 of the total luminosity. The distant third component revolves around the common barycenter on 11 yr orbit with a very high eccentricity (0.934) and this movement is also detectable via the period variation, which is clearly visible in the O−C diagram of times of minima observations. The use of minima times for the combined analysis helps us to independently determine the distance to the system (64.02 ± 9.42 pc) and also to confirm the orientation of the orbit in space.

Conclusions. New minima observations and also spectroscopy would be very profitable, especially during the next periastron passage in the year 2017.

Key words. binaries: eclipsing – binaries: visual – stars: fundamental parameters – stars: individual: KR Com

1. Introduction

Multiple stellar systems (i.e., of a multiplicity of three and higher) are excellent objects to be studied. Besides the statistics and their relative frequency among the stars, it is important to investigate these systems in detail, also because of their stellar evolution, their origin, to test the influence of the distant components to the close pair, etc.

One of these systems is KR Com (HD 115955, HIP 65069), which is also A component of the visual binary A 2166 (WDS J13202+1747). Its relative brightness is about 7.2 mag in *V* filter and its combined spectral type has been classified as F8V, Abt (1981). The system has been discovered as a photometrically variable one from the *Hipparcos* data by Selam (2004). Its orbital period is about 0.408 days only, but both eclipses are rather shallow (because of a close bright companion). Although both minima are of similar depths, the system has been incorrectly classified as a β Lyrae one, Kazarovets et al. (1999).

The close binary system has been extensively studied spectroscopically by Rucinski et al. (2002). The radial velocity curve of KR Com has been derived and also an influence of the third body in the system to the close pair and its properties has been discussed in subsequent papers by e.g., D'Angelo et al. (2006). A very low value of the mass ratio of this system has been found, about 0.09 only, which makes KR Com an exceptional case among the W UMa-type binaries. The photometry and light curve solution of the close pair is still missing, which led us to observe this interesting target.

On the other hand, the close visual companion B (with an angular distance about only 0.1″) was detected in 1980 by McAlister et al. (1983). The movement around a barycenter is very fast, its orbital period is about 11 yr and the eccentricity is very high about 0.9. The orbit has been derived by Hartkopf et al. (1996). Owing to the small angular separation between both components, any photometric and also spectroscopic observations cannot be done only for KR Com, and the influence of the third component has to be considered in the analysis. The eclipsing binary is the brighter component ($\Delta m \sim 0.6$ mag), and Rucinski et al. (2002) give the luminosity ratio $L_3/(L_1 + L_2) = 0.56$. They also presented a broadening function, which indicated a slowly rotating third component, and in D'Angelo et al. (2006) the authors provided an estimate about the third-body mass $M_3 = 1.19\ M_\odot$, while the individual masses of the close binary are 1.42 and 0.129 $M_\odot$.

Thanks to the unusually low mass ratio of the eclipsing pair and the presence of the close interferometric component B we deal with a unique system, which is very useful to be studied in detail.

2. Photometry

Owing to its relatively high brightness, the system has not been observed photometrically and studied in detail. There exist the light curves from the *Hipparcos* data (H_p filter), and

★ Photometric tables are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/519/A78

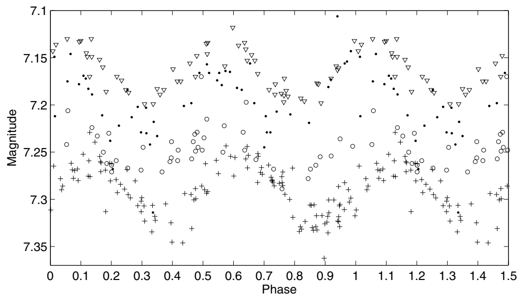

Fig. 1. Observations of KR Com from Hipparcos (plus) and ASAS (circles from 2009, dots from 2005, and triangles from 2003).

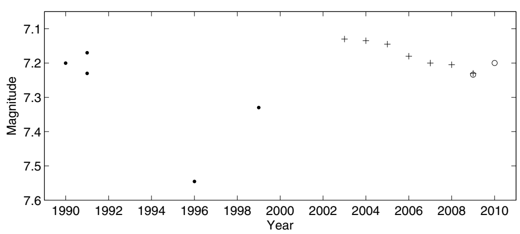

Fig. 2. Long-term variation of brightness of KR Com (in quadratures). Dots represent the various catalog data, the plus signs stand for the ASAS data, and the open circles mark our observations.

from the ASAS survey (V filter), see Fig. 1. Because of the low photometric amplitude and high scatter, these can hardly be used for any analysis of the light curve.

Thanks to the observations obtained by ASAS, which cover more than six years, we have found that there is a long-term photometric decrease of KR Com. It can be seen in Fig. 1, where we present the light curves from from different epochs. As one can see, a steady decrease of its brightness is on the order of 0.1 mag during the last six years.

The nature of this long-term behavior is questionable, as is which component of the system yields this variation. On the other hand, we have tried to find some historical data in various catalogs, which contain at least some information about its magnitude in photometric filters. VIZIER[1] lists 145 catalogs containing several data about KR Com, from which a few usable data points were selected. The most complete are the measurements in the V filter. In Fig. 2 we have plotted the data after 1990. The long-term variation is clearly visible, nevertheless this plot has a few flaws. For some of the points the photometric filter was not exactly the Johnson's V filer, but rather some "similar" one. And secondly, for some of the data points it was quite hard to find an exact date of the observation, only a mean epoch is presented. The most deviating point from 1996 is a typical one. This particular data point comes from "The PM2000 Bordeaux proper motion catalogue" (Ducourant et al. 2006), and in its description is mentioned that the filter used is a non-standard one, a combination of two different filters. Exactly the same problem arises for the second deviating point from 1999, which comes from the "M2000: An astrometric catalog in the Bordeaux Carte du Ciel" (Rapaport et al. 2001). However, both these magnitudes use the same combination of filters and the difference between them during three years is easily visible. A period of this variation could only be vaguely estimated, but it is probably longer than the period of the third body.

One can speculate about the magnetic activity cycles in the system. Because of the spectral type (F8V), these can play a role, see Hall (1989). These cycles could slightly modulate the orbital period of the close pair. Moreover, accepting this hypothesis, according to Applegate (1992) there is also a modulation of the luminosity of the star on the order of $\delta L/L \sim 0.1$. If we propose that the most luminous component (the primary one) undergoes this variation, a variability of the brightness of the whole system results in only about 0.05 mag, which is much lower than observed since 1990. On the other hand, removing these two questionable data points discussed above, one can obtain a variation with an amplitude of about only 0.1 mag, which could be described by this mechanism. Therefore, the nature of this variation still remains an open question.

We have observed the system during the seasons 2009 and 2010. In total there are 17 nights of observations, but for the light-curve analysis we used only 7 nights of observations obtained from March 2010 to April 2010 and carried out with the same telescope and detector at the private observatory by one of the authors (RU). Owing to high brightness of the target, the refractor with a diameter of only 75 mm was used, equipped with the G2/KAF 0402ME CCD camera and standard B, V, and R filters according to specification by Bessell (1990). All the measurements were processed by the software C-M [2], which is based on aperture photometry and using the standard DaoPhot routines (Tody 1993).

The observations were transformed into the standard system using the well-known transformation equations[3]. Star HD 115981 was used as a comparison, while the check star to control the non-variability of the two was star HD 116206. The atmospheric extinction has been neglected because the stars are very close to each other (11 arcmin), their spectral types are also similar, and the observations have never been obtained below 25 deg above horizon. We used this approach because our observations have an accuracy not better than 0.01 mag (for the scatter in individual filters see below), therefore any additional correction on the order of 0.001 mag is practically useless for the transformation. The individual exposure times range from 25 to 140 s.

The rest of observations were used only to determine the minima times for a period analysis. These new ones as well as the already published ones are given in Table 1, where the type of minima refers to the following ephemeris: $2\,454\,924.538 + 0.4079711 \cdot E$. For all these observations, the Kwee-van Woerden method (hereafter KW, Kwee & van Woerden 1956) was used for determining the time of minimum. This method is suitable for symmetric minima (which is the case for KR Com), because its principle is based on comparing the ascending and descending branch of the minima. We do believe that our error estimates are much more reliable than those already published because first, we did a detailed analysis of the KW result for each minimum, which means that we used different data sets (neglecting some of the observed points) and compared these results. And secondly, we also used a polynomial fitting to determine the time of minimum and compared this result with the KW one. The error of the particular minimum light was computed as a maximum difference between all the different results from different methods from the mean value. All minima times given in Table 1 are

[1] http://vizier.u-strasbg.fr/viz-bin/VizieR

[2] See http://c-munipack.sourceforge.net/

[3] See http://brucegary.net/AllSky/x.htm

Table 1. Minima times of KR Com.

HJD-2 400 000	Error	Type	Filter	Reference[a]
48 500.2095	0.0075	Pri	Hp	HIP
48 500.4200	0.0129	Sec	Hp	HIP
52 638.8769	0.0165	Sec	*V*	ASAS – [1]
52 758.41911	0.00232	Sec	*V*	ASAS
52 758.62161	0.00301	Pri	*V*	ASAS
53 058.4796	0.0002	Pri	*C*	Krajci (2005)
53 102.11786	0.00255	Pri	*V*	ASAS
53 150.2695	0.0005	Pri	*C*	Krajci (2005)
53 475.0061	0.0004	Pri	*V*	Nagai (2006)
53 487.86332	0.00518	Sec	*V*	ASAS
53 488.05344	0.00767	Pri	*V*	ASAS
53 829.11608	0.00468	Sec	*V*	ASAS
54 225.87197	0.00849	Sec	*V*	ASAS
54 226.07038	0.00326	Sec	*V*	ASAS
54 233.4095	0.0009	Pri	*C*	[2]
54 580.40196	0.00273	Sec	*V*	ASAS
54 613.0406	0.0002	Sec	Ic	Nagai (2009)
54 921.47502	0.00150	Sec	*B*	this paper
54 921.47435	0.00246	Sec	*V*	this paper
54 921.47702	0.00178	Sec	*R*	this paper
54 921.47534	0.00051	Sec	*I*	this paper
54 924.53515	0.00043	Pri	*B*	this paper
54 924.53553	0.00048	Pri	*V*	this paper
54 924.53559	0.00227	Pri	*R*	this paper
54 924.53549	0.00031	Pri	*I*	this paper
54 940.44566	0.00113	Pri	*R*	this paper
54 971.44977	0.00098	Pri	*B*	this paper
54 971.45562	0.00085	Pri	*V*	this paper
54 971.45419	0.00052	Pri	*R*	this paper
54 944.52261	0.00457	Pri	*V*	ASAS
54 944.32228	0.00565	Sec	*V*	ASAS
55 259.67912	0.00319	Sec	*R*	this paper
55 274.37115	0.00175	Sec	*B*	this paper
55 274.36049	0.00135	Sec	*I*	this paper
55 274.36870	0.00543	Sec	*R*	this paper
55 274.35921	0.00329	Sec	*V*	this paper
55 274.56764	0.00335	Pri	*B*	this paper
55 274.56959	0.00143	Pri	*I*	this paper
55 274.56684	0.00293	Pri	*R*	this paper
55 274.56834	0.00264	Pri	*V*	this paper
55 280.49301	0.00093	Sec	*B*	this paper
55 280.49220	0.00069	Sec	*R*	this paper
55 280.48942	0.00109	Sec	*V*	this paper
55 281.50792	0.00089	Pri	*B*	this paper
55 281.50389	0.00085	Pri	*R*	this paper
55 281.50817	0.00050	Pri	*V*	this paper
55 293.53729	0.00061	Sec	*B*	this paper
55 293.53830	0.00157	Sec	*R*	this paper
55 293.53559	0.00099	Sec	*V*	this paper
55 294.56261	0.00110	Pri	*B*	this paper
55 294.56418	0.00157	Pri	*R*	this paper
55 294.56473	0.00120	Pri	*V*	this paper
55 357.38912	0.00235	Pri	*I*	this paper
55 358.41029	0.00257	Sec	*I*	this paper

Notes. [(a)] HIP – *Hipparcos* observations, ASAS – data from the ASAS survey, [1] – see `http://var.astro.cz/ocgate`, [2] – unpublished yet, see `http://eclipsingbinary.web.fc2.com/vsnetmin.htm`

heliocentric ones. Eleven new minima times were also derived from the data of the ASAS survey (Pojmanski 2002).

3. The light curve analysis

For the light-curve analysis we used the program PHOEBE (Prša & Zwitter 2005), which is based on the Wilson-Devinney

Table 2. Light curve parameters of KR Com.

Parameter	Value	Parameter	Value
T_1 [K]	5549 ± 244	L_1 (B) [%]	50.67 ± 0.20
T_2 [K]	6072 ± 270	L_2 (B) [%]	17.75 ± 0.19
q (=M_2/M_1)	0.091 (fixed)	L_3 (B) [%]	31.58 ± 0.20
e	0 (fixed)	L_1 (V) [%]	47.63 ± 0.24
i [deg]	52.14 ± 0.46	L_2 (V) [%]	18.98 ± 0.23
x_1 (B)	0.774	L_3 (V) [%]	33.39 ± 0.24
x_2 (B)	0.699	L_1 (R) [%]	47.05 ± 0.72
x_1 (V)	0.635	L_2 (R) [%]	19.04 ± 0.67
x_2 (V)	0.565	L_3 (R) [%]	33.90 ± 0.72
x_1 (R)	0.548	Derived quantities:	
x_2 (R)	0.485	R_1 [$R_\odot$]	1.33 ± 0.04
g_1	0.323 ± 0.014	R_2 [$R_\odot$]	0.49 ± 0.02
g_2	0.351 ± 0.021	$M_{bol,1}$ [mag]	4.34 ± 0.18
A_1	0.499 ± 0.027	$M_{bol,2}$ [mag]	6.13 ± 0.24
A_2	0.484 ± 0.015	σ [mag] (B)	0.00745
F_1	1.690 ± 0.066	σ [mag] (V)	0.01583
F_2	1.647 ± 0.148	σ [mag] (R)	0.06737

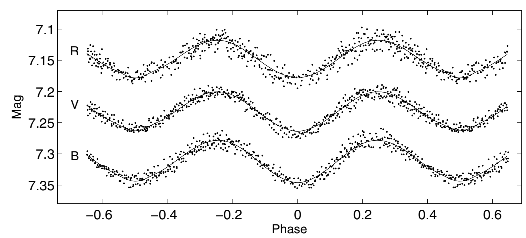

Fig. 3. Our new observations of the light curves of KR Com in three filters. The *B* and *R* curves are shifted for better clarity. The theoretical fits and parameters are described in the text and Table 2.

algorithm (Wilson & Devinney 1971). The model atmospheres made by Kurucz (1996) were used. The derived quantities are: the individual temperatures T_1 and T_2, the inclination i, the luminosities L_i, the gravity darkening coefficients g_i, the limb darkening coefficients x_i, the albedo coefficients A_i, and the synchronicity parameters F_i. The limb darkening was approximated via linear cosine law, and the values of x_1 and x_2 were interpolated from the van Hamme's tables, van Hamme (1993).

Because the system has been analyzed spectroscopically in detail by Rucinski et al. (2002), we used the mass ratio value $q = M_2/M_1 = 0.091$ derived from spectroscopy for the analysis of our *B*, *V*, and *R* photometry. The other relevant parameters of the light curve were computed (with fixed circular orbit) and the results are presented in Table 2. The final fits and the photometric data are plotted in Fig. 3. The scatter in the *B* and *V* filters is about 0.010–0.015 mag, in the *R* about 0.025 mag, and the numbers of data points are 451, 468, and 474, for *B*, *V*, and *R*, respectively. The individual observational errors of the measurements were about 5–10 times lower than a typical peak-to-peak scatter of the measurements in the particular filter. The same applies for the measurement errors for the comparison and check stars. Their respective errors are also on the order of 0.003 mag only, but these values represent merely the mathematical results of errors from the photometry of the stars. More plausible physical errors are much above these values, about 0.01 mag. This is actually a very similar situation as for the minimum estimate and the error of the KW method as discussed in the previous section. No additional short-time variation has been found in the data. The *BVR* photometry used for the analysis is available in electronic form at the CDS.

The errors of the individual parameters were derived from the covariance matrix, following a standard procedure of error estimates, see e.g., "Numerical recipes. The art of scientific computing", Press et al. (1986).

From the light-curve analysis we see that the two components are in contact (A-type contact system), but their individual temperatures differ about more than 500 K. On the other hand, the difference between the temperatures of 523 ± 364 K is only marginally significant. We tried to find an appropriate solution with equal temperatures (which resulted in a value of about 6100 K), but this solution resulted in χ^2 about 13% worse than the solution presented in Table 2. Another approach was to fix the temperature of the primary to T_1 = 6100 K and to fit only the secondary temperature. This resulted in fit with χ^2 about 9% worse than our final solution. Both alternatives have been tested via an F-test to gauge how liable they are to introduce another free parameter (temperature) to the model. We concluded that introducing this new parameter is significant at a level about 86% and 84.5% for these two different approaches.

Our resulting values of parameters from the light curve fit can be compared with the estimates published in Rucinski et al. (2002). A value of the third light (33% of total light) agrees well with their estimate (about 56% of $L_1 + L_2$). The individual components are probably of F+G spectral types for the primary and secondary, respectively. The secondary component has apparently undergone a mass transfer to the primary.

We were able to partly reveal the nature of the third body in the system via its temperature. This can be estimated thanks to the individual luminosities in the filters, from which one can derive the magnitudes in the particular filters. These values resulted in B = 8.96 mag, V = 8.39 mag, and R = 8.05 mag. As an independent comparison one can also check the value from the Washington Double Star Catalog (WDS)[4], where the V magnitudes 7.78 and 8.38 mag are given for the primary and secondary component of the visual pair, which excellently agrees with our value of 8.39 mag. From our estimates of the *BVR* magnitudes, the photometric indices $B-V$ = 0.57 mag and $V-R$ = 0.34 mag can be compared with the color-temperature relations, e.g., by Houdashelt et al. (2000). This gives temperature estimate of the third component of 5900 ± 200 K, which indicates a spectral type between F8 and G6. On the other hand, if we try to derive also the radius of this component from the relation between the radii, luminosities and temperatures $R_3 = \sqrt{L_3/L_1 \cdot (T_1/T_3)^4} \cdot R_1$, we obtain values from 0.93 to 0.99 $R_\odot$, which indicates a later spectral type, about G8-K1 (Harmanec 1988).

4. Combined solution for the visual orbit and period variations

As we mentioned above, the A-B system revolves around a barycenter with a period about 11 yr. Because this orbit has been derived about 15 years ago and many new observations are available since then, there is a need for new up-to-date solution for this orbit.

We used all available interferometric observations for the analysis of the pair collected in the "Fourth Catalog of Interferometric Measurements of Binary Stars[5]", Hartkopf et al. (2001). There are 25 usable measurements (see Table 3). In some of these observations the position angle θ has to be changed by 180° (i.e., quadrant change, interchange of the components), the values presented in Table 3 are the corrected ones.

Table 3. Interferometric observations of A-B pair.

Date	θ [deg]	ρ [arcsec]	References
1980.1566	0.9	0.145	McAlister et al. (1983)
1980.4817	2.0	0.142	McAlister et al. (1983)
1983.0510	10.0	0.117	McAlister et al. (1987)
1983.0701	12.2	0.106	McAlister et al. (1987)
1984.0558	22.6	0.059	Hartkopf et al. (1996)
1986.4067	327.7	0.058	McAlister et al. (1989)
1987.1194	345.5	0.076	Fu et al. (1997)
1987.2642	340.2	0.083	McAlister et al. (1989)
1987.2859	343.0	0.089	Fu et al. (1997)
1987.2886	348.8	0.089	Fu et al. (1997)
1987.2914	346.8	0.089	Fu et al. (1997)
1988.1022	345.5	0.097	Fu et al. (1997)
1989.2300	353.6	0.117	McAlister et al. (1990)
1990.2081	357.9	0.132	Balega et al. (1994)
1990.2621	356.0	0.136	Hartkopf et al. (1992)
1990.2759	356.0	0.135	Hartkopf et al. (1992)
1991.25	357.0	0.136	Perryman & ESA (1997)
1991.3187	0.7	0.140	Hartkopf et al. (1994)
1992.3098	4.3	0.138	Hartkopf et al. (1994)
1992.3127	4.2	0.139	Hartkopf et al. (1994)
1993.1971	7.7	0.128	Hartkopf et al. (1994)
2002.3224	359.8	0.140	Horch et al. (2008)
2002.3224	0.0	0.140	Horch et al. (2008)
2002.3224	0.0	0.139	Horch et al. (2008)
2006.1917	17.8	0.077	Mason et al. (2009)

A movement of the contact binary around the barycenter with the distant component has to produce a periodic variation of orbital period of KR Com, a well-known "light-time effect" (hereafter LITE), see Irwin (1959). The amplitude of the LITE depends on the inclination of the 11 yr orbit, the individual masses and also on the distance of KR Com. The distance from *Hipparcos* was originally derived as 76.51 ± 5.46 pc, i.e., parallax π = 13.07 ± 0.87 mas (Perryman & ESA 1997), but the more recent value is 83.97 ± 5.32 pc, i.e., parallax π = 11.91 ± 0.71 mas, van Leeuwen (2007). Nevertheless, the value of the parallax from the *Hipparcos* satellite could also be influenced by the movement on the long orbit. During the run of the satellite, the change of the position angle of the distant component was only about 15°, because in that time the B component was near apastron on its orbit. On the other hand, if one compares the error of its parallax with the other stars from the *Hipparcos* catalog with the similar parallaxes, the error is apparently not deviating significantly.

For an analysis of the period changes of KR Com we collected all available minima observations. The very first ones are from *Hipparcos* data (recalculated primary minimum and derived also a secondary one), while the most recent ones are our new observations of 2010. All these heliocentric minima times are given in Table 1. We found that all the published minima times have their respective errors strongly underestimated (10 times or even more).

We used a similar approach as described in Zasche & Wolf (2007) for analyzing the interferometric data together with the times of minima. The only difference was a calculation of both amplitudes – the semimajor axis of the visual orbit and the semi-amplitude of LITE in the O−C diagram. The main advantage of this approach is that we can independently calculate the distance

[4] http://ad.usno.navy.mil/wds/
[5] http://ad.usno.navy.mil/wds/int4.html

Table 4. Final parameters of the long orbit.

Parameter	Value
HJD_0	2 453 058.4640 ± 0.0021
P [day]	0.40797003 ± 0.00000239
p_3 [day]	4011.0 ± 98.4
p_3 [yr]	10.98 ± 0.27
T_0	2 442 055.1 ± 118.0
a [arcsec]	0.1131 ± 0.0189
ω_3 [deg]	301.8 ± 3.8
e_3	0.9340 ± 0.0239
i [deg]	67.68 ± 2.03
Ω [deg]	210.03 ± 1.25
A [day]	0.0171 ± 0.0019
$f(M_3)$ [$M_\odot$]	0.3262 ± 0.0896
M_3 [$M_\odot$]	1.598 ± 0.423
a_{12} [AU]	3.677 ± 0.821
a_3 [AU]	3.563 ± 1.027
π [mas]	15.62 ± 1.80

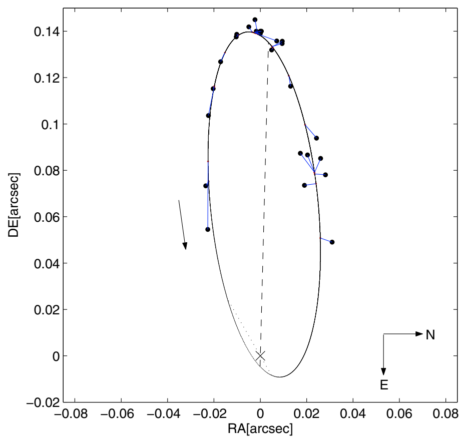

Fig. 4. Orbit of A-B pair on a plane of the sky. The dashed line represents the line of the apsides, while the dotted one stands for the line of the nodes. The cross indicates the position of the eclipsing binary.

(or parallax) to the system and compare it to the *Hipparcos* one. Therefore, the set of parameters to be computed is the following: $HJD_0, P, p_3, T_0, i, a, \omega, \Omega, e_3, A$, where a denotes the semimajor axis in arcseconds, while A stands for the semiamplitude of LITE. We used the least-squares method and the simplex algorithm (see e.g., Kallrath & Linnell 1987). One can also discuss the use of quadratic ephemeris because of some mass transfer between the components, but this was not used in our analysis due to insufficient coverage of the O−C diagram with data points in longer time scales. The two minima times based on *Hipparcos* data were only roughly estimated and therefore their use for the analysis is questionable.

The analysis results in a set of parameters presented in Table 4, where we list all computed values and some of the derived quantities. The final fits are presented in Figs. 4 and 5. For plotting the O−C diagram, the individual minima in different filters were averaged to one point for better clarity. Figure 6 shows the residuals after subtraction of the fit. As one can see, some long-term variation cannot be ruled out with the current data. This could be caused e.g., by a mass transfer between the components, but only future observations can confirm or rule out

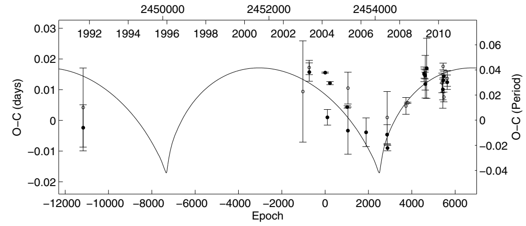

Fig. 5. O−C diagram of KR Com. The primary minima are plotted as dots, the secondary ones as open circles. It is obvious that the respective errors of the published minima times should be larger than presented.

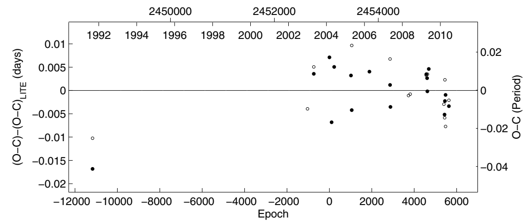

Fig. 6. O−C diagram of residuals of KR Com.

this possibility. Another potential explanation are magnetic cycles with a period of about 20 years (Applegate 1992), which cause not only a brightness variation, but also this period variation. A combination of both mass transfer and magnetic cycles is also possible.

The distance to the system was derived from the fit, resulting in $d = 64.02 \pm 9.42$ pc, closer than from the *Hipparcos* data. However, this value is only roughly estimated because it is derived from comparing the values of A and a, but the detection of the LITE variation and deriving its amplitude is still problematic, and the 11 yr period is not yet sufficiently covered by data. Due to this reason, and due to the relatively large difference between our derived parallax and the value from *Hipparcos*, we introduced Fig. 7. In this figure we fixed the semimajor axis of the visual orbit (this value is much better defined than the amplitude of LITE) and plotted the values of the parallax π and mass of the third component M_3 with respect to the amplitude A of LITE. As one can see, our resulting value of $A = 0.0171$ days yields the values of M_3 and π given in Table 4. If we consider the range of potential values of A according to its error, the values of π are still far from the value derived by *Hipparcos*. Moreover, the mass of the third body with a decreasing value of parallax is growing rapidly. On the other hand, if we presume that the mass of the third component is lower, about e.g., 1.1 $M_\odot$, then the amplitude of LITE is only about 0.013 days (which cannot reliably describe the fit in the O−C diagram) and the parallax results in approximately 16.5 mas, which is even more distant than the *Hipparcos* value.

The other quantity, which can be compared with the previous results, is e.g., the mass of the distant component M_3. D'Angelo et al. (2006) presented a value about 1.19 $M_\odot$, while our estimation is a bit higher, about 1.60 $M_\odot$. This value has been derived from the assumption that the masses of the individual components are $M_1 = 1.42\ M_\odot$ and $M_2 = 0.129\ M_\odot$, which have been taken as constant input values. The resulting value of M_3 is surprising, especially if we take into consideration that the luminosities in all filters resulted in slightly lower values (B: 46%,

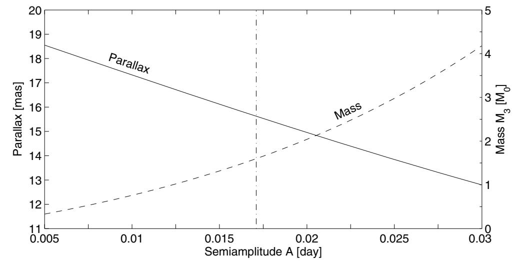

Fig. 7. Diagram of semiamplitude of LITE versus mass of the third body and parallax of the system with the fixed semimajor axis of the visual orbit. The dash-dotted line represents the value of A from our final solution.

V: 50%, R: 51% of $L_1 + L_2$) than assumed by D'Angelo et al. (2006). If the mass of the third body is higher and the luminosity lower, this could indicate that this component is also a binary, or the star is underluminous than one would expect for a star of the main sequence.

5. Discussion and conclusions

The triple system KR Com revealed some of its basic physical properties for the first time. The light curve with shallow minima (due to a bright third component) shows that the system has a relatively low inclination of about only 52°. That we know the inclinations of both orbits is one aspect of KR Com system's uniqueness.

On one hand, a difference between the inclination of the close pair and the inclination of the orbit of the third distant component ($i_3 = 67.8°$) is still relatively small, therefore one could speculate about a common origin of all three components (see e.g., Zakirov 2008). On the other hand, a presence of two orbits which are not strictly coplanar is a necessary condition for a so-called Kozai cycles (Kozai 1962), which could play a role in the formation of this system. As mentioned by D'Angelo et al. (2006), the typical product of the Kozai mechanism is a close pair and a distant component on a non-coplanar orbit, which is the case here.

The other computable quantity in this triple system is its nodal period, or the precession of the orbits, which can change the inclination of the close eclipsing pair and therefore also the depths of the minima, see e.g., Mayer (2005). Regrettably, the nodal period here results in a value of about 100 000 yr.

Today there are only 34 eclipsing binary systems known among the visual double stars that have known visual orbits. In all these systems one should expect a period variation of times of minima observed for these systems, but surprisingly, the LITE that agrees with the visual orbit has been detected in only seven systems (i Boo, VW Cep, ζ Phe, V819 Her, V772 Her, QS Aql, V505 Sgr). The system KR Com seems to be another example. The visual orbit with a period about 11 yr is well-covered by interferometric data, and the combined solution of visual orbit and O−C diagram of minima times is also dominated by the visual orbit. Therefore, the very first minima estimates based on *Hipparcos* data with their large errors were almost useless for the analysis. The other interesting fact is that the already published minima show much larger residuals than their published errors.

However, the combined fit brings new light into the system and confirms for example the ω and Ω values. Because the same fit to the interferometric data could be realized by changing both angles by 180° (orientation of the orbit towards the observer), the LITE fit helps us to confirm the orientation of the orbit in the space without any need for spectroscopy. Nevertheless, the spectroscopic data and new times of minima would be also very profitable, especially in the upcoming periastron passage, which will occur in 2017.

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Astronomy & Astrophysics

Unique sextuple system: 65 Ursae Majoris⋆

P. Zasche[1], R. Uhlář[2], M. Šlechta[3], M. Wolf[1], P. Harmanec[1], J. A. Nemravová[1], and D. Korčáková[1]

[1] Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Private Observatory, Pohoří 71, 25401 Jílové u Prahy, Czech Republic
[3] Astronomical Institute, Academy of Sciences, Fričova 298, 251 65 Ondřejov, Czech Republic

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ABSTRACT

Context. The study of stellar multiple systems provides us with important information about the stellar formation processes and can help us to estimate the multiplicity fraction in the Galaxy. 65 UMa belongs to a rather small group of stellar systems of higher multiplicity, whose inner and outer orbits are well-known. This allows us to study the long-term stability and evolution of the orbits in these systems.

Aims. We obtained new photometric and spectroscopic data that when combined with interferometric data enables us to analyze the system 65 UMa and determine its basic physical properties.

Methods. We perform a combined analysis of the light and radial velocity curves, as well as the period variation by studying the times of the minima and the interferometric orbit. A disentangling technique is used to perform the spectra decomposition. This combined approach allows us to study the long-term period changes in the system for the first time, identifying the period variation due to the motion on the visual orbit, in addition to some short-term modulation.

Results. We find that the system contains one more component, hence we tread it as a sextuple hierarchical system. The most inner pair of components consists of an eclipsing binary orbiting around a barycenter on a circular orbit, both components being almost identical of spectral type about A7. This pair orbits on an eccentric orbit around a barycenter, and the third component orbits with a period of about 640 days. This motion is reflected in the period variation in the minima times of the eclipsing pair, as well as in the radial velocities of the primary, secondary, and tertiary components. Moreover, this system orbits around a barycenter with the distant component resolved interferometrically, whose period is of about 118 years. Two more distant components (4″ and 63″) are also probably gravitationally bound to the system. The nodal period of the eclipsing-pair orbit is on the order of only a few centuries, which makes this system even more interesting for a future prospective detection of changing the depths of minima.

Conclusions. We identify a unique solution of the system 65 UMa, decomposing the individual components and even shifting the system to higher multiplicity. The study of this kind of multiple can help us to understand the origin of stellar systems. Besides 65 UMa, only another 11 sextuple systems have been studied.

Key words. binaries: eclipsing – stars: fundamental parameters – stars: individual: 65 UMa – stars: early-type

1. Introduction

As members of more complex multiple systems, the eclipsing binaries can provide us important information about their physical properties, as derived from different methods. This is the case for 65 UMa, a system whose the close components form an eclipsing binary, and additional components found to be gravitationally bounded to this pair (Pourbaix et al. 2004). Thanks to the combined analysis, we have been able to derive the radii, masses, and evolutionary statuses of the close components, in addition to some properties of the distant ones. These systems are still very rare and mostly lie relatively close to the solar system. Only 39 such systems are known where a close eclipsing binary is a member of a wide visual binary and we know both orbits, their mutual inclinations, ratio of periods, etc. For instance, the ratio of periods can tell us something about the long-term stability of the system. These unique systems are the most suitable for studies of dynamical effects, the short and long-term evolution of the orbits, etc. (see e.g. Söderhjelm 1975).

The study of systems of higher multiplicity is still relatively undeveloped yet, and can provide insight into their formation. Moreover, Goodwin & Kroupa (2005) found that the majority of the early-type stars are found in multiple systems. Star-forming theories are still based on many ad hoc assumptions and the physical characteristics of the multiple systems can provide strong constraints on some of them. These can be e.g. the mass ratios of the inner and outer pairs, the ratio of periods, and inclinations, see for instance (Goodwin et al. 2007; Tokovinin 2008). In addition, the multiplicity fraction is one of the most crucial parameters in theoretical models and nowadays we know of only 20 quintuples, 11 sextuples, and 2 septuple systems (Eggleton & Tokovinin 2008).

2. The system 65 UMa

The multiple system 65 UMa (=WDS J11551+4629) consists of four visible components. The angular distance between the primary and component D (=HR 4561) is about 63″, while the C component is at a distance of about 4″. The primary 65 UMa

⋆ Reduced photometric and spectroscopic data, and Tables A.1–A.4 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/542/A78

AB = DN UMa, the brightest member of the system, was also resolved to be a binary via classical micrometric measurements by Aitken (1908). Since then, many precise interferometric observations of this close pair were carried out. Moreover, the primary component was discovered to be a variable (Gimenez & Quesada 1979). Later, Gimenez & Quesada (1982) found the star to be an eclipsing binary with the orbital period of about 1.7304 d. Its variability was not discovered earlier owing to its rather shallow eclipses of only about 0.09 mag. This is caused by the presence of other components in the aperture and therefore a large fraction of the third light, which reduces the photometric amplitude of the eclipses. The light curve (hereafter LC) analysis presented by Garcia & Gimenez (1986) was slightly indicative of an eccentric orbit. The radial velocity curve (hereafter RV) was analyzed by Popper (1986). All of these studies found that the close binary consists of two very similar stars.

The position angle between the A and B components slowly changes, therefore an orbit of this pair was derived most recently by Aristidi et al. (1999), who found a period of about 137 yr and a semi-major axis about 225 mas. The position angle of the pair has changed since this last paper by about 40°, hence a new analysis is required. Moreover, the combined analysis of the visual orbit together with the times-of-minima variation due to the movement on this orbit and the radial-velocity variations can reveal some of the other parameters of the orbit and also of both AB and C components. The more distant C and D components also belong to this multiple system, but these show no detectable mutual motion and can be assumed to be motionless. The MSC catalog by Tokovinin (1997) gives their periods 11 kyr and 591 kyr, respectively.

A distance to 65 UMa was derived from the Hipparcos data. Perryman et al. (1997) gives the value of distance d = 246 ± 108 pc, while the new reduction of van Leeuwen (2007) presented the value $d = 212 \pm 30$ pc. The combined spectral type of the AB pair was classified as A3Vn by Cowley et al. (1969), while the spectrum of the D component is A2p (Slettebak 1963), and Joshi et al. (2010) carried out an analysis of this star. On the other hand, the spectral classification of the C component has never been performed. Therefore, the mass of the C component is also poorly constrained and the only information about this star that we have is a rough estimate of the magnitude difference (see below).

3. Observations and data reduction

In total, the target was observed on 82 nights: 29 nights for photometry, and 53 nights for spectroscopy. The complete *BVRI* light curves of the eclipsing pair were obtained in 2010 at the private observatory of one of the authors (RU). However, owing to the relatively high brightness of the target, only a small 254-mm reflector of moderate focal length was used. This telescope was unable to separate the two 4″ distant components, therefore the resultant LC was a composite AB+C light curve. The CCD photometric observations were obtained in standard B, V, and R filters according to the specification of Bessell (1990). All of the observations used for the LC were obtained with the same telescope and instrument setup, and the reduction was also identical. Furthermore, the complete set of minima times used for the analysis is given in Tables A.1–A.4 (available at the CDS), two new minima were measured by Petr Svoboda, Czech Republic.

The CCD spectra were obtained at Ondřejov observatory, Czech Republic, using the 2.0-m telescope equipped with a SITe-005 800 × 2000 CCD detector. These spectra cover a wavelength region 626–676 nm. All of them were secured between March 2010 and July 2011 and have a resolving power $R \sim 12\,700$. Their S/N values range typically between 100 and 300.

For all of the spectra, the wavelength calibration was done using a ThAr comparison spectra obtained before and after the stellar spectra itself. The data reduction was performed following the standard procedures of the data reduction package IRAF[1]. The flatfields were taken in the beginning and end of each night and their means were used in the data reduction. After then, the radial velocities were obtained with the program SPEFO (Horn et al. 1996; Škoda 1996), using the zero point correction by measuring the telluric lines. In total, 55 spectra were obtained in this way.

All available data used for the analysis, the photometry, times of minima, spectroscopy, and the interferometric measurements are also listed (see the CDS tables).

Table 1. Parameters of the visual (A-B) orbit.

Parameter	Aristidi et al. (1999)	This work
p_{A-B} [yr]	136.538 ± 8.4	118.209 ± 0.690
a_{A-B} [mas]	225 ± 18	208.2 ± 9.7
A_{A-B} [d]	–	0.0428 ± 0.0023
T_{A-B}	2447140.9 ± 149.7	2447516.9 ± 126.8
Ω_{A-B} [deg]	169.7 ± 4.6	92.1 ± 4.2
ω_{A-B} [deg]	26.9 ± 2.1	202.7 ± 1.3
i_{A-B} [deg]	39.7 ± 1.9	38.1 ± 2.4
e_{A-B}	0.531 ± 0.014	0.504 ± 0.006

4. Visual orbit and the period analysis

To begin with, we analyzed the visual orbit. The orbital motion influences the apparent period of the inner eclipsing pair, hence the periodic variation in the times of minima are analyzed according to the visual orbit parameters.

Since its discovery as a double, 35 observations of the A-B pair have been obtained. These have been collected in the Washington Double Star Catalog (hereafter WDS[2], Mason et al. 2001). We analyzed the data, obtaining the parameters of the visual orbit presented in Table 1, and the final fit together with the data is given in Fig. 1. As one can see from Table 1, the parameters differ significantly in some aspects. Besides the higher precision, the most significant difference is found for the orientation of the orbit in space. It is obvious that the same fit to the data can be obtained with different sets of parameters when we only interchange the values of two parameters: $(\Omega, \omega) \rightarrow (\Omega + 180°, \omega + 180°)$. However, when dealing with astrometric data set only, one cannot distinguish between these two identical solutions. The only way to do so is to use also the RV data, or the times-of-minima variation.

For the minimum-times observations, we have only a limited set of data points. If we consider the period of the A-B pair to be about 118 yr, we have data for only about one-quarter of the orbital period covered with minima times at the present day. Yet, we can try to carry out an analysis of these data, by fixing the orbital parameters from astrometry (these in Table 1). We have

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] http://ad.usno.navy.mil/wds/

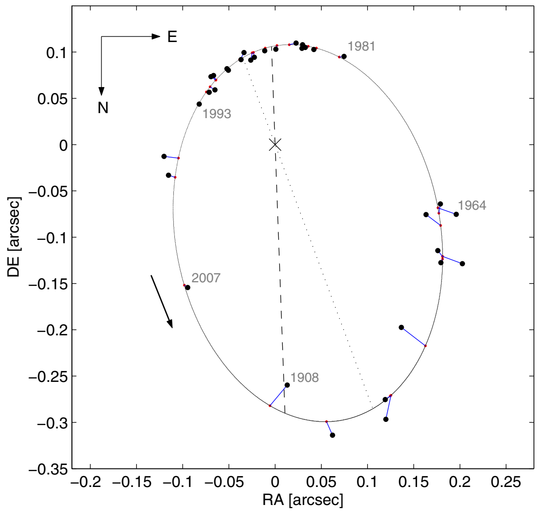

Fig. 1. Visual orbit of 65 UMa pair (A-B) as displayed on the sky. The eclipsing binary is placed in [0, 0]. The dotted line represents the line of the apsides, while the dashed one is the line of the nodes. See Sect. 4.

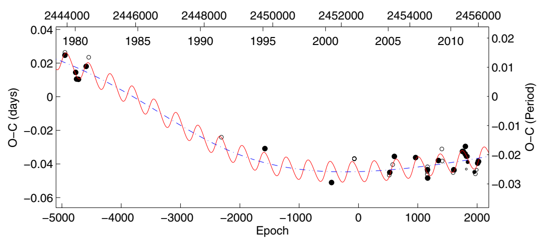

Fig. 2. Period variations of the eclipsing pair. Primary minima have been plotted as dots, and secondary as circles. The dashed line represents the 118 yr orbit, while the solid one is the 640 day orbit.

regularly observed the minima of this interesting target for the past four years to detect the period variation.

This led to an interesting finding that there is also an additional variation. We therefore analyzed our data set (43 data points in total) assuming two periodic terms. We used the LIght-Time-Effect hypothesis (hereafter LITE, described e.g. by Irwin 1959). The results of our analysis can clearly be seen in Figs. 2 and 3. The long-term periodic modulation (blue) is caused by the 118 yr visual orbit, while the short-period one is the newly discovered orbit, whose final parameters derived from our analysis are given in Table 2. This variation is clearly visible especially in the more precise recent data points after subtraction of the long-period term, see Fig. 3. Here we use the following labeling of the components: Aa1 and Aa2 for the eclipsing binary components, Ab for the 640 day orbit, and B for the 118 yr orbit (i.e. following the WDS notation). Thanks to the high precision of our new observations, the hypothesis of a non-circular orbit for 65 UMa eclipsing pair was ruled out. The complete list of times of minima together with the original *BVRI* photometry are given in Tables A.1–A.4 (available at the CDS). There is a problem with some of the minima times, whose accuracy is not always given, hence we cannot perform a reliable chi-square test of the

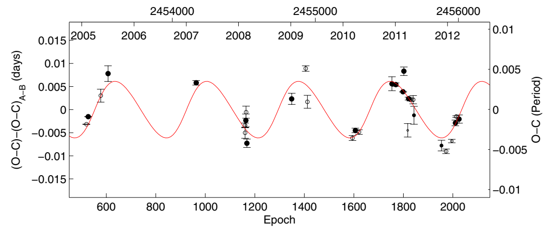

Fig. 3. Period variation in the times of minima after subtraction of the 118 yr term. Only the variation caused by the component Ab and the most recent minima have been displayed.

Table 2. Final parameters of the short (Aa-Ab) orbit.

Parameter	Value
$p_{\mathrm{Aa-Ab}}$ [d]	641.5 ± 16.7
$A_{\mathrm{Aa-Ab}}$ [d]	0.00621 ± 0.00147
$T_{\mathrm{Aa-Ab}}$	24 49615.4 ± 38.9
$\omega_{\mathrm{Aa-Ab}}$ [deg]	0.0 ± 15.2
$e_{\mathrm{Aa-Ab}}$	0.169 ± 0.048

640 day hypothesis. However, using the weightening scheme for the data points, the LITE fit based on the 640 day hypothesis gives the sum of square residuals 0.00318, while disregarding the possibility of a 640 day period the sum is 0.01222.

Using the approach of combining the two LITE terms, one can also derive the parallax of the system independently of the Hipparcos value and the total mass of the system. The method is as follows: $(A_{\mathrm{A-B}}, a_{\mathrm{A-B}}) \Rightarrow \pi \Rightarrow M_{\mathrm{tot}}$. To briefly describe the method, the amplitude of LITE and the angular semi-major axis of the visual orbit are directly connected via the parallax (Mayer 1990). Using our new computed parallax and the Kepler's third law, we calculated the total mass of the system (e.g. Hilditch 2001). The values presented in Table 2 and the LITE semi-amplitude $A_{\mathrm{A-B}}$ were calculated using this approach. This means that the values of $p_{\mathrm{A-B}}, T_{\mathrm{A-B}}, \Omega_{\mathrm{A-B}}, \omega_{\mathrm{A-B}}, i_{\mathrm{A-B}}$, and $e_{\mathrm{A-B}}$ were fixed, but the parameters $A_{\mathrm{A-B}}, p_{\mathrm{Aa-Ab}}, A_{\mathrm{Aa-Ab}}, T_{\mathrm{Aa-Ab}}, \omega_{\mathrm{Aa-Ab}}$, and $e_{\mathrm{Aa-Ab}}$ were fitted as free parameters. From this analysis, a new value of the parallax $\pi = 4.28 \pm 0.49$ mas was obtained, which yields the distance $d = 234 \pm 29$ pc. Such a value of parallax is slightly lower than the Hipparcos value ($\pi_{\mathrm{Hip}} = 4.72 \pm 0.58$ mas). Using this new value of the parallax, we than computed the total mass of the system $M_{\mathrm{tot}} = 8.25 \pm 1.85\ M_{\odot}$. Aristidi et al. (1999) found that $M_{\mathrm{tot}} = 9.1 \pm 11.6\ M_{\odot}$.

The relative motion of the component C around AB is very slow, but detectable. During more than 200 years of observations, over 60 measurements were obtained (see the WDS) that revealed a change in position angle of about 5°. We analyzed these data, determining a period of longer than 14 000 yr. However, this result is very preliminary owing to the poor coverage of only 1/64 of the orbital period.

5. Light and radial velocity curves

To analyze the LC and RV curves, we had to consider a precise ephemeris of the eclipsing pair. These followed from the minimum times analysis and resulted in the elements for the primary minima

$$\mathrm{HJD} = 2\,455\,651.4491(5) + 1.7304736(32) \cdot \mathrm{E}. \quad (1)$$

Table 3. Parameters from the KOREL analysis.

Parameter	Value
$q_{\rm Aa1-2}$ $(=M_{\rm Aa2}/M_{\rm Aa1})$	0.995 ± 0.012
$K_{\rm Aa1}$ [km s^{-1}]	133.3 ± 4.2
$K_{\rm Aa2}$ [km s^{-1}]	135.7 ± 4.2
$q_{\rm Aa-Ab}$ $(=M_{\rm Ab}/M_{\rm Aa1+Aa2})$	0.69 ± 0.11
$K_{\rm Ab}$ [km s^{-1}]	19.9 ± 2.7
$q_{\rm A-B}$ $(=M_{\rm B}/M_{\rm A})$	0.42 ± 0.14
$K_{\rm B}$ [km s^{-1}]	0.41 ± 0.30

However, the analysis was not straightforward because of the additional components in the system. We assumed that the C component does not affect the spectra significantly, since its distance is about 4″. The observing conditions and seeing were usually better than 2″ during most nights. Hence, four other components were found to be present in each of the spectra. We used the program KOREL (Hadrava 2004) to disentangle the spectra.

To perform the spectral disentangling, the orbital elements of both orbits were fixed. Hence, the most crucial for the analysis were the values of the mass ratios and amplitudes of the radial velocity curves. The ephemerides of the close eclipsing pair were also kept fixed because these are much more reliably known from the minima-times analysis.

The parameters $p_{\rm Aa-Ab}$, $T_{\rm Aa-Ab}$, $\omega_{\rm Aa-Ab}$, $e_{\rm Aa-Ab}$, $p_{\rm A-B}$, $T_{\rm A-B}$, $\omega_{\rm A-B}$, and $e_{\rm A-B}$ were fixed. The results of the other relevant parameters using KOREL are listed in Table 3. Despite the results of the mass ratios not being very conclusive, we were able to make some preliminary estimations of the masses of the individual components, as described below in Sect. 6. Since KOREL does not provide an error estimation, the errors in the individual parameters given in Table 3 resulted from the following analysis. Several solutions in KOREL were calculated, from which only those with χ^2 value closer than 5% from our best solution were considered. The errors in the parameters were assumed to be the maximum difference between these different solutions.

The program KOREL enables us to obtain the RVs of the individual components, which can be used for some further analysis. We used our knowledge of the ephemerides of the inner pair and the orbital parameters of the third body (i.e. 640 day orbit), to subtract the 640 day term from the RVs of the eclipsing pair. This can be clearly seen in Fig. 4, where the upper plot represents the original radial velocities, while the bottom plot represents the velocities after the subtraction of this term. We achieved significant improvement in the quality of the RVs, which could be used to perform a combined LC and RV analysis.

The LC and RV curves of the eclipsing pair were analyzed using the program PHOEBE (Prša & Zwitter 2005), which is based on the Wilson-Devinney program (WD, Wilson & Devinney 1971). The derived quantities are given in Table 4, while the LC has been plotted in Fig. 5. The values of synchronicity F_i for both eclipsing components were not derived from the combined LC and RV analysis. These were calculated from the spectra, and used to compute the values $v \sin i$ yielding the F_i values. The errors in F_i are the standard deviations in F_i measured for different spectra and different lines. The limb darkening was approximated using a linear cosine law, and the values of x_i were interpolated from the tables given in van Hamme (1993). In Table 4, we used the labeling of the two eclipsing components 1 and 2 in the indices instead of Aa1 and Aa2 for a better clarity.

The primary temperature was fixed at value T_1 = 8000 K, which agrees with both the A7 spectral type (Cox 2000) and the masses of the components (see Table 4). Therefore, it is legitimate to ask why a spectral classification of an A3 star was made for the eclipsing binary (Cowley et al. 1969). This is due to presence of the component Ab on a 640 day orbit, whose spectral type is probably of A3 and its light dominates the spectra. Moreover, Garcia & Gimenez (1986) speculated that the eclipsing binary components might be of A8-9 spectral type. The large value of the third light is also well-established owing to the three components that are present in the photometric aperture (in our notation, components Ab+B+C).

The component Ab dominates the spectrum. This body has a well-defined orbit, hence its lines can also be plotted with the 640 day period. On the other hand, Ab orbits around a barycenter with the eclipsing pair. We can also plot the residuals from the LC fit from the eclipsing pair (from the original RVs), which should vary in anti-phase with respect to the Ab lines. This is shown in Fig. 6, where we have plotted the 640 day fit to our

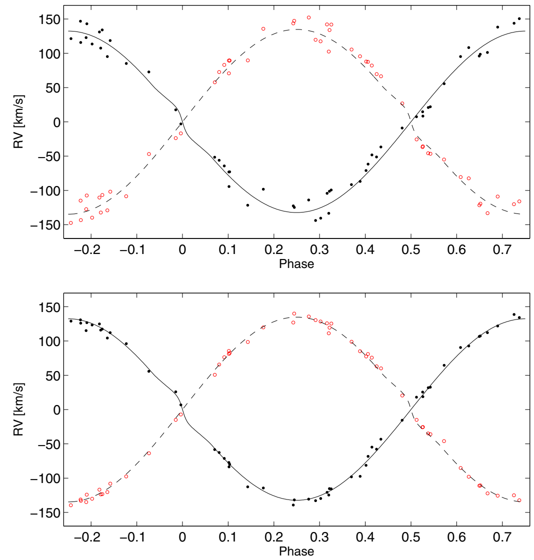

Fig. 4. Radial velocity curves of the 65 UMa eclipsing pair. The *upper* plot shows the original RVs before correction for the 640 day variation. The *bottom* plot shows the RVs of the eclipsing pair after the correction.

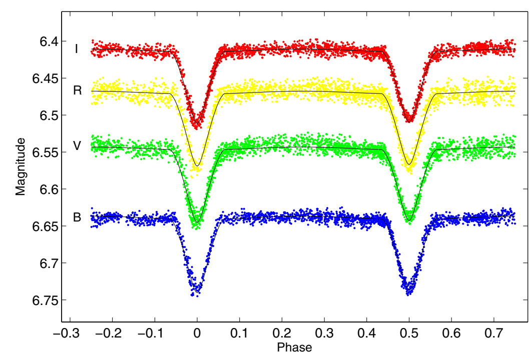

Fig. 5. *BVRI* light curves of 65 UMa together with the final PHOEBE fit. The light curve parameters are given in Table 4.

Table 4. Light curve parameters of 65 UMa eclipsing pair.

Parameter	Value
T_1 [K]	8000^*
T_2 [K]	7948 ± 20
i [deg]	86.5 ± 0.2
$g_1 = g_2$	1.00^*
$A_1 = A_2$	1.00^*
F_1	0.423 ± 0.094
F_2	0.384 ± 0.077
L_1 (B) [%]	10.7 ± 0.4
L_2 (B) [%]	9.7 ± 0.3
L_3 (B) [%]	79.6 ± 1.5
L_1 (V) [%]	10.7 ± 0.5
L_2 (V) [%]	9.8 ± 0.5
L_3 (V) [%]	79.5 ± 2.1
L_1 (R) [%]	10.7 ± 0.7
L_2 (R) [%]	9.9 ± 0.7
L_3 (R) [%]	79.5 ± 3.3
L_1 (I) [%]	10.6 ± 0.4
L_2 (I) [%]	9.9 ± 0.4
L_3 (I) [%]	79.5 ± 1.8
Derived quantities:	
R_1 [$R_\odot$]	1.86 ± 0.08
R_2 [$R_\odot$]	1.81 ± 0.08
M_1 [$M_\odot$]	1.74 ± 0.06
M_2 [$M_\odot$]	1.71 ± 0.06

Notes. $^{(*)}$ Fixed.

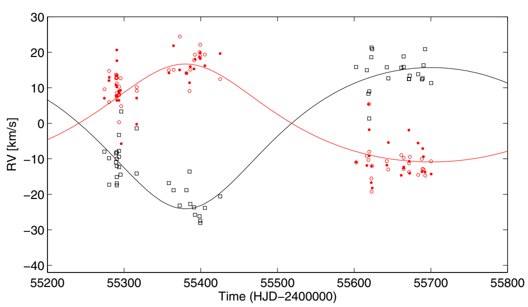

Fig. 6. Radial velocity curves on the 640 day orbit. The black squares stand for the Ab lines in the spectrum, while the red circles represent the radial velocity residuals after subtraction of the eclipsing pair RV curve (filled for primary, open for secondary).

spectra, which were acquired over two consecutive seasons 2010 and 2011.

Moreover, during the photometric monitoring of 65 UMa, two new variables were identified in the field. One of them was HD 103795 (spectrum K2III, according to Upgren 1962), while the other one was SAO 43913 (spectrum F0, according to Slettebak & Stock 1959). Neither was ever reported to be a variable, despite both having been observed by the Hipparcos satellite. However, our CCD photometry indicates that both are probably variable with amplitudes a few hundreds of magnitude. SAO 43913 is probably a pulsating star (maybe δ Sct) with a period of about three hours, but the type of variability of HD 103795 remains unclear.

6. Discussion and conclusions

We have performed our first attempt to perform a detailed combined solution of all available data for 65 UMa, namely photometry, spectroscopy, and interferometry, obtaining quite a reliable picture of this unusual sextuple hierarchical system (see Fig. 7).

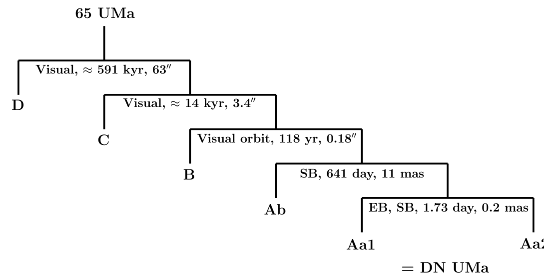

Fig. 7. Schematic structure of the whole system 65 UMa.

The inner close eclipsing pair consists of two almost-identical stars of A7 spectral type. This finding is consistent with the photometric indices $B-V$, $V-R$, and $R-I$ being constant for the whole phase of the eclipsing binary at a level of 0.005 mag. The stars move on circular orbits with periods of about 1.73043 d, both being located on the main sequence. Thanks to the combined analysis, we were also able to compute its distance as $d = 234 \pm 29$ pc, independently of the Hipparcos satellite data. The 640 day orbit was confirmed by both the minima times and the RV variations. Applying the spectral disentangling and rough estimation of the mass ratios from this analysis, one can estimate the masses of the outer components. The Ab component is probably of A1 spectral type and has a mass of about 2.4 ± 0.4 $M_\odot$, from the total mass of the 118 yr visual orbit, we can estimate the mass of the fourth component (in WDS named B), to be about 2.4 ± 2.0 $M_\odot$. If we assume both these masses of Ab and B components, we can estimate the magnitude difference. Aristidi et al. (1999) found this value to be 1.9 ± 0.1 mag, while here we derive 0.7 ± 4.5 mag. The very large error is due to the large uncertainty in the mass of the fourth body. Another approach is to use the standard mass-luminosity relation and derive the individual luminosities of the components. Using this approach, we have plotted Fig. 8, where all components of the system 65 UMa are placed in the color–magnitude diagram. As one can see, the two eclipsing binaries are slightly under-luminous, while the D component seems to be over-luminous. The same finding about its higher luminosity was found elsewhere, e.g. Joshi et al. (2010) or Aurière et al. (2007).

However, some properties of the Aa-Ab orbit remain unclear, such as the inclination angle between the orbits. We can do some rough estimation of this quantity. The KOREL $K_{\rm Aa}$ value and the predicted amplitude of radial-velocity variations from the LITE$_{\rm Aa-Ab}$ are connected via $\sin i_{\rm Aa-Ab}$. Hence, we obtain $i_{\rm Aa-Ab} \approx 47°$, which lies well between the inclinations i of the eclipsing pair and the $i_{\rm A-B}$ of the visual orbit. Nevertheless, its error is large but this is still only an estimation. We can also compute the predicted minimal angular separation of the Aa-Ab pair for a prospective interferometric detection. This resulted in about 11 mas, which is very favorable for modern stellar interferometers, because the magnitude difference between the Aa and Ab components should also be rather low. On the other hand, the angular separation of the eclipsing pair components is still rather low, at about only 0.18 mas.

Dealing with a multiple system, we should also consider the nodal period of the close pair and the 640 day orbit, hence the

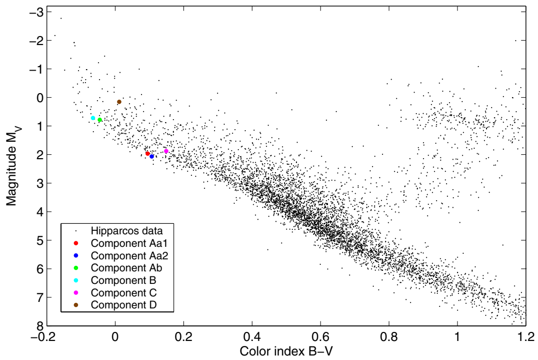

Fig. 8. Color–magnitude diagram for all components of the system. Their position is compared with the Hipparcos stars (small black dots).

change in the inclination of the eclipsing binary (Söderhjelm 1975). The most crucial here is the ratio of periods ${p_{\mathrm{Aa-Ab}}}^2/P$, which implies that the nodal period was about 650 years, a duration that should be practical to observe. Unfortunately, we do not have a complete set of orbital parameters of the Aa-Ab pair, so this is only first rough estimation. However, this nodal period is not too long and potentially detectable. Further observations would help us to detect the change in the eclipse depths. Despite these being rather shallow, this effect was detected in only nine other cases, hence it would be interesting to reattempt detections, especially with the modern ultra-precise satellite photometry.

Nevertheless, 65 UMa is a rather unusual system, we presently know of only 11 other sextuple systems (see Eggleton & Tokovinin 2008). The mass ratio of close to unity for the inner pair seems to agree with some theoretical models of star formation, e.g. Delgado-Donate et al. (2003). Moreover, some studies (e.g. Tokovinin & Smekhov 2002) indicate that about one-third of all multiples are higher-order systems. Goodwin et al. (2007) discussed a finding that there is a difference between the number of observed and expected higher-order multiples (quadruples and higher). Perhaps the discovery of other systems similar to 65 UMa would diminish this discrepancy.

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First detailed analysis of multiple system V2083 Cyg

P. Zasche,[1]★ P. Svoboda[2] and M. Šlechta[3]

[1]*Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, V Holešovičkách 2, CZ-180 00 Praha 8, Czech Republic*
[2]*Private Observatory, Výpustky 5, CZ-614 00 Brno, Czech Republic*
[3]*Astronomical Institute, Academy of Sciences, Fričova 298, CZ-251 65 Ondřejov, Czech Republic*

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ABSTRACT

The main aim of this paper is the first detailed analysis of multiple system V2083 Cyg, to reveal its basic physical properties. The system was studied using the methods of light-curve and radial-velocity curve analysis, together with interferometric data from the visual pair obtained during the last century. It was found that the close subsystem contains two very similar stars of spectral type A7–8. Moreover, a third body is orbiting around this pair with a period of about 177 yr. Due to the discrepancy in the total mass derived with the two methods, the possibility arises that the third body is perhaps also a binary, or some object with lower luminosity but higher mass than a normal main-sequence star. Another explanation is that the *Hipparcos* value of parallax is incorrect and the system is much closer to the Sun.

Key words: binaries: eclipsing – binaries: visual – stars: fundamental parameters – stars: individual: V2083 Cyg.

1 INTRODUCTION

Eclipsing binaries as members of more complex multiple systems can provide us with important information about their physical properties, derived using different methods. This is the case for V2083 Cyg, which is a system in which the close components form an eclipsing binary and the third distant body orbiting the close pair is detected as a visual component. Thanks to combined analysis, we are able to derive the radii, masses and evolutionary status of the close components and also some properties of the distant one. Such systems are still very rare and mostly lie relatively close to the Solar system. Nowadays, only 33 such systems are known in which a close eclipsing binary is a member of a wide visual binary and we know both orbits, mutual inclinations, ratio of periods, etc. Such unique systems are the most suitable ones for studies of dynamical effects, such as the short- and long-term evolution of the orbits (see e.g. Söderhjelm 1975).

2 THE SYSTEM V2083 CYG

The system V2083 Cyg (= HD 184242 = HIP 96011, RA $19^{h}31^{m}16\overset{s}{.}36$, Dec. $+47^{\circ}28'52\overset{''}{.}24$, $V_{max} = 6.86$ mag) is an Algol-type eclipsing binary with an orbital period of about 1.87 d. It is also the primary component of a visual double star designated as WDS J19313+4729 in the Washington Double Star Catalog (WDS)[1] (Mason et al. 2001). The secondary component of this double star is about 220 mas distant and is a little fainter. On the other hand, the magnitude difference is not very certain, because different authors list different values. The WDS catalogue itself gives 7.50 and 7.93 mag for both components.

The system is a rather neglected one and there have only been a few papers published regarding it. It was discovered as an eclipsing binary from *Hipparcos* data (Perryman et al. 1997), which also reveal that the light curve (hereafter LC) shows two similar minima and the classical features of an Algol-type star.

The spectral type of the system is not known very precisely at present. Abt (1985) presented the spectral classification of the whole AB system as Am (K/H/M=A3/A8/A9), Renson, Gerbaldi & Catalano (1991) give a composite spectral type of A3–A9, while the spectral type A3 was presented by Cannon & Pickering (1918), Ochsenbein (1980) and many others. This could indicate that the combined spectrum is composed from components of slightly different spectral types. The photometry of V2083 Cyg obtained from the *Hipparcos* mission gives a colour index $B - V = 0.279$ mag (indicating spectral type A9, Popper 1980), while the infrared $J - H$ and $H - K$ indices, which are less influenced by interstellar reddening, as derived from the 2MASS survey give spectral types of about A4 and A7 (Cox 2000).

The visual orbit of the two components was derived by Seymour et al. (2002). They presented an orbital period of the double of about 372 yr, an angular semimajor axis of about 498 mas and an eccentricity of 0.16. However, as they mention, the orbit is still only a preliminary one.

3 PHOTOMETRY AND SPECTROSCOPY

We started collecting photometric data for the system in 2008 April. In total there are 31 nights of observations, but for the light-curve

★E-mail: zasche@sirrah.troja.mff.cuni.cz
[1] http://ad.usno.navy.mil/wds/

analysis we used only 27 nights of observations obtained from 2008 April–2009 September and carried out with the same telescope and detector at a private observatory by one of the authors (PS). Owing to the high brightness of the target, only a small 34-mm refractor was used at the private observatory in Brno, Czech Republic, using the SBIG ST-7XME CCD camera and standard *BVR* filters from the specification by Bessell (1990). All the measurements were processed by the software C-MUNIPACK,[2] which is based on aperture photometry and uses the standard DAOPHOT routines (Tody 1993). The other nights were used only for deriving the precise times of minima for the system.

Besides our new observations, we also used photometric data obtained within the SuperWASP (Wide Angle Search for Planets) survey (SWASP: Pollacco et al. 2006). However, these data are not of high enough quality to be used for the LC analysis. Hence, we made use of the SWASP photometry only for deriving the minima times of V2083 Cyg for prospective period analysis. For all of the minima the Kwee–van Woerden method was used (Kwee & van Woerden 1956), and all are given in Table A1. The linear ephemeris is as follows: HJD = 244 8501.1237 + 1.867 493 429E.

The CCD spectra were obtained at Ondřejov observatory, Czech Republic, using the 2.0-m telescope equipped with a SITe-005 800 × 2000 CCD detector. These spectra cover a wavelength region 626–676 nm. All of them were secured between 2010 April and 2011 May and have a linear dispersion of about 17 Å mm^{-1}. Their signal-to-noise ratio (S/N) values range typically between 100 and 200.

For all of the spectra used, the wavelength calibration was made via ThAr comparison spectra obtained before and after the stellar spectra themselves. Flat-fields were taken at the beginning and end of the night and their means were used for the reduction. After this, the radial velocities (hereafter RV) were obtained with the program SPEFO (Horn et al. 1996), using zero-point correction via measuring the telluric lines. In total 19 spectra were obtained in this way. Moreover, two Elodie spectra (Moultaka et al. 2004) obtained in 1999 were also added for analysis.

A list of derived radial velocities from all of the available spectral observations is given in Table 1. In the last column the reference 'Elodie' or 'Ondřejov' is given. For all spectra we also tried to identify the third component lines, however these radial velocities are rather uncertain and are affected by relatively large errors (see Sections 5 and 6 below).

Table 1. Radial velocities of V2083 Cyg as derived from the spectra from the Elodie archive and from the Ondřejov observatory.

HJD: 240 0000	RV1	RV2	RV3	Ref.
51405.3658	95.594	−81.861		Elodie
51407.4156	129.872	−117.06		Elodie
55316.5290	20.920	2.771	−16.272	OND
55380.5210	−122.394	142.771	−16.336	OND
55385.3570	122.946	−99.062	−16.775	OND
55385.5530	56.001	−29.860	−18.597	OND
55386.3640	−73.970	99.094	−14.986	OND
55386.5650	−.442	25.184	−17.640	OND
55405.3670	55.349	−26.402	−16.327	OND
55425.3970	−117.384	141.598	−16.145	OND
55496.2990	−121.010	140.992	−16.273	OND
55496.4630	−99.677	124.485	−16.277	OND
55497.2890	141.451	−119.863	−15.212	OND
55622.5420	116.769	−96.782	−15.048	OND
55622.6370	89.474	−66.160	−14.284	OND
55671.4500	−18.008	36.024	−14.574	OND
55671.5840	−72.089	92.471	−14.950	OND
55671.6310	−86.135	105.183	−14.784	OND
55689.5750	144.545	−122.291	−16.380	OND
55692.3700	−119.493	143.646	−15.231	OND
55692.5540	−98.435	122.422	−15.080	OND

Table 2. The final LC and RV parameters of V2083 Cyg.

Parameter	Value	Parameter	Value
a [R$_\odot$]	9.57 ± 0.15	L_1 (B) [per cent]	26.7 ± 0.7
$q = M_2/M_1$	0.97 ± 0.07	L_2 (B) [per cent]	34.9 ± 0.9
γ [km s^{-1}]	10.78 ± 0.68	L_3 (B) [per cent]	38.4 ± 0.8
T_1 [K]	7630 (fixed)	L_1 (V) [per cent]	26.7 ± 0.6
T_2 [K]	7623 ± 45	L_2 (V) [per cent]	34.7 ± 0.9
e	0 (fixed)	L_3 (V) [per cent]	38.6 ± 0.8
i [deg]	80.47 ± 1.60	L_1 (R) [per cent]	26.4 ± 0.6
$x_1 = x_2$ (B)	0.412	L_2 (R) [per cent]	34.2 ± 0.9
$x_1 = x_2$ (V)	0.356	L_3 (R) [per cent]	39.4 ± 1.0
$x_1 = x_2$ (R)	0.356	Derived physical quantities:	
$g_1 = g_2$	1.000 (fixed)	R_1 [R$_\odot$]	2.12 ± 0.17
$A_1 = A_2$	1.000 (fixed)	R_2 [R$_\odot$]	2.45 ± 0.20
F_1	0.81 ± 0.13	M_1 [M$_\odot$]	1.71 ± 0.11
F_2	0.84 ± 0.11	M_2 [M$_\odot$]	1.66 ± 0.09

4 LC AND RV ANALYSIS

The complete LC (in *BVR* filters) and RV curves were analysed simultaneously, using the program PHOEBE (Prša & Zwitter 2005), which is based on the Wilson–Devinney algorithm (Wilson & Devinney 1971). The derived quantities are as follows: semi-major axis a, mass ratio $q = M_2/M_1$, systemic velocity γ, secondary temperature T_2, inclination i, luminosities L_i, gravity-darkening coefficients g_i, limb-darkening coefficients x_i, albedo coefficients A_i and synchronicity parameters F_i. The limb darkening was approximated via a linear cosine law and the values of x_i were interpolated from van Hamme's tables (see van Hamme 1993).

For the whole analysis, we followed this procedure: at the beginning we fixed the temperature of the primary component at $T_1 =$ 7930 K (corresponding to spectral type A7, Cox 2000). We were trying to find the best LC+RV fit according to the lowest value of root-mean-square (rms). A solution was reached, but this one was unacceptable due to the fact that resulting values of M_1, M_2, L_1, L_2, T_1 and T_2 are in contradiction with each other. In particular, the resulting spectral types as derived from M, L and T differ significantly from each other. For this reason, we tried a different starting value of T_1. With this method we were changing the temperature T_1 in the range from 8520–7020 K (spectral types A3 to F0) and trying to find a consistent solution. For all of these attempts, the value of T_1 remained fixed.

Our final parameters as derived from the LC+RV fit are given in Table 2. The plot of the LC is shown in Fig. 1, while the RV curves with the fits are given in Fig. 2. The value of eccentricity was fixed at 0. For discussion about the physical parameters of the components (eclipsing and also the third one), see Section 6.

For the entire computation process, the values of albedos A_i and gravity-darkening coefficients were set at their appropriate values (A_i = 1 or 0.5 and g_i = 1 or 0.32) according to the component's temperature (T_i < 7200 K or T_i > 7200 K). Another problematic

[2] See http://c-munipack.sourceforge.net/

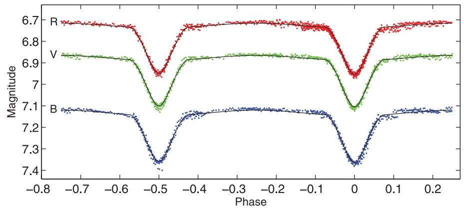

Figure 1. Light curves in *B* (blue), *V* (green), and *R* (red) filters for V2083 Cyg; the solid line represents the final fit (see the text).

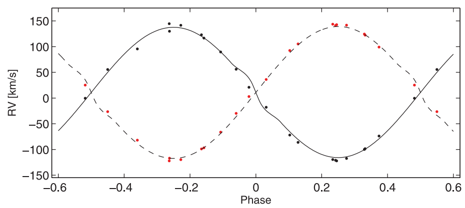

Figure 2. Radial velocity curves of V2083 Cyg for the primary (solid line), and the secondary (dashed line); the lines represent the final fit (see the text and Table 2).

issue was the values of F_i, which tended to decrease down to 0 for both components for each of the T_1 values, dropping down very quickly after a few steps of iterations. For this reason we tried a different approach. From the spectra of the system we estimated the values $\upsilon \sin i$, which were used to derive the values of F_i for both components. Therefore, the values of F_i as given in Table 2 are not derived from the combined LC and RV analysis but from the spectra.

The fitting process with PHOEBE was carried out assuming three luminosities. Besides the luminosities of the primary and secondary components of the eclipsing binary pair, the additional third light L_3 was also considered. This luminosity corresponds to the visual component B and is presented in the combined light for the entire time period (the two visual components are too close). From this value one can speculate about some physical parameters of the third body in the system; see Section 6 below.

5 VISUAL ORBIT

The close eclipsing pair is orbiting around a common barycentre with the third distant component of the system. Recent precise interferometric observations are to be used for determining the parameters of this visual orbit. Since its discovery as a double star by Aitken (1904), 61 astrometric observations of the double (i.e. position angle and separation) have been obtained. We took these data from the WDS data base. The very last observation was obtained in 2009.

Since its discovery, the position angle of the pair has changed by about 88°. Thanks to this movement, the orbit of the pair around a barycentre has been derived. The orbit was published by Seymour et al. (2002), who computed an orbital period of about 372 yr. However, since this most recent study three new interferometric observations have been published, so we decided to perform a new analysis with the complete data set.

Our new computation led to the visual orbit parameters given in Table 3 and the orbit plotted in Fig. 3. For the computation we

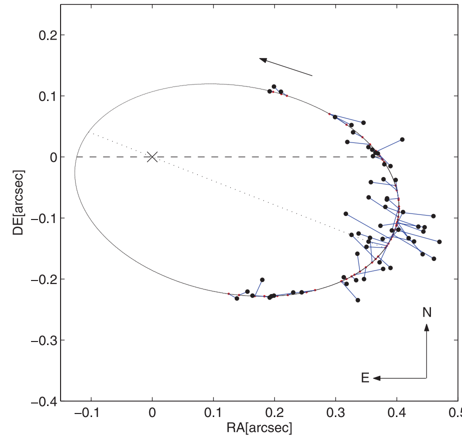

Figure 3. Visual orbit of V2083 Cyg as displayed on the sky. The individual observations are connected with their theoretical positions on the orbit. The dashed line represents the line of the nodes, the dotted one the line of the apsides. Parameters of the fit are given in Table 3.

used the following approach. Starting with the orbital parameters as published by Seymour et al. (2002), the final fit reached a very different solution. Moreover, several different minima in the parameter space were found, as derived from this astrometric data set. Some minima were found with very long orbital periods, but this solution seems to be less probable due to the poor coverage of the data. The most significant minimum (the deepest one) was found near the period of 177.4 yr. However, we would like to emphasize that the orbital solution is still a preliminary one. New precise observations secured every year would be very welcome to aid in derivation of the orbital parameters more conclusively and especially in setting more solid constraints on p_3 and a values. These values are the most important for discussion about the nature of the third component (see Section 6 below).

In Fig. 4 a plot of total mass versus period is shown, as well as the rms of the particular fit versus period. For our final solution reached (minimum rms with $p_3 = 64778.357$ d), the value of total mass was computed (using the *Hipparcos* parallax); this is shown as the dashed lines in Fig. 4. The relation between the two vertical axes (parallax and total mass) is defined via Kepler's third law using our final solution. As one can see from the bold line of the mass–period relation, the total mass as derived from our final solution is close to the minimal mass in this period range (the uncertainty of the *Hipparcos* parallax $\pi_{HIP} = 4.32 \pm 0.57$ is shown as a grey area). Of course, this analysis is very sensitive to the input weighting

Table 3. Final parameters of the long orbit.

Parameter	Seymour et al. (2002)	This work
p_3 [day]	135869	64778 ± 427
p_3 [yr]	372	177.4 ± 1.2
a [mas]	498	291.9 ± 1.4
T_0	2438395	2400006 ± 375
Ω [deg]	73.6	174.54 ± 2.9
ω [deg]	189	334.89 ± 5.3
i [deg]	64	48.73 ± 3.6
e	0.16	0.471 ± 0.018

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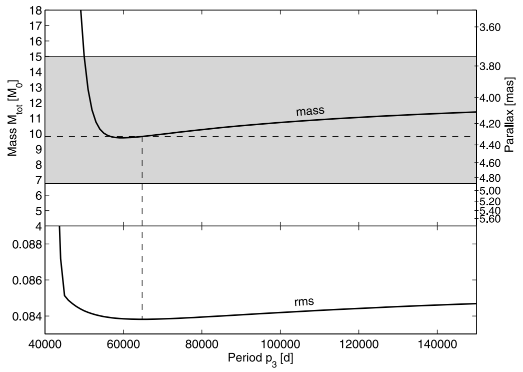

Figure 4. Plot of period–mass and period–rms relations. The dashed lines represent our final fit. For details see the text.

scheme. The individual weights of the data points were set equal to each other, because for most of the observations σ or some other error estimations are missing. No minimum of rms near a period of 372 yr, as proposed by Seymour et al. (2002), is seen. One might ask why such a different solution was reached using only three new interferometric observations. The main reason (besides perhaps different weighting) is that these three new measurements provide strong constraints on the fit. This is due to the fact that the position angle between our most recent data and those from Seymour et al. (2002) has changed by about 20°, which is about a quarter of the total position-angle range covered. All of these calculations (e.g. Kepler's law) used the set of recommended values of fundamental parameters as proposed by Harmanec & Prša (2011).

On the other hand, we also tried to compute the predicted change in the third-body velocities over the time span of more than 11 yr covered by our spectroscopic data. Taking into account some assumptions (masses), the change in velocity that resulted was greater than 20 km s^{-1}. Such a large velocity difference should be easily detectable in our RV3 data. Unfortunately, we were not able to identify the third-component lines in the Elodie spectra and in newer data from Ondřejov there is no such difference; hence we can only speculate about our findings. The reason could be either different masses or a much longer orbital period. Another explanation is an incorrect identification of the third-body lines in the spectra.

6 PHYSICAL PARAMETERS

Taking into account all results as presented above, one can build up a picture of the system, its geometry and orientation in space. From the combined LC and RV analysis it appears that both eclipsing components are probably main-sequence stars, located well within their respective Roche lobes. According to their masses and temperatures, it seems that their individual spectral types are probably A7 and A8 (e.g. Popper 1980; Harmanec 1988; Andersen 1991) for the primary and secondary, respectively. However, according to their luminosities, it seems as though the stars are of slightly earlier spectral type (about A5).

Another task was to derive the value of the third light L_3 from the LC solution and to obtain a magnitude difference between the two visual components. The value resulting was about 0.49 mag, which is in rough agreement with the value $\Delta m = 0.43$ mag presented in the WDS catalogue.

Discussion regarding the third body is still difficult due to certain aspects of the problem. The most problematic issue is still the uncertainty of the *Hipparcos* value of parallax. The relatively high error of about 13 per cent could lead to distances in a wide range from 204–267 pc. Thanks to this uncertainty, the value of total mass as computed from the visual orbit (see Table 3) could also lie between 6.54 and 15.41 $M_\odot$, with a mean value of 9.81 $M_\odot$.

Subtracting the masses of both eclipsing components, we obtain an interesting result for the mass of the third body of about 6.44 $M_\odot$ (with upper and lower limits of about 12.24 and 2.97). Such a massive third body cannot easily be a main-sequence A star as predicted from the Δm value. One possible explanation for this discrepancy is that this component is also a double star. If we speculate that there are two identical stars, then such stars have to be of only slightly later spectral type than the eclipsing components (because of the total mass). Assuming two F0 stars, we can hardly satisfy the magnitude difference between the components. However, this explanation is still questionable because the third lines in the spectra do not show a double profile.

To solve this discrepancy we tried to use the program KOREL (Hadrava 2004) to disentangle the spectra taken at Ondřejov observatory. However, it was not able to solve the problem either. The final parameters on one hand confirmed our findings about the LC+RV solution (the mass ratio q from KOREL was about 0.993) but on the other hand also resulted in a value of mass ratio $q_3 = M_3/M_{12} > 1$. This would indicate that the third body is more massive than the eclipsing pair, but also less luminous. Solving the problem of its lower luminosity and higher mass by introducing a degenerate object is a highly speculative solution. Hence, the nature of the third body still remains an open question. The KOREL radial velocities of the third body were also used and these are the values presented in Table 1 in the RV3 column.

7 DISCUSSION AND CONCLUSIONS

The multiple system V2083 Cyg is still rather neglected and this is the first detailed analysis of it. The components of the eclipsing binary are of spectral type A and are well-detached, with no evidence of circumstellar matter, emission in the spectra, etc. This close pair is also orbiting around a common barycentre with a third component with a period of about 177 yr. The mutual inclination of the two orbits is 31.°8; therefore we can only speculate about a common origin of the system.

The nature of the third component is still rather problematic to derive. From the combined LC and RV analysis it appears that the third body is slightly less luminous than the eclipsing pair. However, the *Hipparcos* parallax indicates a higher total mass of the system than computed from all component masses. A possible explanation is that the value of the *Hipparcos* parallax is underestimated and the real distance of V2083 Cyg is lower (even outside the error bars of the *Hipparcos* data). This would not be an exceptional case, because for some systems *Hipparcos* data yield an incorrect parallax due to the presence of a close visual companion (e.g. Docobo et al. 2008). Another possible explanation is that this body is also a binary, but there are some problems with this explanation too (luminosity and the spectral lines of such a body). For this reason, new more detailed observations would be greatly welcome.

However, if the hypothesis of binarity of the third component is proven, it will shift the triple system to a quadruple one. On one hand, such systems of higher multiplicity are of great interest, but on the other hand we would then have to deal with the very incomplete statistics of such systems among stars (see e.g. Eggleton & Tokovinin 2008; Eggleton 2009).

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APPENDIX A

The minima obtained using the Kwee–van Woerden method (Kwee & van Woerden 1956) are here given in Table A1.

Table A1. Heliocentric minima of V2083 Cyg.

HJD: 240 0000	Error	Type	Filter	Observer
54609.69354	0.00179	prim	–	SWASP
54638.63794	0.00035	sec	–	SWASP
54639.57227	0.00042	prim	–	SWASP
54652.64554	0.00089	prim	–	SWASP
54668.51720	0.00046	sec	–	SWASP
54669.44747	0.00046	prim	–	SWASP
54683.46156	0.00027	sec	–	SWASP
54684.39467	0.00095	prim	–	SWASP
54994.39887	0.00091	prim	B	PS
54994.39888	0.00113	prim	V	PS
54994.39948	0.00128	prim	R	PS
55049.49292	0.00110	sec	B	PS
55049.49015	0.00104	sec	R	PS
55049.49055	0.00062	sec	V	PS
55051.35585	0.00081	sec	B	PS
55051.35567	0.00078	sec	V	PS
55051.35645	0.00107	sec	R	PS
55064.43157	0.00091	sec	B	PS
55064.43162	0.00057	sec	V	PS
55064.43102	0.00064	sec	R	PS
55076.57570	0.00116	prim	B	PS
55076.57197	0.00108	prim	V	PS
55076.57194	0.00165	prim	R	PS
55093.37749	0.00087	prim	B	PS
55093.37848	0.00068	prim	V	PS
55093.37624	0.00063	prim	R	PS
55374.43431	0.00021	sec	I	RU
55429.52450	0.00028	prim	I	RU
55740.46289	0.00056	sec	R	PS
55797.42284	0.00043	prim	I	RU

Note: PS – Petr Svoboda, RU – Robert Uhlař.

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The Study of Triple Systems V819 Her, V2388 Oph, and V1031 Ori

P. Zasche[1], R. Uhlář[2] and P. Svoboda[3]

[1] Astronomical Institute, Charles University Prague, Faculty of Mathematics and Physics,
V Holešovičkách 2, Praha 8, CZ-180 00, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Private Observatory, Pohoří 71, Jílové u Prahy, CZ-254 01, Czech Republic
[3] Private observatory, Výpustky 5, Brno, CZ-614 00, Czech Republic

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ABSTRACT

The systems V819 Her, V2388 Oph, and V1031 Ori are triples comprised of an eclipsing binary orbiting with a distant visual component on a longer orbit. A detailed analysis of these interesting systems, combining the two observational techniques: interferometry and apparent period variation, was performed. The interferometric data for these three systems obtained during the last century determine the visual orbits of the distant components in the systems. The combined analysis of the positional measurements together with the analysis of apparent period changes of the eclipsing binary (using the minima timings) can be used to study these systems in a combined approach, resulting in a set of parameters otherwise unobtainable without the radial velocities. The main advantage of the technique presented here is the fact that one needs no spectroscopic monitoring of the visual orbits, which have rather long periods: 5.5 yr for V819 Her, 9.0 yr for V2388 Oph, and 31.3 yr for V1031 Ori, respectively. The eccentricities of the outer orbits are 0.69, 0.33, and 0.92, respectively. Moreover, the use of minima timings of the eclipsing pairs helps us to derive the orientation of the orbit in space with no ambiguity around the celestial plane. And finally, the combined analysis yielded also an independent determination of the distance of V819 Her (68.7 ± 1.8 pc), and V2388 Oph (70.6 ± 8.9 pc). We also present a list of similar systems, which would be suitable for a combined analysis like this one.

Key words: *binaries: eclipsing – binaries: visual – Stars: fundamental parameters – Stars: individual: V819 Her, V2388 Oph, V1031 Ori*

1. Introduction

Multiple stellar systems (*i.e.*, of multiplicity three and higher) are excellent objects to be studied. The importance of such systems lies in the fact that we can study their stellar evolution, origin, tidal interaction, test the influence of the distant components to the close pair, study Kozai cycles, the dynamical effects and precession of the orbits, but also the statistics and relative frequency of such systems among the stars in our Galaxy (and outside), see *e.g.,* Tokovinin (2007), Guinan and Engle (2006), or Goodwin and Kroupa (2005).

A few years ago we introduced (Zasche and Wolf 2007) a new method of combining the different observational techniques: namely the analysis of the visual orbit (positional measurements of double stars obtained *via* interferometry, in former times *via* micrometry) together with the apparent period changes of the eclipsing pair (study of times-of-minima variation), into one simultaneous fitting procedure. This approach deals with very favorable triple systems, where one of its components is an eclipsing binary, while the distant component is being observed *via* interferometry. In general, for the triple systems the orbital periods of the wide orbits are usually the crucial issue. The shorter periods are mostly being discovered *via* spectroscopic monitoring, while the longer ones *via* interferometric detection of the distant components. The space in between these two methods is often harvested *via* a so-called Light-Time Effect (hereafter LITE, see *e.g.,* Irwin 1959), which is able to discover the orbits of components with orbital periods from hundreds of days to hundreds of years (Zakirov 2010). The whole method is using a well-known effect of detecting apparent periodic shifting of the eclipsing binary period as the eclipsing pair revolves around a barycenter with the third component. In principle, every triple system with an eclipsing binary should display some amount of apparent periodic modulation of the inner eclipsing period (the only exception is the face-on orientation of the wide orbit). Hence, a long-term monitoring of such systems can be very fruitful. Therefore, in 2006 we started photometric monitoring of selected systems. Results are partly presented in this paper.

Raghavan *et al.* (2010) published their results about the multiplicity fraction of the solar-type stars as compared with previous results on different spectral types (showing that the multiplicity fraction rapidly decreases to lower mass stars). Hence, one can expect that also the number of multiples within the group of eclipsing binaries would be large. On the other hand, there is still a limited number of such systems, for which both inner and outer orbits are known. The problem is usually the period of the outer orbit (sometimes of the order of hundreds of years), and surprisingly also the brightness of the systems. The stars observed *via* interferometry need to be rather bright (usually < 10 mag), but for such bright targets the photometry is often hard to obtain because these can easily saturate the modern CCD detectors mounted on even modest telescopes. And finally, also the presence of the third component makes the eclipses of the inner pair more shallow due to its brightness (the third component often cannot be separated and is also observed in the aperture). All of these reasons make such triple systems rather rare and unusual, and currently we still know only about 30 visual multiple systems with eclipsing components for which both orbits are known (see *e.g.,* Zasche *et al.* 2009).

2. The Approach for the Analysis

From the potentially interesting systems suitable for the combined analysis, we have chosen three stars, following the criteria introduced here. All of the triple stars are rather bright: $V=5.57$ mag for V819 Her, $V=6.26$ mag for V2388 Oph, and $V=6.06$ mag for V1031 Ori. All of them are observable from our observatories in the Czech Republic, all have rather deep minima (which make them suitable for small telescopes), and all have rather short periods of the visual orbits (5.5 to 31.3 years).

For the three selected stars, we used the following approach. At first, all of the available interferometric observations were collected and analyzed. These measurements are stored *e.g.*, in the "Washington Double Star Catalog"[1] (hereafter WDS, Mason *et al.* 2001), together with the orbital information (if available). Analyzing the complete set of observations, we obtained an updated solution of the visual orbit and the set of its parameters $(a, p, i, e, \omega, \Omega, T)$, where a is the semi-major axis, p is the period of the outer orbit, i is its inclination, e the eccentricity, ω the argument of periastron, Ω the longitude of the ascending node, and T the time of periastron passage. The least-squares method and the simplex algorithm were used (see *e.g.*, Kallrath and Linnell 1987) for computing.

With this solution, we collected all available times of minima observations, mostly stored in the online database[2], Paschke and Brát (2006). Many new observations for these three systems were also obtained and the times of minima derived by the authors, see Tables 4 and 5 in Appendix. Having a preliminary solution of the visual orbit and plotting the available times of minima in the $O-C$ diagram, one can easily judge whether a system is suitable for a combined analysis or not.

The selection mechanism was rather easy – sufficient coverage of the long orbit at least in part of its period, in the best case the whole period p covered by both methods, especially during the periastron passages. With the values of parameters derived from the visual orbit, the times of minima were analyzed using the LITE hypothesis (see *e.g.*, Mayer 1990). This led to the set of the LITE parameters $(p, A, e, T, \omega_1, JD_0, P)$, where JD_0 and P are the linear ephemerides of the eclipsing pair, and A is the amplitude of the LITE. This amplitude tells us what is the magnitude of the delay caused by the third body, hence its value is largely affected by the mass of the third body and inclination between the orbits. The angles ω_1 derived from the LITE and ω derived from the visual orbit can be the same, or can be shifted by 180°. This ambiguity in argument of periastron is due to the fact that we usually do not know which of the two components on the visual orbit is the eclipsing binary (because we cannot separate the two stars photometrically). However, the combined solution is able to solve this and only one ω value is computed

[1] *http://ad.usno.navy.mil/wds/*
[2] *http://var.astro.cz/ocgate/*

in the code. The other possibility is to measure the radial velocities on the long orbit.

If the system was found to be suitable for a combined approach, we used the code introduced in our previous work (Zasche and Wolf 2007). The starting values of the fit are the preliminary values of parameters as derived for separate solutions. After several iteration steps using the simplex algorithm, the final and acceptable solution was reached. This solution usually gives a fair and acceptable solution for both our data sets for a particular system. The whole computational procedure is stable and converge rather rapidly when both methods have good orbital coverage. If this is not the case and the fitting process provides spurious results, we can also proceed iteratively and fit only some parameters, not to let the programme compute all the parameters simultaneously in one step.

There still remains an open question – of how the amplitude A of the LITE and the semimajor axis a of the visual orbit are connected? Here comes the most important step in our approach, a way how to derive the distance to the system. If we know the distance to the triple (which is usually true, because the stars are bright and close and were mostly observed by the Hipparcos satellite), both a and A are directly connected. The individual masses of all three components are known, because we know the eclipsing binary masses from the light curve and radial velocity curve solution (from the already published papers) and the total mass of the whole system from the visual orbit. Hence, using our combined analysis yielding also both A and a values, the distance to the multiple system can be easily derived independently of other techniques. The detailed description of how the values are connected and the distance can be derived is given in Zasche and Wolf (2007). The same approach was used in Zasche and Wolf (2007) for the system VW Cep, and also for KR Com in Zasche and Uhlář (2010).

Our final fit for all systems was obtained minimizing the total χ-square value, which is being easily computed as a sum of both χ-square values of LITE together with the χ-square value of the visual orbit (see *e.g.*, Zasche 2008 for discussion).

2.1. The Weightening Scheme

The problem with the individual uncertainties in both methods was solved in the following way. The individual errors of the minima times observations were used (when available) for computing, only in these cases where this information was missing we assumed an artificially high value of 0.01 day uncertainty. This was usually the case of old photoelectric data, where the error was not published in the original paper.

Because of unavailable error estimation for the older astrometric data, we have to use a different approach. For the positional measurements the individual weights were used instead of the uncertainties. These very different techniques provide us with an order of magnitude different precision when deriving the positions of the two components, despite the fact that the technique is called in general "interferometric" (*e.g.*, visual interferometry *vs.* long-baseline Palomar Testbed Interferometer). Therefore, the weightening scheme was the following:

- 1 – Visual interferometer
- 5 – Interferometric technique (phase grating interferometer)
- 5 – Hipparcos satellite
- 10 – Speckle interferometric technique (CHARA speckle, USNO speckle)
- 10 – Adaptive optics
- 100 – Long-baseline visual/IR/radio interferometer (Palomar Testbed Interferometer)

As is stated below, the individual published errors of the times of minima are usually underestimated. Artificially increasing these values we tested how the final fit changes. Obviously, the larger the errors in one method (times of minima analysis) – the closer the final fit to the other method (visual orbit). This was tested, but the finding was that doubling the errors of the data points in the minima times data set led to only slight change of the final fit and its parameters (not more than 2–3%).

3. Individual Systems

3.1. V819 Her

V819 Her (= HD 157482 = HR 6469 = HIP 84949 = MCA 47) is an Algol-type eclipsing binary with its magnitude about 5.57 in *V* filter. The photometric analysis was performed by van Hamme *et al.* (1994), who analyzed the color indices and derived the individual spectral types as F2V and F8 for the eclipsing pair, while G8 IV–III for the third component, similar result was also found by Scarfe *et al.* (1994) analyzing the spectra of the system. The third component is also photometrically variable, probably due to the spots on its surface. The eclipsing pair is orbiting around a common center of mass with a third star in a 5.5 yr period visual orbit, having the eccentricity of about 0.67, and the LITE due to this movement is evident. The wider pair was discovered by speckle interferometry in 1980 (McAlister *et al.* 1983) and has been extensively observed by this technique and more recently with the Palomar Testbed Interferometer (Muterspaugh *et al.* 2008), and also using the CHARA Array (O'Brien *et al.* 2011). In addition, the eclipsing pair was resolved (Muterspaugh *et al.* 2006), yielding also the mutual inclination of both orbits as $33.^{\circ}5$ (most recently by O'Brien *et al.* 2011).

This is the only system in our sample where the LITE was analyzed together with the interferometry and radial velocity data before (see Muterspaugh *et al.* 2006). The first analysis of the LITE together with the visual orbit was that by Wasson *et al.* (1994), who also observed many times of minima over a 10 yr period. However, since then a lot of new measurements were obtained, so a new up-to-date analysis would be very profitable, especially when dealing with our new unpublished photometric observations.

The measurements of the eclipses of the inner pair were carried out during the epoch 2008–2014 by two of the authors (RU and PS) at their private observatories in the Czech Republic and northern Italy. These data were mostly obtained by small 35 mm cameras equipped with CCD detectors. Such small instruments were used because of the high brightness of the target. All of the observations were routinely reduced with dark frames and flat fields. The resulting times of minima were calculated using a standard Kwee-van Woerden method (Kwee and van Woerden 1956). The new times of minima are given in Tables 4 and 5 in Appendix together with the already published ones. The errors of the individual observations are given together with the type, filter and reference.

We used the same computational approach as introduced in Section 2. In total, 102 times of minima (of which 43 are our new unpublished data) were used for the analysis, together with 114 interferometric measurements of the visual double. The observations of minima times obtained in different filters during one night, were averaged into one point. All the data points used are given in Tables 4 and 5 in Appendix.

The analysis started with the values of parameters as presented in Muterspaugh *et al.* (2008) and then followed the procedure as described above. The resulting fits of the combined analysis are plotted in Figs. 1 and 2 and the parameters are given in Table 1. As one can see, the final fit of the 5.5 yr variation is clearly visible in Fig. 1, in agreement with the visual orbit plotted in Fig. 2. The 5.5 yr period is now well-defined, and also the periastron passages are well-covered, hence we can also try to calculate the distance to the system.

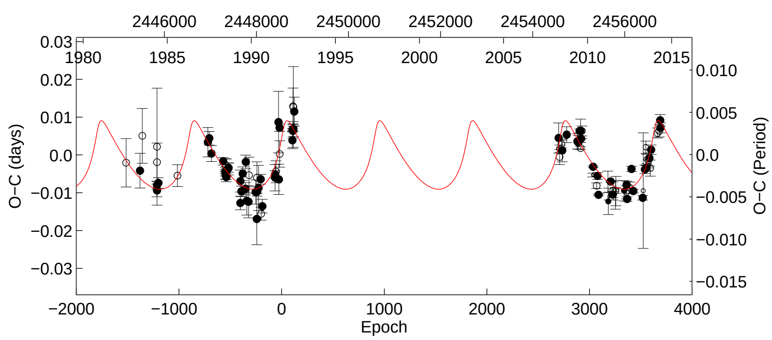

Fig. 1. $O-C$ diagram of V819 Her, plotted with all available times of minima observations. The dots stand for the primary, while the open circles for the secondary minima. The solid curve represents the final LITE fit as derived from the combined solution of the triple. The larger symbols indicate observations with higher precision.

F

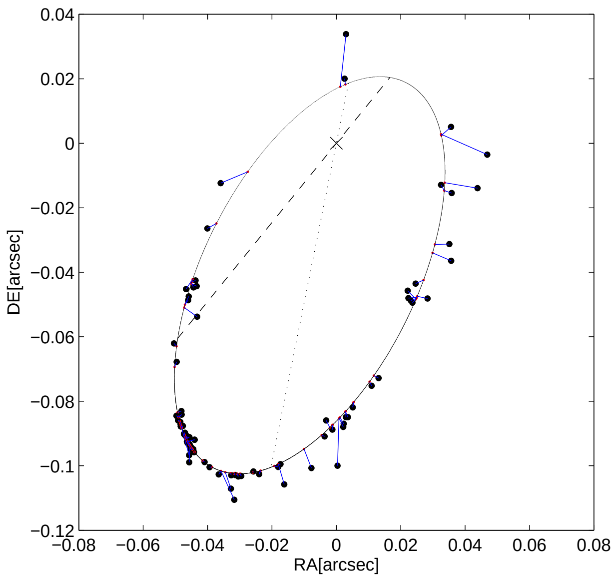

Fig. 2. Visual orbit of V819 Her as projected on the sky. The individual observations are plotted as dots, connected with their theoretical positions on the orbit with short abscissae. The dashed line represents the line of the apsides, while the dotted one stands for the line of the nodes. The eclipsing binary is located in the coordinates (0,0).

Scatter of the data points in Fig. 1 is slightly larger than one would expect from the individual error bars plotted. It is probably caused by a photometric variability of the third component, which could also influence the shape of both primary and secondary minima. Hence, also the times of minima and precision of their derivation can be affected. The magnitude of $O-C$ scatter caused by a presence of spots was studied *e.g.*, by Watson and Dhillon (2004), who found it to be well below our minima precision, of the order of seconds only. On the other hand, our recent study of two binaries with asymmetric light curves and application of standard Kwee-van Woerden method for minima times derivation led to rather different finding that this can be up to 15 minutes (Zasche 2011) for very asymmetric light curves. Nevertheless, as one can see from Fig. 1, the individual error bars are rather underestimated. This is usually caused by a fact that the errors of minima are usually only the formal errors as derived from the Kwee-van Woerden method itself, but real uncertainty should be order of magnitude larger. On the other hand, it is noteworthy that the scatter of our new observations is lower than the scatter of the older data from 1980's and 1990's, despite the fact that we were using an order of magnitude smaller telescopes, but equipped with CCD cameras instead of photoelectric photometers.

Table 1

Final parameters of combined solution for V819 Her

	V819 Her	
Parameter	Present study	Muterspaugh *et al.* (2008)
JD_0	2448546.5954 (7)	2452627.17 (0.29)
P [d]	2.2296330 (19)	2.2296330 (19)
p [day]	2015.8 (54.9)	2019.66 (0.35)
p [yr]	5.519 (0.150)	5.530 (0.001)
A [day]	0.0090 (8)	0.0088 (9)[a]
T	2452621.6 (81.2)	2452627.5 (1.3)
ω [deg]	223.8 (3.5)	222.50 (0.22)
e	0.687 (11)	0.6797 (7)
i [deg]	56.82 (1.63)	56.40 (0.13)
Ω [deg]	140.8 (5.9)	141.96 (0.12)
a [mas]	74.6 (3.7)	74.4 (0.9)[a]
$f(m_3)$ [$M_\odot$]	0.193 (22)	0.177 (30)[a]
M_3 [$M_\odot$]	1.86 (0.30)	1.799 (0.098)
a_{12} [a.u.]	2.16 (0.15)	2.11 (0.08)[a]
a_3 [a.u.]	2.97 (0.20)	2.99 (0.16)[a]
d [pc]	68.8 (1.8)	68.65 (0.87)

The errors given in the parenthesis, as resulted from the program.
Remark: [a] – calculated from the original values

In Table 1 we compare our present results with the previous values of parameters as given in Muterspaugh *et al.* (2008). Some of the parameters were calculated from the published values, just to be compared with our results. As one can see, the agreement is quite high for most of the parameters, but the errors given by Muterspaugh *et al.* (2008) seem to be rather optimistic. On the other hand, we present only our formal mathematic errors as resulted from the computational code, which can be slightly different from a more realistic physical errors. However, the superb precision of the results published by Muterspaugh *et al.* (2008) is due to the fact that they analyzed the radial velocities and interferometry of a state of the art quality, covering several periods of the outer orbit. Hence, the Table 1 can serve as a demonstration of our method based on rather different approach and providing comparable results, with no need of radial velocities on the long orbit.

As mentioned above, we also tried to compute the distance to the system from our combined "period variation *vs.* visual orbit" method. Also this value (about 68.8 pc) resulted in very good agreement with the previously derived values, with no need of long-term spectroscopic monitoring. This value confirms the previous findings by other authors (*e.g.,* Muterspaugh *et al.* 2008, Scarfe *et al.* 1994, or O'Brien *et al.* 2011) that the Hipparcos value 74.0 ± 4.8 mas (van Leeuwen 2007) is a bit shifted.

3.2. V2388 Oph

V2388 Oph (= HD 163151 = HIP 87655 = FIN 381) is a W UMa-type eclipsing binary, a bit fainter than V819 Her, of about 6.3 mag in *V* filter. It was discovered as a variable star relatively late, in 1995 by Rodríguez *et al.* (1998). They also classified the star as a W UMa contact type (despite incorrectly classified as β Lyr on SIMBAD), with the individual temperatures 6450 K and 6130 K for both components and an orbital period of the eclipsing pair of about 0.8 days. Both minima are more than 0.2 mag deep, hence it is an easy target to be observed. Later, Rucinski *et al.* (2002) observed the star spectroscopically and classified both components as F-types.

The system was discovered as a visual binary star by Finsen (1964), and since then many new observations of the pair were carried out. Baize (1988) published its slightly eccentric orbit with a period of about 8.3 yr. Later, Söderhjelm (1999) provided a better visual-orbit solution with a period of 8.9 yr. And the most recent study by Docobo and Andrade (2013) presented the best solution of the data covering more than 50 years with a period of 9.008 yr and eccentricity 0.327.

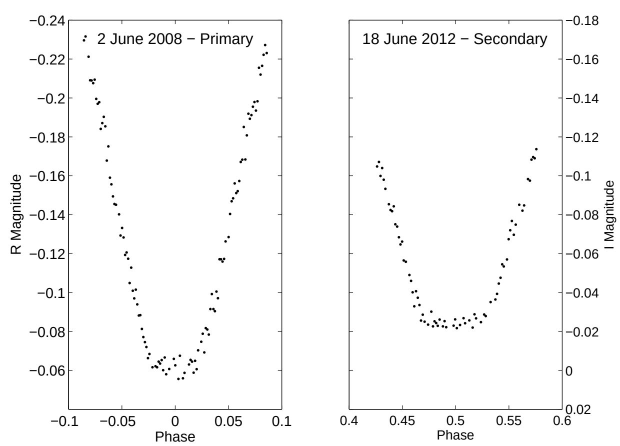

Fig. 3. Two observations of minima of V2388 Oph, clearly showing the total eclipses.

Since its discovery as a variable star, many observations of both primary and secondary minima of the eclipsing pair were obtained. The light curve analysis has been carried out a few times. The last one is that by Yakut *et al.* (2004), who observed the system in *BVR* filters and analyzed the light curve. Moreover, they also tried to combine the visual orbit parameters as published by Söderhjelm (1999) and the apparent period variation of the eclipsing binary applying the LITE hypothesis. However, their analysis is incorrect, leading to the large disagreement with the implied masses from the distance and visual orbit. The problematic point of their analysis was the fact that they only had to their disposal data with poor coverage of the third-body period (nine times-of-minima data points) and they only fit the amplitude of the LITE, fixing all other parameters. Moreover, their light curve analysis is dubious because of the fact that their fit did not show any total eclipse (in contradiction with the analysis by Rodríguez *et al.* 1998). Our observations clearly show that there is a total eclipse lasting more than one hour (see Fig. 3). Hence, their inclination angle for the eclipsing pair should be higher, closer to the 90°, yielding different masses of the components.

At this point, our present analysis seems to be much more reliable. We evaluated a much larger data set of minima observations (almost three times longer time base, more than 70 new observations carried out and reduced by the authors), and our fitting procedure incorporates all relevant parameters for the combined fit of the visual orbit together with the period variation of the eclipsing pair. Our analysis is based on 93 minima times observations (see Tables 4 and 5 in Appendix), mostly our new ones, which were analyzed following the procedure as described in Section 2. The starting values for the parameters are the ones presented by Docobo and Andrade (2013). The final solution of our combined fit is presented in Figs. 4 and 5. The values of all parameters are given in Table 2. The scatter of the minima times is quite large, but this is probably the physical scatter of the observations and maximum what can be obtained from the small ground-based telescopes, because the individual observations were obtained using different instruments, reduction, weather conditions, etc. To repeat once again, the errors of most of the already published observations are usually underestimated and only formal ones as derived from the Kwee-van Woerden method. There is also a possibility of a kind of chromospheric activity (Yakut *et al.* 2004), which is quite common in this kind of late-type contact binaries. Moreover, the spot on the surface (Rodríguez *et al.* 1998) makes the whole curve asymmetric, which also brings some difficulties when deriving the times of minima, see the discussion on the $O-C$ precision in Section 2.

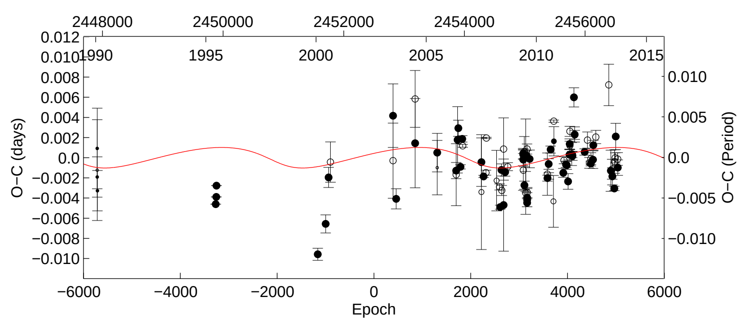

Fig. 4. $O-C$ diagram of V2388 Oph. See Fig. 1 for description of the symbols.

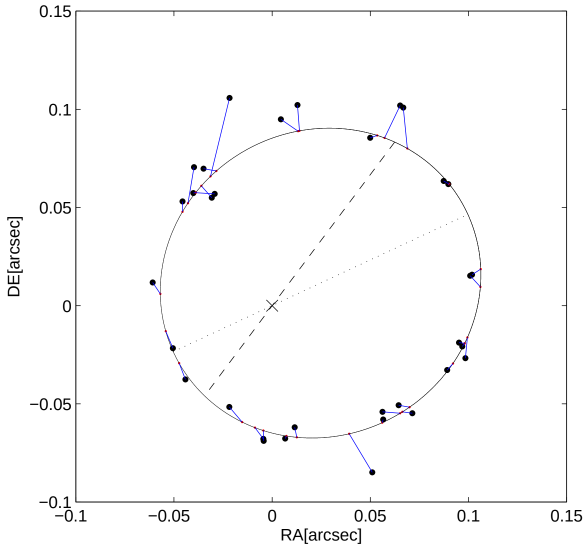

Fig. 5. Visual orbit of V2388 Oph.

Table 2

Final parameters of combined solution for V2388 Oph

	V2388 Oph	
Parameter	Present study	Docobo and Andrade (2013)
JD_0	2452500.3842 (4)	–
P [d]	0.80229787 (69)	–
p [day]	3277.9 (22.5)	3290.1 (5.5)
p [yr]	8.975 (60)	9.008 (15)
A [day]	0.00102 (6)	–
T	2454197.2 (27.0)	2454210.0 (18.3)
ω [deg]	208.4 (3.3)	238.3 (10.0)
e	0.329 (4)	0.327 (2)
i [deg]	171.6 (5.2)	160.9 (5.0)
Ω [deg]	323.2 (2.8)	353.6 (10.0)
a [mas]	83.0 (3.0)	85.3 (2.0)
$f(m_3)$ [$M_\odot$]	$7.8\ (1.4) \cdot 10^{-5}$	–
M_3 [$M_\odot$]	0.54 (0.06)	–
a_{12} [a.u.]	1.26 (0.09)	–
a_3 [a.u.]	4.60 (1.02)	–
d [pc]	70.6 (8.9)	–

Despite large scatter of the minima, we also tried to compute the distance to the system from the values a and A. However, the total mass of the eclipsing pair is necessary for the calculation. This value was derived from the mass function as derived from the radial velocities by Rucinski *et al.* (2002) and using the inclination presented by Rodríguez *et al.* (1998). From this value of $M_{12} = 1.96 \pm 0.03$ M$_\odot$ we derived the mass of the third body $M_3 = 0.54 \pm 0.06$ M$_\odot$ (see Table 2) and also the distance to the system V2388 Oph.

At this point it is also advisable to comment the masses of the visual binary presented by Docobo and Andrade (2013). They gave the values 1.7 M$_\odot$ for the primary, while 1.3 M$_\odot$ for the secondary of the visual double, and also a note about the magnitude difference of about 0.2 mag only. But this is also rather doubtful value, because stars on the main sequence with such masses should have much larger magnitude difference (see *e.g.*, Harmanec 1988). Also the "Delta-m catalogue" [3] lists the magnitude difference about $\Delta m = 1.5$ mag, which implies much different components of the visual pair. Our resulting values provide a better fit to the Δm value. The amplitude of the eclipsing pair variation is not so large to shift the Δm value so low. Therefore, we can speculate about the origin of such a large magnitude change during the last 40 years suspecting that the photometric variation comes from the third component. This could explain why in 1960's the magnitude difference was about 0.3 mag (van den Bos 1963), while about 40 years later this difference was about one magnitude larger (Horch *et al.* 2010).

From our analysis the distance to the system is about 70.6 ± 8.9 pc. The original Hipparcos value was 67.9 ± 4.0 pc (Perryman *et al.* 1997), later recomputed to 83.3 ± 6.1 pc (van Leeuwen 2007). On the other hand, Yakut *et al.* (2004) presented the distance 68 ± 4 pc, and Docobo and Andrade (2013) gave two values 74.3 ± 2.2 pc, and 72.3 ± 2.1 pc, respectively. The scatter of these values is still rather large, but our result has also high uncertainty. This is due to the poor coverage of the LITE fit and its still not very well-defined amplitude.

3.3. V1031 Ori

The system V1031 Ori (= HD 38735 = HR 2001 = HIP 27341 = MCA 22) is an Algol-type eclipsing binary, discovered as a variable by Strohmeier and Knigge (1961). Later, Olsen (1977) classified the star as an eclipsing binary and gave the correct orbital period of about 3.4 day. The most detailed analysis is that by Andersen *et al.* (1990), who observed the whole light curve in *uvby* filters, and also obtained 26 spectrograms of this multiple system. The analysis revealed that it is a detached binary, with rather deep minima of about 0.4 mag in the *V* filter, both components are of A spectral type, and the distance to the system is about 215 ± 25 pc. The more recent parallax from the Hipparcos gave the distance 205 ± 36 pc (van Leeuwen 2007). Most recently, the original data by Andersen *et al.* (1990) were recalculated by Torres *et al.* (2010).

[3] *http://ad.usno.navy.mil/wds/dmtext.html*

Moreover, V1031 Ori was also discovered as a visual binary (McAlister *et al.* 1983), and more than twenty observations were carried out since its discovery. The magnitude difference between the two visual components is of about 1.5 mag. Recent interferometric observations obtained during the last decade revealed a rapid movement on the visual orbit, indicating rather short orbital period. The first rough estimation of the visual orbit is a short discussion about the speckle data by Andersen *et al.* (1990), who proposed a period of more than three thousand years. A recent attempt at the orbital solution from the available interferometric data was that by Zasche *et al.* (2009), who proposed a visual orbit period of about 93 yr and a circular orbit based, however, on very poor data coverage. Since then a few new observations were carried out, which can help us to better constrain the orbital properties of the double.

A similar approach as introduced above was applied to this system. However, the task was a bit simplified, because the distance was not computed. The distance can only be derived when both methods (visual orbit as well as the LITE fit) have well-defined amplitudes (*i.e.,* the amplitude of LITE as well as the semimajor axis of the visual orbit), but this is not true in this case. The periastron passage has only been covered very poorly in both methods (see below), and our fit is still only preliminary.

T a b l e 3

Final parameters of combined solution for V1031 Ori

	V1031 Ori	
Parameter	Present study	Zasche *et al.* (2009)
JD_0	2452500.3044 (3)	–
P [d]	3.4055587 (26)	–
p [day]	11432 (1252)	33843 (2414)
p [yr]	31.3 (3.4)	92.66 (6.61)
A [day]	0.0144 (69)	–
T	2453025 (948)	2430580 (2849)
ω [deg]	160.8 (27.0)	180.3 (28.5)
e	0.921 (19)	0.001 (0.001)
i [deg]	46.9 (13.0)	76.3 (8.2)
Ω [deg]	305.2 (11.3)	291.9 (9.4)
a [mas]	94.4 (6.4)	176 (7)
$f(m_3)$ [$M_\odot$]	0.13 (0.03)	–
M_3 [$M_\odot$]	2.65 (0.69)	–
a_{12} [a.u.]	6.93 (1.67)	–
a_3 [a.u.]	12.4 (3.0)	–

Our resulting fit is presented in Figs. 6 and 7. The parameters are given in Table 3. As one can see, the visual orbit is very different from the one proposed in Zasche *et al.* (2009). This is due to the fact that in the previous work only a

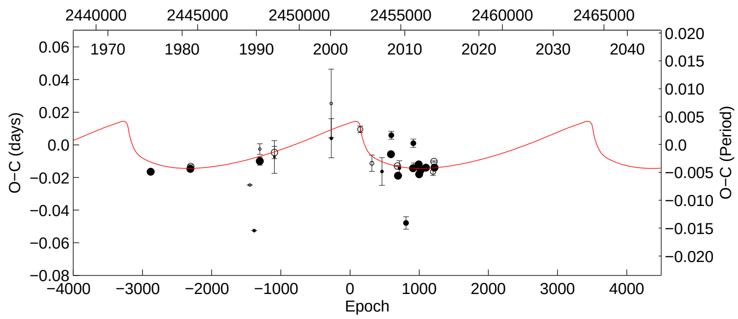

Fig. 6. $O-C$ diagram of V1031 Ori. See Fig. 1 for description of the symbols.

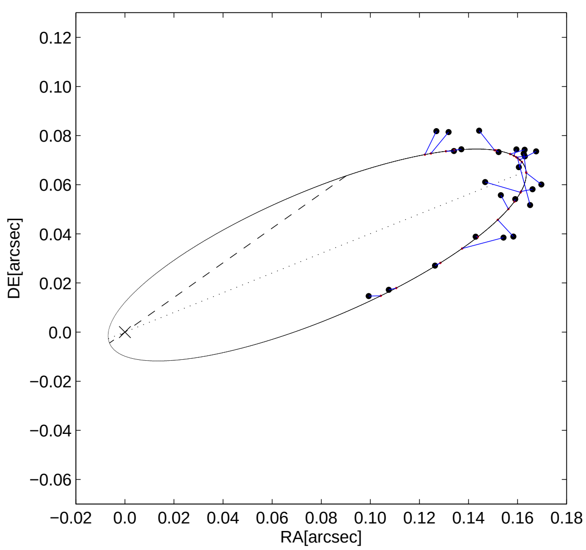

Fig. 7. Visual orbit of V1031 Ori.

small arc of the orbit was covered with observations, and these observations were obtained away from the periastron. New observations were secured closer to the periastron passage, hence a new orbit with better defined parameters was derived. We observed several new minima during the last five years and also collected some already published observations (see Tables 4 and 5 in Appendix), which show only mild additional variation. This is due to the fact that these were obtained away from the periastron passage, where the apparent period change of the eclipsing binary is very slow, see Fig. 6. On the other hand, the orbit as derived from the recent interferometric observations is defined quite well, because the binary just completed one revolution since its discovery. Quite interesting is a value of high eccentricity of the long orbit. Our final result about the mass of the third component of about 2.65 $M_\odot$ is in good agreement with the previous finding by Andersen *et al.* (1990), who proposed a mass of 2.2 $M_\odot$.

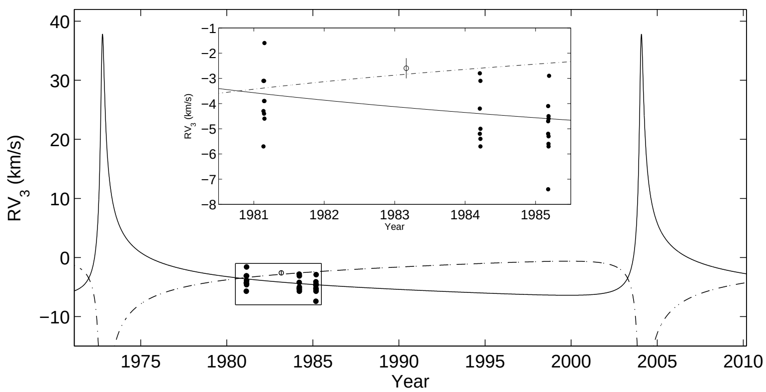

Fig. 8. Radial velocities of V1031 Ori as measured by Andersen *et al.* (1990). The third component's velocities are plotted as dots, the radial velocity of barycenter of the eclipsing pair as open circle. The small rectangle is zoomed for a better clarity.

In Fig. 8 we present the predicted radial velocity variation plotted together with the observations of the third-body lines and the systemic velocity (*i.e.*, radial velocity of the barycenter) of the eclipsing pair as published by Andersen *et al.* (1990). As one can see, our fit computed from the parameters listed in Table 3 is able to describe the observed velocities quite well, however its conclusiveness is still poor due to only small time interval of the observations. Hence, some new observations close to the upcoming periastron passage in 2035 would be very useful.

4. Discussion and Conclusions

We performed the combined analyses of the visual orbit and the apparent period changes of three eclipsing binaries V819 Her, V2388 Oph, and V1031 Ori. These systems belong to a still rather limited group of stars, where the eclipsing binary is a part of multiple stellar system, and the long orbit was observed *via* interferometry. The long-term collecting of the spectroscopic data for several years or decades is a bit complicated nowadays (due to time allocation policy on larger telescopes). Hence, this method which does not need any radial velocities of the long orbit could be a way how to work around this problem.

On the other hand, there are still only a few systems where this approach has been applied. We can divide the group of eclipsing subsystems in the visual doubles (where the visual orbit was derived) into three groups (see *e.g.*, Zasche *et al.* 2009):

- Systems, where both the visual orbit and the LITE was computed simultaneously: QS Aql, i Boo, VW Cep, KR Com, V772 Her, V819 Her, V2388 Oph, V1031 Ori, ζ Phe, V505 Sgr, DN UMa, and HT Vir.
- Those for which the visual orbit is known (as well as the solution of the light and radial velocity curves), but the LITE was not detected yet: ET Boo, V831 Cen, V2083 Cyg, MR Del, LO Hya, DI Lyn, GT Mus, δ Ori, η Ori, β Per, V592 Per, V1647 Sgr, V906 Sco, BB Scl, ξ Tau, and δ Vel.
- And finally stars, for which the orbit is known, but no light curve analysis (nor the LITE analysis) was performed: V559 Cas, V773 Cas, V871 Cen, V949 Cen, BR Ind, V635 Mon, CN Hyi, V410 Pup, XY Pyx, and λ Sco.

A future detailed analysis of all these systems would be of interest, especially for shifting the systems from the lower two groups into the first one. The combined analysis as presented in this paper would be very useful in this way. When having the complete set of orbital parameters for both orbits in a particular system, one can obtain the ratio of the periods, mutual inclination of the orbits, their eccentricities, mass ratios, etc. All of these parameters can help to better understand the formation processes in the multiple stellar systems (see *e.g.*, Halbwachs *et al.* 2003, or Tokovinin 2008).

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The data mining II: An analysis of 33 eclipsing binary light-curves observed by the INTEGRAL/OMC

P. Zasche *

Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, México, DF 04510, Mexico
Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic

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Stars: fundamental parameters

ABSTRACT

Thirty-three eclipsing binaries were selected for an analysis from a huge database of observations made by the INTEGRAL/OMC camera. The photometric data were processed and analyzed, resulting in a first light-curve study of these neglected eclipsing binaries. The system CY Lac was discovered to be an eccentric one. In several systems from this sample even their orbital periods have been confirmed or modified. Due to missing spectroscopic study of these stars, further detailed analyses are still needed.

* Address: Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, México, DF 04510, Mexico. Fax: +420 221912577.
E-mail address: zasche@sirrah.troja.mff.cuni.cz

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1. Introduction

The INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) satellite produces many observations since its launch in 2002, not only in gamma part of the spectra. The onboard OMC (Optical Monitoring Camera) was designed to obtain the observations in optical *V* passband. These observations are in fact only a by-product of the mission, but nowadays there are many observations available.

Despite the fact that the database of these measurements is freely available on internet, the analyses are still very rare. The most recent one using the OMC data is that by Jurcsik et al. (2009) about a new β Cep star.

This investigation is directly following our previous papers (Zasche, 2008 and Zasche, 2009). The selection criteria used here were also the same: maximum number of data points and non-existence of any detailed light-curve analysis of the particular system. There were 33 systems selected for the present paper.

2. Analysis of the individual systems

All observations of these systems were carried out by the same instrument (50 mm OMC telescope) and the same filter (standard Johnson's V filter). Time span of the observations ranges from November 2002 to October 2008. A transformation of the time scale has been done following the equation $JulianDate - ISDCJulianDate = 2,451,544.5$. Only a few outliers from each data set were excluded. The PHOEBE programme (see e.g. Prša and Zwitter, 2005), based on the Wilson–Devinney algorithm (Wilson and Devinney, 1971), was used for the analysis.

Due to missing information about the stars, and having only the light-curves in one filter, some of the parameters have to be fixed. At first, for all systems we have used the "Detached binary" mode (in Wilson & Devinney mode 2) and also the "Semidetached with the secondary component filling its Roche lobe" (mode 5 in Wilson & Devinney) for computing. For both modes a "q-search method" was used, which means trying to find the best fit with different values of the mass ratio q ranging from 0 to 1 with a step 0.1. The limb-darkening coefficients were interpolated from van Hamme's tables (see van Hamme, 1993), the linear cosine law was used. The values of the gravity brightening and bolometric albedo coefficients were set at their suggested values for convective atmospheres (see Lucy, 1968), i.e. $G_1 = G_2 = 0.32, A_1 = A_2 = 0.5$. In all cases (except for CY Lac) the orbital eccentricity was set to 0 (circular orbit). Therefore, the quantities which could be directly calculated from the light curve are the following: The luminosity ratio L_1/L_2, the temperature ratio T_1/T_2, the inclination i, ephemerides of the system, the Kopal's modified potentials Ω_1 and Ω_2, the synchronicity parameters F_1 and F_2, the third light l_3, and the mass ratio q. Using the parameters introduced above, one could also derive the value of the radii ratio R_1/R_2.

The distinguishing between the minima has been done only according to the observational point of view, which means that the deeper one is the primary one. This results in a fact that the primary component could be neither the larger one, nor the more massive one. In two cases the secondary components result to be the more luminous ones (V1450 Aql and V714 Sco), and in several cases also the more massive ones.

All of the basic information about the analyzed systems are introduced in Table 1, where are the *B* and *V* magnitudes from

Table 1
Basic information about the analyzed systems, taken from the literature.

Star	Mag B GCVS	Mag V GCVS	(B-V) GCVS	(B-V) Nomad	Sp.	Sp. S&K	q S&K	Type S&K	Minima	Mag OMC	Mag MinI	Mag MinII	Data
V408 Aql	14.10			0.790		(A2)+[G8IV]	0.170	EA/SD	16	13.08	14.20	13.23	822
V964 Aql	13.20			0.360		(A3)+[G0IV]	0.410	EA/SD	4	13.73	14.89	14.04	511
V1426 Aql	9.63	9.18	0.45	0.433	G0				10	9.14	9.60	9.31	823
V1450 Aql	9.28	8.99	0.29	0.272	A0V+A?					8.87	9.16	9.11	2234
LP Ara	10.48	10.2	0.28	0.253	B8	B8+[A8]	0.090	EA/DS	0	10.05	11.01	10.49	541
DQ Car	11.3	11.1	0.2	0.203	A0	A0+[G1IV]	0.240	EA/SD	3	11.04	11.67	11.60	567
DR Car	11.80			0.060	B5	B5+[G0IV]	0.260	EA/SD	0	11.34	12.76	11.57	556
BZ Cas		11.4		0.399	A0	A0+[G1.5IV]	0.320	EA/SD	49	11.27	12.36	11.41	560
V654 Cas	11.4	10.9	0.5	0.363	B3-B5V					10.85	11.86	10.91	585
PQ Cen	10.50			0.192		(A8)+[K0IV]	0.260	E/SD	3	10.63	11.60	10.70	379
V379 Cen	8.80	8.1	0.70	-0.007	B5Vn	B5V+[A3]	0.350	EA/SD	4	8.78	9.84	9.10	258
V Cir	10.80	10.7	0.10	0.637		(B0)+[B3]	0.490	EB/DM	26	10.74	11.68	11.03	441
DO Cyg	11.2	10.7	0.5	0.346	A0	A0+[G2IV]	0.200	EA/SD	83	10.74	11.60	10.79	636
DP Cyg	13.20			0.130		(A2)+[K6IV]	0.200	EA/SD	2	12.85	14.28	13.13	641
V536 Cyg	11.90			0.386		(A2)+[K1IV]	0.120	EA/SD	16	11.26	13.02	11.33	624
V537 Cyg	11.4	10.6	0.8	0.884	A-B	A(5)+[G8IV]	0.130	EA/SD	20	10.64	10.97	10.67	625
V616 Cyg	13.80			0.250		(B7)+[F4]	0.370	EA/SD	33	12.89	14.10	12.98	544
V642 Cyg	12.90			0.230		(A5)+[K0IV]	0.150	EA/SD	15	12.61	14.48	12.67	728
V703 Cyg	13.50			-0.570					3	12.90	14.54	13.04	692
V359 Her	10.30	10.03	0.27	0.305	F0	F0+[G9IV]	0.320	EA/SD	141	9.95	10.58	10.04	505
CY Lac	11.53	11.32	0.21	0.041	B5	B5V+[F0]	0.300	EA/SD	0	11.35	11.71	11.68	557
YY Nor	13.20			0.270		(B9)+[G0IV]	0.400	EA/SD	0	12.73	15.13	12.91	494
HM Nor	11.5	11.1	0.4	0.400		(A5)+[K0IV]	0.150	EA/SD	0	11.22	14.02	11.34	496
V537 Oph	12.50			0.140		(F0)+[F0]	1.000	EA/DW	2	12.19	12.69	12.60	498
BS Sco	11.1	10.7	0.4	0.391	B5V	B5V+[G2IV]	0.280	EA/SD	0	10.59	12.42	10.70	549
V569 Sco	10.70			0.641	A3	A3+[A4]	0.940	EA/DM	14	10.68	11.52	11.46	520
V714 Sco	12.20					(A7)+[G7IV]	0.330	EA/SD	0	11.92	12.66	12.51	576
BN Sgr	9.60	9.28	0.32	0.566	G2-5	F6+[K0IV]	0.400	EA/SD	3	9.28	10.10	9.42	869
V780 Sgr	12.80			0.390		(A5)+[G2IV]	0.110	EA/SD	0	13.35	14.37	13.43	912
V2168 Sgr	12.50			0.680					1	13.30	15.08	13.42	511
XY Vel	11.50			0.549		(A5)+[G8IV]	0.210	EA/SD	4	11.94	13.81	12.07	583
YY Vel	11.3	11.1	0.2	0.113		(A2)+[K1IV]	0.220	EA/SD	0	11.03	11.81	11.10	541
AZ Vel	12.70			0.260		(A8)+[F5]	0.500	EA/SD	2	12.58	14.04	12.96	620

the GCVS (Kukarkin et al., 1971 and Malkov et al., 2006), the $B-V$ values from the GCVS and also from the NOMAD catalogue (Zacharias et al., 2004). The spectral types are taken from the published literature and also from the Svechnikov and Kuznetsova (S&K, Svechnikov and Kuznetsova, 1990). The estimated mass ratio and also the type of the eclipsing binary have been taken from S&K (EA stands for the Algol type, while EB for the β Lyrae type, SD for semi-detached systems, DS for detached ones with subgiant

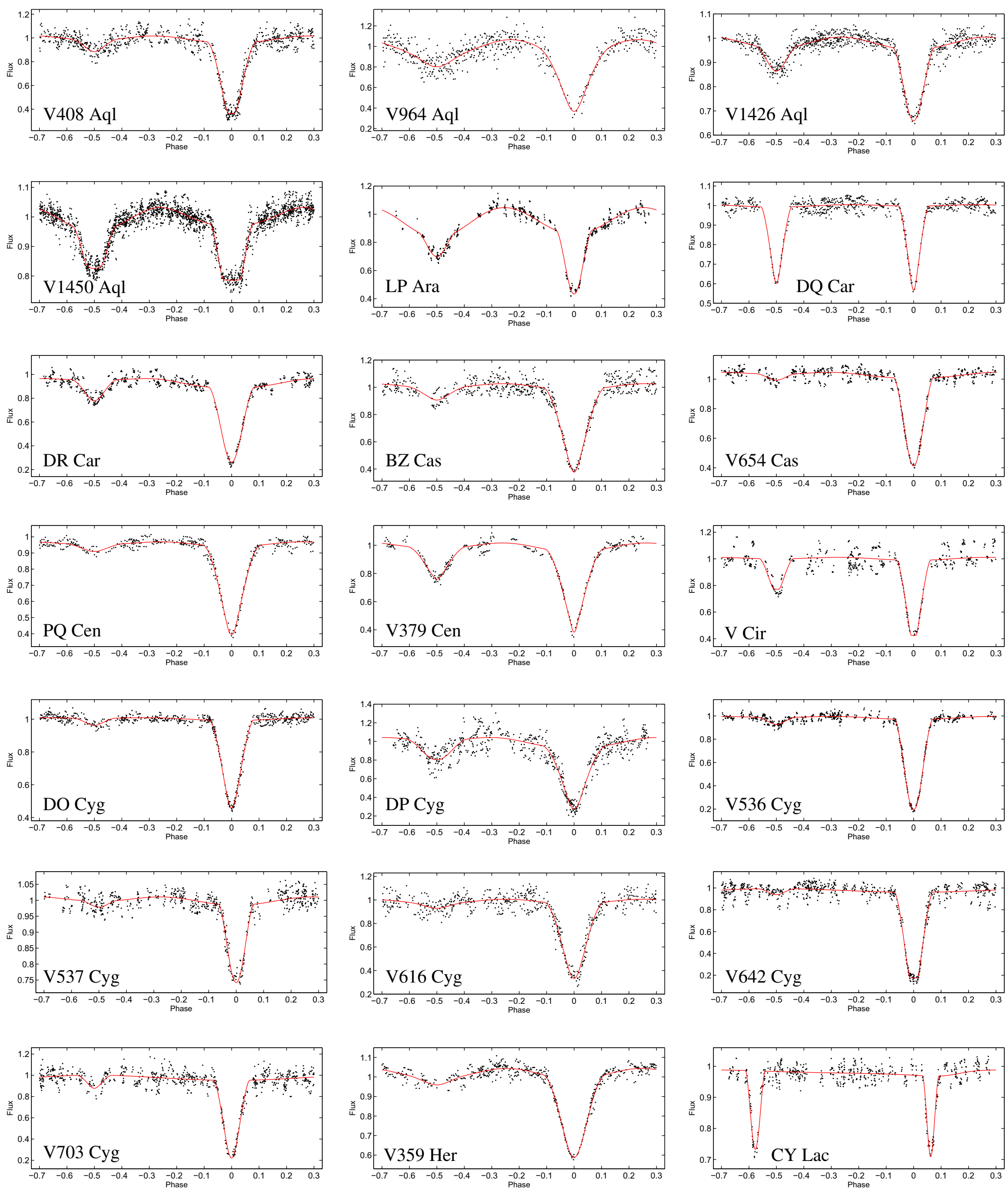

Fig. 1. The light-curves of the analyzed systems.

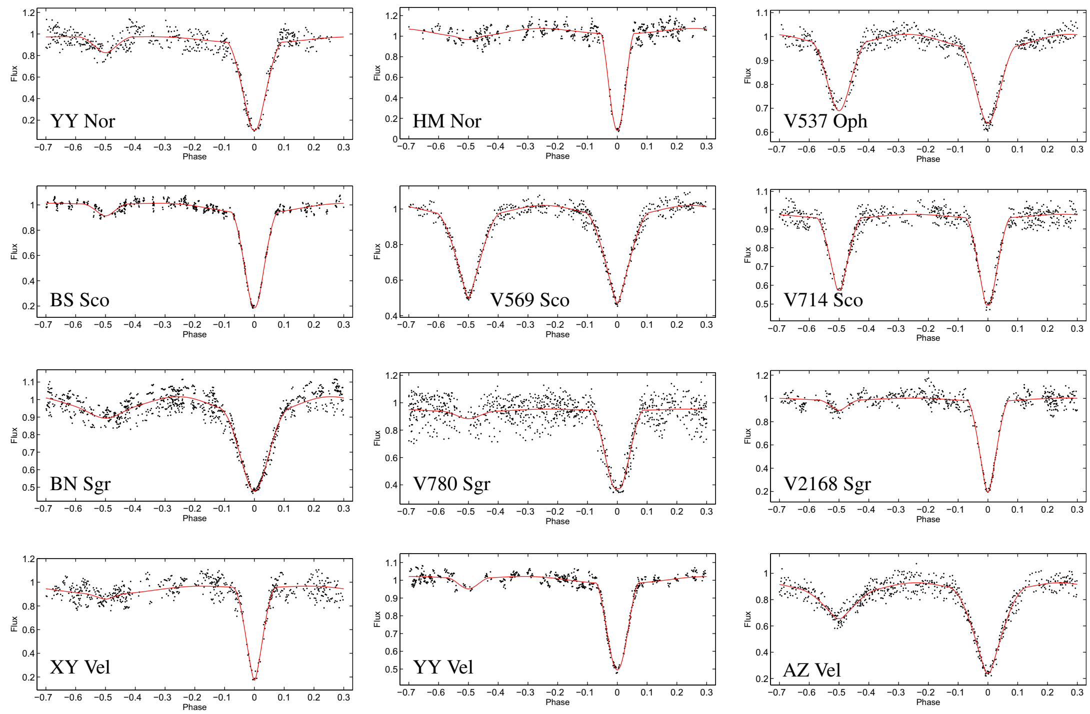

Fig. 2. The light-curves of the analyzed systems.

secondary, and DM for detached main sequence ones).'Minima' stands for the number of published times of minima and the last four columns introduce the actual OMC magnitudes in Johnson's *V* filter, the depths of both primary and also secondary minima in *V* filter, and finally the number of data points used for this analysis.

The results are introduced in Figs. 1 and 2 and Table 2, where are given all relevant parameters of the analyzed systems: HJD_0 and *P* are the ephemerides of the system, *i* stands for the inclination, *q* denoted the mass ratio, the 'Type' refers the mode used for the best solution ('D' for a detached na 'SD' for a semi-detached one, see above), Ω_i stands for the Kopal's modified potentials, T_i for the effective temperatures, L_i for the luminosities, R_i for the radii, F_i for the synchronicity parameters, and x_i for the limb-darkening coefficients (the linear cosine law was used), respectively. Inclinations smaller than 90° mean that the binary rotates counter-clockwise as projected onto a plane of sky. Only two systems (V780 Sgr and AZ Vel) have their respective orbital periods shorter than 1 day and CY Lac was found to be the eccentric eclipsing binary. In some systems their orbital periods were found to be different from the values published in the literature (e.g. in GCVS). The most reliable information about its orbital elements was found in the online 'O-C gateway'[1] (Paschke and Brat, 2006).

The parameters of CY Lac are the following: the eccentricity $e = 0.2565$ and the argument of periastron $\omega = 2.575$ rad. In this system both primary and secondary minima have approximately equal depths, so the primary and secondary components (and also both minima) could be interchanged. This is the only case, where (due to its eccentricity) the value of HJD_0 in Table 2 does not refer to the time of minimum light suitable for future observations. One time of minimum light for this system has been derived: 2454248.8262 ± 0.0049.

Another interesting fact of this sample is that about one half of the investigated systems have the luminosity of the third unseen body above a statistically significant value about 5%. This result is not surprising, because e.g. Pribulla and Rucinski (2006) also discovered that more than 50% of binaries exist in multiple systems. One could speculate about a prospective future discovery of such components in these systems. Due to missing detailed analysis (spectroscopic, interferometric, etc.), the only possible way how to discover these bodies nowadays is the period analysis of their times of minima variations. In the system BZ Cas such an analysis exists and the third body was discovered with orbital period about 61 yr, see Erdem et al. (2007).

3. Discussion and conclusions

The light-curve analyses of 33 selected systems have been carried out. Using the light-curves observed by the Optical Monitoring Camera onboard the INTEGRAL satellite, one can estimate the basic physical parameters of these systems. Despite this fact, the parameters are still only the preliminary ones, affected by relatively large errors and some of the relevant parameters were fixed at their suggested values. The detailed analysis is still needed, especially spectroscopic one, or another more detailed light curve one in different filters. Together with a prospective radial-velocity study, the final picture of these systems could be done. Particularly, the systems V1450 Aql and CY Lac seem to be the most interesting ones. The first one is massive semi-detached system, which shows total eclipses and the second one due to its eccentric orbit.

[1] see http://var.astro.cz/ocgate/.

Table 2
The light-curve parameters of the individual systems, as derived from our analysis.

Parameter Star	HJD_0 2450000+	P [days]	i[deg]	$q = M_2/M_1$	Type	Ω_1	Ω_2	T_1/T_2	L_1[%]	L_2[%]	L_3[%]	R_1/R_2	F_1	F_2	x_1	x_2
V408 Aql	2742.574	2.83503997	89.094	0.6	SD	6.0478	–	1.815	63.75	14.96	21.29	0.713	5.106	1.883	0.499	0.787
V964 Aql	2729.309	1.26290000	85.342	0.5	SD	3.1582	–	0.993	84.54	11.90	3.57	1.196	1.485	0.000	0.690	0.682
V1426 Aql	2709.109	1.17515945	77.683	0.7	SD	4.9504	–	1.367	68.58	29.21	2.21	0.940	0.000	3.187	0.472	0.635
V1450 Aql	2740.317	4.81261051	93.106	1.5	SD	10.9790	–	1.040	19.41	73.20	7.39	0.396	9.906	2.634	0.457	0.478
LP Ara	2674.116	8.53282038	77.079	0.2	SD	4.7800	–	1.143	70.52	29.48	0.00	1.135	3.748	2.316	0.500	0.500
DQ Car	2825.284	1.73367847	92.179	0.8	D	7.1553	5.9273	0.841	52.68	43.71	3.61	1.036	5.332	0.000	0.350	0.309
DR Car	3146.403	3.99577477	97.608	0.7	SD	5.4403	–	2.197	70.65	29.35	0.00	0.725	0.000	2.220	0.292	0.472
BZ Cas	3551.758	2.12646842	95.307	0.6	D	3.7192	3.0535	1.548	74.75	9.74	15.51	0.988	0.000	0.207	0.319	0.452
V654 Cas	2656.527	4.94207240	79.681	0.3	SD	5.9987	–	2.532	72.26	10.51	17.24	0.593	0.000	0.388	0.285	0.537
PQ Cen	2831.836	1.05718895	87.357	0.4	D	3.4249	2.7701	2.307	81.34	3.54	15.12	1.204	0.000	0.544	0.500	0.255
V379 Cen	2651.290	1.87469639	89.393	0.6	D	3.9956	3.2835	1.331	66.22	20.52	13.26	1.061	1.838	0.880	0.514	0.563
V Cir	3062.298	4.40923643	91.678	0.6	D	5.5716	5.1156	1.655	84.16	15.84	0.00	1.425	3.755	0.000	0.074	0.279
DO Cyg	4087.345	1.70999742	84.467	0.4	D	4.7945	2.9291	2.078	66.11	5.09	28.80	0.834	0.504	1.498	0.291	0.533
DP Cyg	2746.748	2.34691815	86.792	0.3	SD	3.1773	–	1.795	87.17	12.83	0.00	1.205	1.272	0.000	0.529	0.814
V536 Cyg	2836.598	6.01045459	84.108	0.5	D	6.3426	3.2831	1.727	82.58	12.81	4.61	0.656	1.161	1.826	0.579	0.500
V537 Cyg	3347.884	4.75843337	77.032	0.9	SD	6.6202	–	1.863	65.70	8.52	25.78	0.766	4.261	3.605	0.436	0.707
V616 Cyg	2653.970	1.32665076	82.405	0.6	D	3.9833	3.0757	1.423	82.80	5.16	12.04	0.918	1.111	0.768	0.502	0.746
V642 Cyg	2761.959	4.44652373	90.046	0.8	D	6.8413	4.3267	2.549	81.49	6.35	12.16	0.656	2.180	1.552	0.316	0.611
V703 Cyg	3125.944	4.14529239	85.315	0.7	D	6.4209	4.1021	2.043	79.22	16.04	4.74	0.738	0.000	0.000	0.440	0.797
V359 Her	3574.180	1.75576649	79.273	0.8	SD	4.0204	–	1.350	65.38	5.34	29.28	0.955	1.089	1.687	0.532	0.757
CY Lac	4094.814	8.35974636	83.474	0.6	D	8.4176	7.7674	1.498	57.81	42.19	0.00	0.672	3.154	4.941	0.406	0.549
YY Nor	2726.466	1.69498989	87.133	0.6	D	4.7717	3.2341	2.097	83.80	16.20	0.00	0.774	0.000	1.271	0.319	0.522
HM Nor	2726.068	4.42628455	76.341	0.2	SD	6.8694	–	1.336	89.57	10.43	0.00	0.569	3.199	0.133	0.544	0.764
V537 Oph	3606.987	1.14718255	80.989	0.7	D	4.3997	3.7075	1.213	47.30	43.48	9.22	0.969	1.411	1.458	0.528	0.665
BS Sco	2876.953	7.62241175	86.533	2.7	SD	8.1521	–	3.274	88.42	6.40	5.18	0.826	2.835	5.084	0.309	0.587
V569 Sco	2673.110	1.04724351	88.826	1.2	D	4.5470	4.7905	0.981	50.78	49.22	0.00	0.974	0.894	0.760	0.454	0.444
V714 Sco	2743.254	1.39644612	88.728	1.2	D	6.0192	5.7818	1.012	47.06	52.94	0.00	0.835	0.696	1.088	0.442	0.449
BN Sgr	2751.347	2.51976721	76.280	1.0	SD	5.3627	–	1.532	65.84	11.54	22.63	0.674	3.282	0.662	0.531	0.689
V780 Sgr	2746.065	0.86031002	84.031	0.9	D	5.7484	3.8418	1.069	59.96	12.28	27.76	0.636	0.000	0.319	0.357	0.378
V2168 Sgr	3118.315	2.06886580	86.908	1.2	D	6.1918	6.5589	1.478	89.89	9.78	0.33	0.953	1.976	1.597	0.450	0.555
XY Vel	2998.041	2.51019823	88.230	0.7	D	6.3452	4.5978	0.764	86.95	4.32	8.73	0.972	5.371	2.438	0.823	0.613
YY Vel	2824.859	4.16420826	78.788	0.7	D	7.0504	3.6171	1.909	62.23	20.99	16.78	0.560	4.581	1.468	0.406	0.653
AZ Vel	2805.448	0.77578092	89.973	0.5	SD	3.1843	–	0.987	78.45	21.55	0.00	1.097	0.000	0.168	0.406	0.403

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The data mining III: An analysis of 21 eclipsing binary light-curves observed by the INTEGRAL/OMC

P. Zasche *

Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic

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Stars: fundamental parameters

ABSTRACT

Twenty-one eclipsing binaries were selected for an analysis from a huge database of observations made by the INTEGRAL/OMC camera. The photometric data were processed and analyzed, resulting in a first light-curve study of these neglected eclipsing binaries. In several systems from this sample even their orbital periods have been confirmed or modified. Thirty-two new minima times of these binaries have been derived.

1. Introduction

The photometric observations are obtained by the INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) satellite since its launch in 2002. The onboard OMC (Optical Monitoring Camera) was designed to carry out the observations in optical *V* passband. These observations are in fact only a by-product of the mission, but nowadays there are many observations available.

This investigation is directly following our previous papers (Zasche, 2008, 2009, 2010). The selection criteria used here were also the same: maximum number of data points and non-existence of any detailed light-curve analysis of the particular system. There were selected twenty-one eclipsing binary systems for the present paper.

2. Analysis of the individual systems

All observations of these systems were carried out by the same instrument (50 mm OMC telescope) and the same filter (standard Johnson's *V* filter). Time span of the observations ranges from December 2002 to January 2009. A transformation of the time scale has been done following the equation *JulianDate* – *ISDC JulianDate* = 2,451,544.5. Only a few outliers from each data set were excluded. The PHOEBE programme (see e.g. Prša and Zwitter, 2005), based on the Wilson–Devinney algorithm (Wilson and Devinney, 1971), was used for the analysis.

Due to missing information about the stars, and having only the light curves in one filter, some of the parameters have to be fixed. At first, for all the systems we have used the "Detached binary" mode (in Wilson and Devinney mode 2) and also the "Semidetached with the secondary component filling its Roche lobe" (mode 5 in Wilson and Devinney) for computing. For both modes a "q-search method" was used, which means trying to find the best fit with different values of the mass ratio *q* ranging from 0 to 1 with a step 0.1. The limb-darkening coefficients were interpolated from van Hamme's tables (see van Hamme, 1993), the linear cosine law was used. The values of the gravity brightening and bolometric albedo coefficients were set at their suggested values for convective atmospheres (see Lucy, 1968), i.e. $G_1 = G_2 = 0.32$, $A_1 = A_2 = 0.5$. In all cases the orbital eccentricity was set to 0 (circular orbit). Therefore, the quantities which could be directly calculated from the light curve are the following: The relative luminosities L_i, the temperature ratio T_1/T_2, the inclination *i*, ephemerides of the system, the Kopal's modified potentials Ω_1 and Ω_2, the synchronicity parameters F_1 and F_2, the third light L_3, and the mass ratio *q*. Using the parameters introduced above, one could also derive the value of the relative radii R_i/a.

* Fax: +420 221912577.
E-mail address: zasche@sirrah.troja.mff.cuni.cz

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Table 1
Basic information about the analyzed systems, taken from the literature.

Star	Mag *B* GCVS	Mag *V* GCVS	$(B-V)$ GCVS	$(B-V)$ Nomad	Sp.	Sp. S&K	*q* S&K	Type S&K	Min	Mag OMC	Mag MinI	Mag MinII	Data
V479 Aql	13.20	13.2	0.0	0.28		(A8)+[G9IV]	0.300	EA/SD	76	12.99	14.14	13.10	408
DY Aqr	10.30	10.23	0.07	0.14	A0	A0+[F3]	0.540	EA/DM	35	10.22	10.87	10.26	479
V646 Cas	10.14	9.73	0.58	0.46	B0IV				24	9.53	9.97	9.76	756
PV Cen	11.40	11.4	0.0	0.21		(A2)+[G4IV]	0.270	EA/SD	2	11.55	12.25	12.05	623
EP Cen	11.30	11.3	0.0	−0.4		(F0)+[G4IV]	0.590	EA/SD	3	11.18	11.69	11.27	470
RW Cet	10.43	10.09	0.34	0.37	A5	A5+[G6IV]	0.400	EA/SD	79	10.16	10.99	10.24	449
RR Cir	11.2	10.9	0.3	0.03					4	11.51	12.57	11.84	450
UX Cir	12.20	12.2	0.0	0.12					2	11.69	12.25	11.77	455
BB Cir	9.40	9.4	0.0	0.38	A2IV	A2IV+[G9IV]	0.290	EA/SD	32	10.04	11.55	10.11	514
UW Cyg	11.00	10.68	0.32	0.22	A5	F0+[K4IV]	0.280	EA/SD	188	10.78	13.48	10.87	457
V445 Cyg	12.40	11.7	0.7	0.44	M5V	(A2)+[G9IV]	0.200	EA/SD	74	12.04	15.01	12.15	462
SX Gem	11.2	11.0	0.2	−0.23	A0	A0+[A7]	0.710	EA/DM	110	11.40	12.27	11.46	315
AB Mus	12.80			0.47		(A8)+[G3IV]	0.520	EA/SD	1	13.38	14.58	13.50	469
UZ Nor	11.20	11.2	0.0	0.06		(A1)+[K0IV]	0.180	EA/SD	0	11.04	14.42	11.13	467
XY Nor	13.00	13.0	0.0	0.02	A6	(A5)+[F1.5]	0.720	EA/DM	16	12.47	12.94	12.72	502
V2383 Oph	11.5	10.3	1.2	1.21	K7V				8	10.29	10.98	10.57	886
FL Ori	11.5	11.5	0.0	0.32	A3V	A3V+[K0IV]	0.200	EA/SD	185	11.05	12.10	11.14	472
SW Pup	9.30	9.01	0.29	0.30	A0V	A0V+[F8IV]	0.460	EA/SD	2	8.97	9.96	9.08	380
V501 Sgr	12.60	12.6	0.0	−0.22		(A3)+[G8IV]	0.230	EA/SD	0	12.36	13.07	12.40	469
V1133Sgr	13.20	13.2	0.0	0.32		(F0)+[G8IV]	0.300	EA/SD	2	12.49	13.47	12.57	317
EL Vel	11.7	11.3	0.4	0.30		(A3)+[G5IV]	0.150	EA/SD	2	11.32	12.34	11.36	422

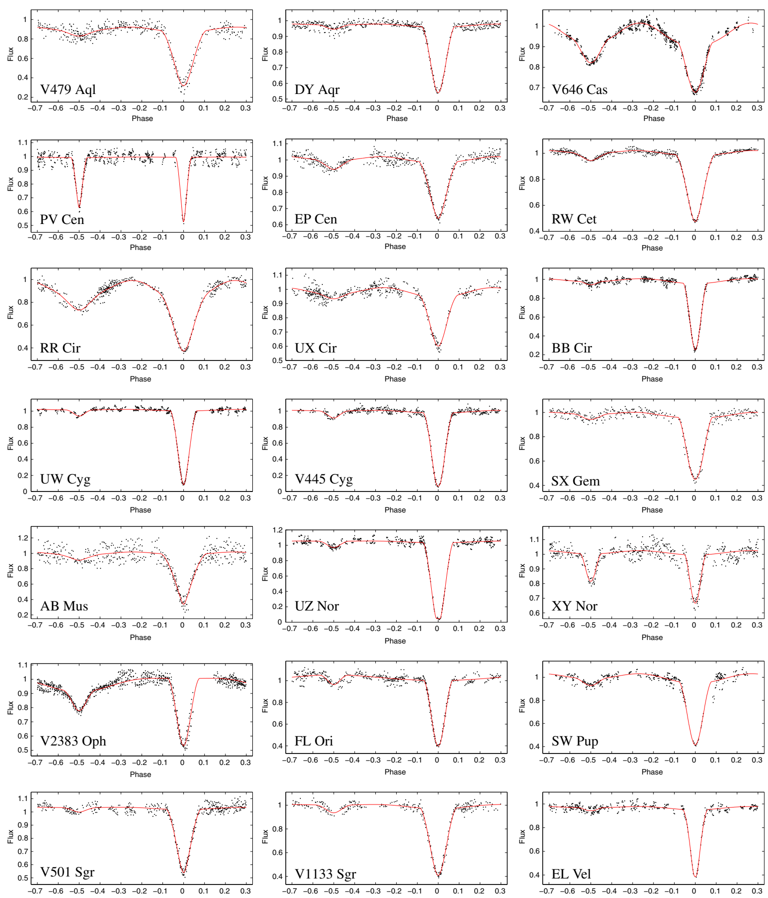

Fig. 1. The light curves of the analyzed systems.

Table 2
The light-curve parameters of the individual systems, as derived from our analysis.

Parameter star	HJD_0 2450000+	P [days]	i [deg]	q	Type	Ω_1	Ω_2	T_1/T_2	L_1 [%]	L_2 [%]	L_3 [%]	R_1/a	R_2/a	F_1	F_2	x_1	x_2
V479 Aql	2765.422	0.83359673	80.152	0.8	SD	4.1135	–	1.558	89.05	8.70	2.25	3.02	3.36	0.000	1.505	0.433	0.565
DY Aqr	2634.187	2.15969977	80.375	0.4	SD	4.8440	–	2.145	72.17	4.49	23.34	2.28	2.62	1.486	2.023	0.319	0.533
V646 Cas	3275.126	6.16261291	69.273	0.7	SD	5.3695	–	1.477	48.45	51.55	0.00	2.28	3.59	2.968	0.727	0.317	0.366
PV Cen	2837.827	3.83468075	88.804	1.0	D	9.0974	9.7506	0.932	54.77	37.80	7.43	1.24	1.14	0.166	1.125	0.681	0.623
EP Cen	2832.788	0.92544905	82.534	0.5	SD	5.4393	–	1.777	40.18	10.22	49.60	2.31	3.22	4.509	0.959	0.364	0.524
RW Cet	3925.933	0.97519630	82.251	0.4	SD	4.8092	–	1.860	63.08	8.24	28.68	2.48	3.11	3.494	0.740	0.398	0.627
RR Cir	2834.296	1.09172354	79.075	0.6	SD	4.0259	–	1.197	80.88	19.12	0.00	3.33	3.57	2.474	0.020	0.771	0.500
UX Cir	3372.779	1.48126165	79.854	0.7	SD	5.8007	–	1.657	55.04	7.20	37.76	2.33	3.20	4.686	1.620	0.543	0.786
BB Cir	3211.257	3.08719168	83.402	0.9	D	6.3804	6.3659	1.721	98.74	1.26	0.00	1.93	1.71	3.510	1.828	0.500	0.500
UW Cyg	2631.030	3.45078022	85.287	0.7	D	6.3882	4.7967	1.710	92.39	7.61	0.00	1.85	2.01	3.765	2.564	0.436	0.636
V445 Cyg	3189.713	1.94778095	87.306	0.7	D	6.7239	4.4609	1.880	87.63	12.37	0.00	1.78	2.40	4.569	3.249	0.544	0.762
SX Gem	3111.556	1.36718292	76.369	0.8	SD	6.8650	–	2.270	62.95	18.47	18.58	1.73	3.60	3.956	1.019	0.265	0.483
AB Mus	2834.149	0.96494625	87.661	0.7	SD	4.1649	–	1.042	71.31	8.59	20.10	3.02	3.16	1.658	1.718	0.142	0.148
UZ Nor	3059.574	3.19609307	86.554	0.6	D	6.2150	3.4925	2.112	87.66	12.34	0.00	1.78	2.65	0.000	0.794	0.266	0.395
XY Nor	3223.125	1.68001447	81.806	0.9	D	8.1800	6.5509	1.206	53.45	46.55	0.00	1.51	1.84	6.530	5.068	0.555	0.702
V2383 Oph	2911.269	0.50220468	82.407	0.9	D	5.4312	6.0771	0.683	77.40	22.60	0.00	2.39	2.12	2.974	4.792	0.500	0.500
FL Ori	4147.705	1.55098194	84.512	0.9	D	6.7050	4.8162	2.349	63.44	11.99	24.57	1.73	2.51	0.947	2.049	0.337	0.649
SW Pup	2979.169	2.74742494	76.517	0.8	D	7.2531	3.7446	1.774	80.99	19.01	0.00	1.86	3.15	6.559	1.234	0.409	0.608
V501 Sgr	3447.115	1.51327251	86.812	0.8	D	5.7024	4.3304	2.345	49.40	3.21	47.39	2.19	2.66	3.266	2.187	0.276	0.522
V1133Sgr	4377.904	0.80532386	81.079	1.1	D	6.3172	4.3754	1.871	63.05	11.71	25.24	2.09	3.21	3.573	0.000	0.398	0.635
EL Vel	2974.883	2.75833767	91.351	0.3	D	6.0711	3.4474	2.162	96.00	0.86	3.14	2.03	1.48	6.360	2.654	0.771	0.500

The distinguishing between the primary and secondary minima has been done only according to the observational point of view, which means that the deeper one is the primary one. This results in a fact that the primary component could be neither the larger one, nor the more massive one. In one case the secondary component resulted to be the more luminous one (V646 Cas), and in V1133 Sgr the more massive one.

The basic information about the analyzed systems are introduced in Table 1, where are the B and V magnitudes from the GCVS (Kukarkin et al., 1971; Malkov et al., 2006), the B–V values from the GCVS and also from the NOMAD catalogue (Zacharias et al., 2004). The spectral types are taken from the published literature and also from the Svechnikov and Kuznetsova (1990). The estimated mass ratio and also the type of the eclipsing binary have been taken from S&K (EA stands for the Algol type, SD for semi-detached systems, and DM for detached main sequence ones). 'Min' stands for the number of published times of minima and the last four columns introduce the actual OMC magnitudes in Johnson's V filter, the depths of both primary and also secondary minima in V filter, and finally the number of data points used for this analysis.

The results are introduced in Fig. 1 and Table 2, where are given all relevant parameters of the analyzed systems: HJD_0 and P are the ephemerides of the system, i stands for the inclination, q (=M_2/M_1) denoted the mass ratio, the 'Type' refers the mode used for the best solution ('D' for a detached na 'SD' for a semi-detached one, see above), Ω_i stands for the Kopal's modified potentials, T_i for the effective temperatures, L_i for the luminosities, R_i/a for the relative radii, F_i for the synchronicity parameters, and x_i for the limb-darkening coefficients (the linear cosine law was used), respectively. Inclinations smaller than 90° mean that the binary rotates counter-clockwise as projected onto a plane of sky. In some systems their orbital periods were found to be different from the values published in the literature (e.g. in GCVS).

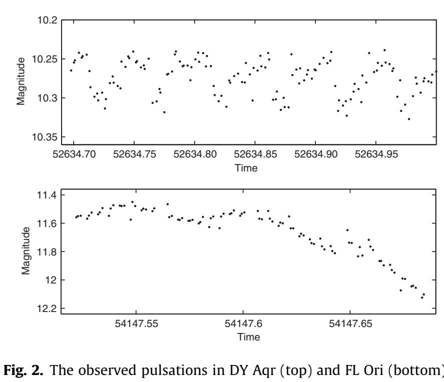

Fig. 2. The observed pulsations in DY Aqr (top) and FL Ori (bottom).

In two systems (DY Aqr and FL Ori) there were found short-periodic pulsations. In Fig. 2 are presented parts of the light curve with evident pulsational behavior. Pulsations in FL Ori have been predicted by Soydugan et al. (2006). On the other hand, the proposed light variations in RW Cet have not been detected in the present data.

Another interesting fact of this sample is that about one half of the investigated systems have the luminosity of the third unseen body above a statistically significant value about 5%. This result is not surprising, because e.g. Pribulla and Rucinski (2006) also discovered that more than 50% of binaries exist in multiple systems. One could speculate about a prospective future discovery of such components in these systems. Due to missing detailed analysis (spectroscopic, interferometric, etc.), the only possible way how to discover these bodies nowadays is the period analysis of their times of minima variations. In the systems RW Cet and FL Ori there exist some indication of period modulation during the last decades. New minima times for some of the systems have been derived from the OMC data, see Table 3.

3. Discussion and conclusions

The light-curve analyses of twenty-one selected systems have been carried out. The light curves observed by the Optical Monitoring Camera onboard the INTEGRAL satellite provide a great opportunity to study and to estimate the basic physical parameters of these systems. Despite this fact, the parameters are still only the preliminary ones, affected by relatively large errors and some of the relevant parameters were fixed at their suggested values. The detailed analysis is still needed, especially

Table 3
The heliocentric minima times as derived from the INTEGRAL data.

Star	HJD 2400000+	Error [days]	Type
V479 Aql	53092.199	0.003	prim
V479 Aql	53308.096	0.002	prim
V646 Cas	53552.4654	0.004	prim
V646 Cas	53564.7782	0.003	prim
V646 Cas	53919.1205	0.01	sec
V646 Cas	54547.7201	0.011	sec
V646 Cas	54140.9981	0.004	sec
PV Cen	54118.589	0.003	prim
EP Cen	54642.0452	0.001	prim
EP Cen	54659.6262	0.001	prim
EP Cen	54670.7307	0.002	prim
RW Cet	53925.9339	0.0005	prim
RW Cet	54640.7550	0.0005	prim
RR Cir	52834.3033	0.001	prim
RR Cir	52837.0403	0.004	sec
RR Cir	54642.1967	0.003	prim
UX Cir	53372.7898	0.006	prim
BB Cir	53217.4341	0.003	prim
V445 Cyg	53968.8264	0.002	prim
V445 Cyg	54060.3704	0.002	prim
SX Gem	53111.5577	0.0002	prim
SX Gem	53113.6186	0.002	sec
AB Mus	54683.9468	0.004	prim
AB Mus	53376.4548	0.002	prim
FL Ori	54327.6181	0.001	prim
SW Pup	52980.5239	0.009	sec
SW Pup	53858.3660	0.01	prim
V501 Sgr	54023.6718	0.006	prim
V501 Sgr	54034.2598	0.005	prim
V501 Sgr	54046.3703	0.006	prim
V501 Sgr	54050.9075	0.004	prim
EL Vel	52979.0020	0.009	sec

spectroscopic one, or another more detailed light curve study in different filters. Together with a prospective radial-velocity study, the final picture of these systems could be done. Particularly, the systems PV Cen and V501 Sgr seem to be the most interesting ones due to relatively high value of the third light. Moreover, the system V646 Cas seems to be a very massive binary, while on the other hand the system V2383 Oph is a low-mass binary of K spectral type.

Acknowledgments

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V456 Ophiuchi and V490 Cygni: Systems with the shortest apsidal-motion periods *(Research Note)*

P. Zasche and M. Wolf

Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz

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ABSTRACT

Our main aim is the first detailed analysis of the two eclipsing binaries V456 Oph and V490 Cyg. The system V456 Oph has been studied both photometrically via an analysis of its light curve observed by the INTEGRAL/OMC and by the period analysis of all available times of minima. V490 Cyg has been studied by means of a period analysis only. Many new times of minima for both systems have recently been observed and derived. This allows us for the first time to study in detail the processes that affect both binaries. The main result is the discovery that both systems have eccentric orbits. For V456 Oph we deal with the eccentric eclipsing binary system with the shortest orbital period known (about 1.016 day), while the apsidal motion period is about 23 years. V490 Cyg represents the eclipsing system with the shortest apsidal motion period (about 18.8 years only). The two components of V456 Oph are probably of spectral type F. We compare and discuss the V456 Oph results from the light curve and the period analysis, but a more detailed spectroscopy is needed to confirm the physical parameters of the components more precisely.

Key words. binaries: eclipsing – stars: individual: V456 Oph – stars: individual: V490 Cyg – stars: fundamental parameters

1. Introduction

The eccentric eclipsing binaries (EEBs) provide a great opportunity for studying the stellar structure of the stars as well as testing the General Relativity outside the solar system. The O−C diagram analysis, which investigates the revolution of the line of apsides in the system has been described elsewhere, e.g. Giménez & García-Pelayo (1983), Giménez & Bastero (1995). Nevertheless, new contributions to this topic with new systems are still welcome, especially for cases where the apsidal motion period is adequately short and a few periods are covered. This is the case for the two somewhat neglected systems V456 Oph and V490 Cyg.

1.1. V456 Oph

V456 Oph (=AN 108.1935 = SAO 123842, V_{max} = 9.95 mag) has been discovered as a variable star by Hoffmeister (1935), with the remark that it is a "short-periodic one, but probably not rapidly changing". After than Guthnick & Prager (1936) incorrectly classified the star as a δ Cep one with a preliminary period of about 14.6 d. No such variation has been detected with the present data. The only spectral classification is that by Roman (1956), who indicated the spectral type A5, but with a remark that because of underexposed plates and uncertain ephemerides this classification is not very secure.

Although the first photoelectric light curve has been published by Demircan et al. (1988), there was no light curve analysis of the system performed until today. The same applies to the spectroscopic analysis, which has not yet been carried out, so the mass ratio of the pair in not known. Soydugan et al. (2006) included the binary in the catalogue of systems located in the instability strip, which means that it possibly contains a δ Scu component. However, no indication of pulsations in V456 Oph has been detected.

1.2. V490 Cyg

V490 Cyg (=AN 76.1939, V_{max} = 12.81 mag) is an Algol-type eclipsing binary, even though the SIMBAD database lists V490 Cyg as a β Lyrae one. The system has been discovered as a variable by Wachmann (1940), and its light curve coverage is too poor for any reliable analysis. Its spectral type was derived to be F8, while Svechnikov & Kuznetsova (1990) give an estimate of the spectral types F8+[G4]. Hegedüs (1988) included this system in his list of stars with possible apsidal motion, but since then it was not studied in detail. Other credible information about the physical properties of the components is missing because there is so little spectroscopy and photometry of this system.

2. The period analysis

2.1. V456 Oph

The set of published times of minima for V456 Oph is quite extensive, covering more than 70 years. Regrettably, the old minima are only photographic and their scatter is so large that one cannot use them for any reliable analysis. We used only the more precise photoelectric and CCD ones, which were published after 1970. These minima roughly follow the linear ephemerides given in GCVS, but there some variations are clearly visible.

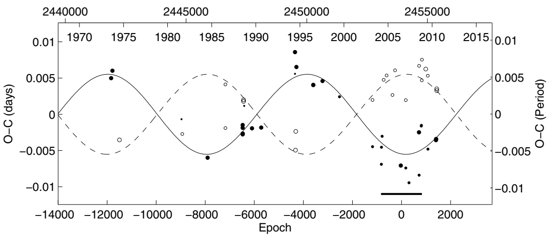

Fig. 1. O−C diagram of V456 Oph. The lines represent the fit according to the apsidal motion hypothesis (see text and Table 2), the solid line stands for the primary, while the dashed line stands for the secondary minima, dots stand for primary and open circles for the secondary minima. The black line near the bottom axis represents the time interval covered with the OMC data used for the light curve analysis.

We tried to collect all available minima times and also to derive some new ones. A few of the already published ones were recalculated once again and corrected for the final analysis. Besides these minima times, we also used the photometry of V456 Oph obtained with the robotized and automated telescopes working today. These are

- ASAS – the automated survey, *V* filter, Pojmanski (2002), `http://www.astrouw.edu.pl/asas/`
- OMC – the OMC camera onboard the INTEGRAL satellite, using the *V* filter, Mas – Hesse et al. (2004), `https://sdc.laeff.inta.es/omc/`
- Pi of the sky – the automated telescope, unfiltered, Burd et al. (2005), `http://grb.fuw.edu.pl/pi/`

Sixteen new minima times were derived from these surveys, and some of the published ones were computed again (see Table 1). Our new minima times were observed in the Ondřejov observatory with the 65-cm telescope. We used the Kwee & van Woerden (1956) method for all these minima. The mean linear light elements suitable for observations are

$$\text{Prim. Min.} = 2453923.9358 + 1.01600124 \cdot \text{E}, \qquad (1)$$

which were also used for deriving the proper epochs and types of the minima times written in Table 1.

If we plot these data points in the O−C diagram, the difference between primary and secondary minima is clearly visible. Following the method of apsidal motion analysis as described in Giménez & García-Pelayo (1983), we tried the computation with orbital inclination $i = 90°$ for the first time. After that we used for the second attempt the inclination $i = 87.88°$ (see Sect. 3), which resulted in almost the same parameters (owing to the term $\cot^2(i)$, which is nearly 0 for our inclination). In Fig. 1 we plot the final fit with the apsidal motion hypothesis on all used data points. This leads to the parameters of the motion of apsides given in Table 2. All uncertainties of the parameters were calculated from the covariance matrix of the fit and from the uncertainty of the inclination. Evidently the apsidal period is very short, about only 23 yr, which places this system among one those with the shortest apsidal motion.

2.2. V490 Cyg

The system V490 Cyg has much lower published times of minima observations. The first rough times-of-minima estimates are those by Wachmann (1948) from his photometry in the 1930's, but these have such a large scatter that they cannot be used for any reliable analysis. However, he also noticed that the secondary minimum is not symmetric with regards to the primary one. Nevertheless, a possible eccentricity and apsidal motion have never been studied since then. The more precise photoelectric and CCD observations have been measured since 1999, but there are only 12 published minima.

A few new CCD observations were obtained in the Ondřejov observatory with the same telescope as for V456 Oph, and two new minima times were also derived from the INTEGRAL/OMC data. The new measurements and the already published ones are presented in Table 3. The suitable linear ephemerides for observations are

$$\text{Prim. Min.} = 2451491.6075 + 1.14023698 \cdot \text{E}, \qquad (2)$$
$$\text{Sec. Min.} = 2451491.5802 + 1.14023698 \cdot \text{E}. \qquad (3)$$

The minima times presented in Table 3 were used for the period analysis, which we did by applying the apsidal motion hypothesis. The only difference in analysis between V490 Cyg and V456 Oph was the assumption of an inclination $i = 90°$ for V490 Cyg because we had no light curve analysis. The difference between primary and secondary is clearly visible, reaching up to 47 minutes, which is surprisingly high for a binary with

Table 1. New and recalculated CCD minima times of V456 Oph.

HJD - 2400000	Error	Type	Filter	Observer/Reference
48113.4210	0.003	Pri	*C*	Paschke, BBSAG 96
48113.42288	0.00108	Pri	*C*	Paschke – recalculated
52724.03387	0.0011	Pri	*V*	ASAS
52724.54831	0.0012	Sec	*V*	ASAS
53089.7944	0.0003	Pri	*V*	Sobotka–OMC, IBVS 5809
53089.79189	0.0012	Pri	*V*	OMC – recalculated
53091.8267	0.0004	Pri	*V*	Sobotka–OMC, IBVS 5809
53091.82625	0.00037	Pri	*V*	OMC – recalculated
53123.32379	0.00045	Pri	*V*	OMC
53188.86367	0.0044	Sec	*V*	ASAS
53305.70440	0.0042	Sec	*V*	OMC
53553.60602	0.0019	Sec	*V*	ASAS
53657.24154	0.00059	Sec	*V*	OMC
54099.69661	0.0034	Pri	*V*	ASAS
54099.19798	0.0028	Sec	*V*	ASAS
54232.79073	0.0009	Pri	*C*	Pi of the sky
54653.93939	0.0012	Sec	*V*	ASAS
54654.43230	0.0037	Pri	*V*	ASAS
54742.8314	0.0009	Pri	*V*	Zasche–OMC, IBVS 5931
54742.83119	0.00045	Pri	*V*	OMC – recalculated
54749.94329	0.00032	Pri	*V*	OMC
54766.7134	0.0012	Sec	*V*	Zasche–OMC, IBVS 5931
54766.71352	0.00032	Sec	*V*	OMC – recalculated
54769.7640	0.0011	Sec	*V*	Zasche-OMC, IBVS 5931
54769.76438	0.00066	Sec	*V*	OMC – recalculated
54930.29129	0.00056	Sec	*V*	OMC
55016.65047	0.0018	Sec	*V*	ASAS
55017.14834	0.0035	Pri	*V*	ASAS
55352.42998	0.00003	Pri	*R*	This paper
55356.49413	0.00004	Pri	*R*	This paper
55357.51014	0.00008	Pri	*R*	This paper
55379.36085	0.00005	Sec	*R*	This paper
55382.40909	0.00019	Sec	*R*	This paper

Table 2. The parameters of the apsidal motion fit for V456 Oph and V490 Cyg.

Parameter	V456 Oph	V490 Cyg
HJD_0	2453923.9358 (27)	2451491.5931 (51)
P [d]	1.01600124 (24)	1.14023698 (23)
P_a [d]	1.01612627 (25)	1.14042668 (23)
e	0.017 (9)	0.045 (15)
ω [deg]	351.1 (1.6)	342.42 (3.4)
$\dot{\omega}$ [deg/cycle]	0.044 (3)	0.060 (12)
U [yr]	22.6 (1.3)	18.8 (3.2)

Table 3. New and already published minima times of V490 Cyg.

HJD - 2400000	Error	Type	Filter	Observer/Reference
51487.6184	0.0002	Sec	*V*	Caton – IBVS 5595
51491.5776	0.0004	Pri	*V*	Caton – IBVS 5745
51495.5994	0.0002	Sec	*V*	Caton – IBVS 5745
52612.43506	0.0047	Pri	*V*	Integral/OMC
52613.024	0.002	Sec	*V*	Sobotka – IBVS 5809
52813.7080	0.0002	Sec	*V*	Caton – IBVS 5595
52841.6237	0.0002	Pri	*V*	Caton – IBVS 5595
53256.6755	0.0001	Pri	*C*	Krajci – IBVS 5690
53260.6752	0.0003	Sec	*C*	Krajci – IBVS 5690
53660.3244	0.0005	Pri	*I*	Agerer – IBVS 5731
53660.331	0.0005	Pri	*V*	Diethelm – IBVS 5713
53913.46115	0.0002	Pri	*R*	This paper
53934.54462	0.0010	Sec	*R*	This paper
54335.35387	0.0013	Pri	*R*	This paper
54685.4130	0.0046	Pri	*I*	Agerer – IBVS 5889
54694.53781	0.0032	Pri	*V*	Integral/OMC
55096.4362	0.0004	Sec	*I*	Agerer – IBVS 5941
55376.3966	0.0002	Pri	*R*	This paper
55392.35998	0.0002	Pri	*R*	This paper
55405.44030	0.0002	Sec	*R*	This paper
55445.34892	0.0002	Sec	*R*	This paper
55462.45268	0.0002	Sec	*R*	This paper
55470.43426	0.0002	Sec	*R*	This paper

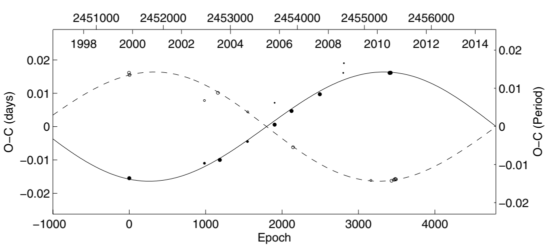

Fig. 2. O−C diagram of V490 Cyg. The lines represent the fit according to the apsidal motion hypothesis (see text and Table 2), the solid line stands for the primary, while the dashed line stands for the secondary minima, dots stand for the primary and open circles for the secondary minima.

such a short orbital period. The analysis led to the parameters of the apsidal motion presented in Table 2. Obviously the resulting value of the apsidal motion period of about 18.8 years is even shorter than for V456 Oph; we are therefore dealing with the shortest apsidal motion period known among the EEBs today.

3. Light curve analysis

The whole light curve of V456 Oph was observed with the OMC camera onboard the INTEGRAL satellite, a description of which is given in Mas – Hesse et al. (2004). The standard V filter was used, but the optical telescope has an aperture of only 5 cm in diameter. We obtained several hundred observations, of which we used 449 for the analysis.

The programme PHOEBE (ver. 0.29, Prša & Zwitter 2005), based on the Wilson-Devinney algorithm (Wilson & Devinney 1971) was used for the analysis. The "detached binary" mode (in Wilson & Devinney mode 2) was used with several assumptions. First, the ephemerides (HJD_0 and P) and the apsidal motion parameters (e, ω, and $\dot{\omega}$) were adopted from the period analysis, because the minima times cover a longer time span, therefore these quantities are derived with higher precision. Secondly, the mass ratio q and temperature of the primary component T_1 were set and the other relevant parameters were adjusted for the best fit. We changed the q and T_1 values in the wide range of values to obtain the best fit according to the rms value and also the physical plausibility of the fit. This means during that the fitting process we scanned the parameter space in q ranging from 0.1 to 1.2 and in T_1 from 15 400 K to 6500 K.

We fitted the other light curve parameters, which are the luminosities L_1 and L_2 in the V filer, the temperature of the secondary T_2, the inclination i, the Kopal's modified potentials Ω_1 and Ω_2, the synchronicity parameters F_1 and F_2, the third light l_3. The limb-darkening coefficients were automatically interpolated by the PHOEBE programme from van Hamme's tables (see van Hamme 1993), using the linear cosine law for the values of $T_{\rm eff}$ and $\log g$ of both components resulting from the analysis. The values of the gravity brightening and bolometric albedo coefficients were set at their suggested values for convective atmospheres (see Lucy 1968), i.e. $G_1 = G_2 = 0.32$, $A_1 = A_2 = 0.5$.

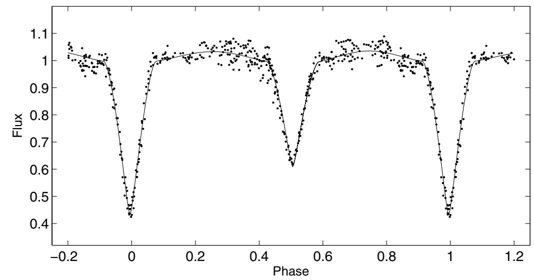

Fig. 3. PHOEBE light curve solution of V456 Oph based on the OMC data, the solid line represents our final solution (see the text and Table 4).

Table 4. The light curve parameters of V456 Oph.

Parameter	Value	Parameter	Value
T_1 [K]	6840	$L_1/(L_1+L_2)$ (V)	59 ± 4%
T_2 [K]	6700 ± 430	$L_2/(L_1+L_2)$ (V)	41 ± 3%
$q\ (= M_2/M_1)$	0.96 ± 0.15	F_1	1.097 ± 0.402
i [deg]	87.88 ± 0.81	F_2	0.843 ± 0.356
Ω_1	5.09 ± 0.32	x_1	0.505 ± 0.021
Ω_2	5.08 ± 0.29	x_2	0.504 ± 0.019
R_1/a	0.249 ± 0.05	R_2/a	0.247 ± 0.04

The best fit was achieved with the light curve parameters given in Table 4, and the figure with the final fit is plotted in Fig. 3. Nonzero eccentricity is clearly visible from this plot, which is quite surprising in a binary with such a short orbital period. No other EEB with a shorter period is known today. The value of the third light is $l_3 = (0 \pm 4)\%$, which indicates that there is no other visible companion to the system in the V filter (under the assumption that this component is also located on the main sequence). We made several attempts with nonzero values of the third light, but these did not lead to a satisfactory solution.

Because there is no spectroscopic analysis, the precise physical parameters cannot be computed directly, but need to be roughly estimated with the assumption that both components are located on the main sequence. We derived the following values: $M_1 = 1.46\ M_\odot$, $M_2 = 1.41\ M_\odot$, $R_1 = 1.51\ R_\odot$, $R_2 = 1.49\ R_\odot$. These are only very preliminary values, but lead to spectral types of about F1 + F2 for the two components. We obtained roughly the same result (F0+F1) with the standard mass-luminosity relation for the main sequence stars (e.g. Malkov 2007), applying the luminosity ratio derived from the light curve analysis.

Table 5. The EEBs with the shortest apsidal motion period.

System	Spectr.	P [d]	e	U [yr]	Reference
V490 Cyg		1.1402	0.045	18.8	This paper
V381 Cas	B3	1.7459	0.0253	19.74	Wolf et al. (2010)
U Oph*	B5+B5	1.6773	0.00305	20.88	Vaz et al. (2007)
V456 Oph	?F1+F2?	1.0160	0.017	22.6	This paper
GL Car*	B0+B1	2.4222	0.146	25.2	Wolf et al. (2008)
V478 Cyg	B0+B0	2.8809	0.0158	27.1	Wolf et al. (2006)

Notes. * Triple system.

The parameters are very different from what one could expect for a main sequence star of spectral type A5 (Roman 1956), and the masses are also different from those estimated by Brancewicz & Dworak (1980), but the presented values provided the best light curve fit, and the parameters of the apsidal motion also agree well with the theoretical values (see below). The spectral type presented by Roman (1956) was only estimated on the basis of poor photographic spectra. On the other hand, there is also the BVR photometry in the NOMAD catalogue (Zacharias et al. 2004), from which $B - V = 0.279$ mag and $V - R = 0.165$ mag. These values indicate (Houdashelt et al. 2000) that the temperature of the system is about 6500 K, therefore of the spectral type about of F5.

4. Discussion

For the light curve analysis of the system V456 Oph the ephemerides and the apsidal motion parameters were fixed, but another approach could be to compute these parameters directly also from the light curve. The problem is that the data coverage for the light curve is rather fairly in time (about only 1/5 of the apsidal period), and the data for the light curve have relatively high scatter as well.

The eclipsing binaries, V456 Oph and V490 Cyg, with their respective apsidal motion periods of about only 20 years place these systems among a few unique ones with apsidal periods below 30 years (see Table 5).

Our next task was to derive the averaged internal structure constant as well and to compare it with the theoretical value. This task was done after subtraction of the relativistic term, which resulted for V456 Oph in the value $\dot{\omega}_{\rm rel}$ = 0.0011 deg/cycle, about only 2.5% of the total apsidal motion rate. Therefore, the internal structure constant is

$$\log k_{2,\,\rm obs} = -2.44 \pm 0.20.$$

The surprisingly high value of the uncertainty is mainly caused by the error of the relative radii from the light curve analysis. We can compare this value with the stellar evolution grids (e.g. by Claret 2004) and the theoretical values of $k_{2,\rm theor}$. Using the value of $\log M = 0.1725$ ($M = 1.49\ M_\odot$), we obtained the value of

$$\log k_{2,\rm theor} = -2.41 \pm 0.05$$

for the main sequence star with an age between 0 and 1.5×10^9 yr. This could be interpreted as a rough estimation of maximum age for this system. No other eccentric eclipsing binary with such a late spectral type is known today. Therefore a detailed analysis of its spectra would be very welcome.

5. Conclusions

We performed the first detailed photometric and period analysis of the two eclipsing systems V456 Oph and V490 Cyg, which yielded the parameters of the apsidal motion with periods of about only 23 and 19 years. With the orbital period of V456 Oph of only about 1.016 days we are dealing with the shortest orbital period among the apsidal motion systems, while the period of apsidal motion of 18.8 years of V490 Cyg makes this system the shortest among the EEBs. However, because we lack a spectroscopic analysis, some of the physical parameters were only roughly estimated and apparently contradict each other. New times of minima observations as well as a detailed spectroscopic analysis are needed.

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On the Apsidal Motion of Thirteen Eclipsing Binaries

P. Z a s c h e

Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague,
CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz

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ABSTRACT

Main aim of this paper is the first light curve and apsidal motion analysis of thirteen eccentric eclipsing binaries and the determination of their basic physical properties. All of the systems were studied by the method of period analysis of times of minima and the light curve analysis. Many new times of minima were derived and collected from the data obtained by the automatic, robotic or satellite telescopes. This allows us to study the apsidal motion in these systems in detail for the first time. From the light curve analysis the first rough estimations of the physical properties of these systems were obtained. The analyzed systems undergo an apsidal motion with the following periods in years: AR CMa (44 ± 10), OZ Hya (117 ± 53), V498 Mon (62 ± 4), V521 Mon (217 ± 37), V684 Mon (74 ± 20), V730 Mon (39 ± 12), GV Nor (197 ± 67), NS Nor (516 ± 230), TZ Pyx (157 ± 37), V385 Sco (1926 ± 980), V629 Sco (56 ± 17), V881 Sco (131 ± 48), V1082 Sco (186 ± 280).

Key words: *binaries: eclipsing – Stars: fundamental parameters – Stars: individual: AR CMa, OZ Hya, V498 Mon, V521 Mon, V684 Mon, V730 Mon, GV Nor, NS Nor, TZ Pyx, V385 Sco, V629 Sco, V881 Sco, V1082 Sco*

1. Introduction

Thanks to the eccentric eclipsing binaries it is possible to test the General Relativity as well as the stellar structure models of stars. The investigation of period changes in these systems on the basis of times-of-minima variation (both primary and secondary ones) is a common method in stellar astrophysics. It was described elsewhere, *e.g.,* Giménez and García-Pelayo (1983), or Giménez and Bastero (1995). Only for a short recap of the method: the sidereal and anomalistic periods of the binary are connected *via* a relation $P_s = P_a(1-\dot{\omega}/2\pi)$, where $\dot{\omega}$ is the rate of the apsidal advance $\omega = \omega_0 + \dot{\omega}E$. The period of such a motion is $U = 2\pi P_a/\dot{\omega}$. The individual equations for computing the time of primary and secondary minima are given in Giménez and García-Pelayo (1983).

The number of new observations of the eclipsing binary (hereafter EB) systems is increasing every year, but for some of the systems the detailed analysis is still missing due to the insufficient data coverage. For our analysis we used the data from the automatic photometric surveys – such as ASAS (Pojmański 2002), and NSVS (Woźniak *et al.* 2004), as well as from the satellite data – the OMC camera onboard the INTEGRAL satellite, see Mas-Hesse *et al.* (2004), and CoRoT[1] satellite, see Baglin *et al.* (2006).

Despite rather low amplitudes of the light curves (none of the systems has the primary minimum as deep as one magnitude in the *V* filter) the ASAS data obtained during the last decade were used for the light curve analysis. The results of this analysis together with the apsidal motion study help us to estimate the internal structure constants of the particular system.

T a b l e 1

Basic information about the analyzed systems, taken from the literature

Star	Mag *B* G/S[a]	Mag *V* G/S[a]	$(B-V)$ G/S[a]	$(B-V)$ NOMAD	Sp.	Sp. S&K[b]	Min	Mag (V) ASAS	Mag MinI	Mag MinII
AR CMa	11.9			0.263		(F0)+[G8IV]	14	10.88	11.65	11.59
OZ Hya	9.9				F2V		11	9.45	9.62	9.61
V498 Mon	10.49			0.322	B5	(B9)+[F6]	47	10.00	10.35	10.34
V521 Mon	10.23	10.19	0.04	0.046	B9	A0+[A1]	29	10.08	10.45	10.40
V684 Mon	8.31	8.44	−0.13	−0.164	B4		44	8.32	8.41	8.41
V730 Mon	8.87	8.86	0.01		B4		14	8.83	8.91	8.91
GV Nor	10.66	10.6	0.06	0.102	B5/8	(A8)+[K0IV]	25	10.55	11.08	11.05
NS Nor	10.3			0.130	A0IV		16	10.11	10.62	10.43
TZ Pyx	10.99	10.7	0.27	0.266	A	(A2)+[A2]	16	10.67	11.36	11.36
V385 Sco		11.0		−0.040	B9	B9+[G8IV]	10	10.93	11.47	11.42
V629 Sco	11.9			0.570		(A2)+[K0IV]	13	11.63	12.04	12.01
V881 Sco	9.61			0.364	A1/A2IV	A0+[F0]	14	9.23	9.67	9.67
V1082 Sco	11.50	10.09	1.41	1.374	B0.5Ia		14	10.11	10.45	10.38

Note: [a] – G/S – taken from GCVS and/or SIMBAD, [b] – S&K – Svechnikov and Kuznetsova (1990)

An overview of the parameters for the systems presented in this paper, taken from already published papers and/or databases (SIMBAD, GCVS – Samus *et al.* 2004) are given in Table 1, however some of them are still only estimations, *e.g.*, the $B-V$ index from the NOMAD survey (Zacharias *et al.* 2004) or spectral types from Svechnikov and Kuznetsova (1990). Also the number of all available times of minima nowadays (including our new ones) is listed as well as the magnitude in the *V* filter together with the depths of both minima for each system (taken from the

[1]The CoRoT space mission was developed and is operated by the French space agency CNES, with the participation of ESAs RSSD and Science Programmes, Austria, Belgium, Brazil, Germany, and Spain. For online data see: *http://idoc-corot.ias.u-psud.fr/*

ASAS survey). However, for most of the systems the $B-V$ index from the photometry seems to be rather high (*i.e.*, very reddened stars), due to the fact that the eccentric systems are usually of early spectral type (*e.g.*, in the catalog of eccentric EBs by Bulut and Demircan 2007, 105 out of 124 systems are of O, B, or A spectral types). Also for the systems where the spectral types are known, their respective $B-V$ indices should be much lower. This indicates rather distant objects and that the interstellar extinction was not subtracted.

2. An Approach for the Analysis

Because the spectroscopic study is missing for most of the systems in our sample, there are several assumptions which have to be considered. For this reason we used a following approach for the analysis:

- At the beginning all of the available minima were analyzed and a preliminary apsidal motion parameters were derived (with the assumption of $i=90^\circ$).
- At second, the eccentricity (e), argument of periastron (ω) and apsidal motion rate ($\dot\omega$) as resulted from the apsidal motion analysis were used for the preliminary light curve (hereafter LC) analysis.
- At third step the inclination (i) from the LC analysis was used for the apsidal motion analysis.
- And finally, the resulted e, ω, and $\dot\omega$ values from the apsidal motion analysis were used for the final LC analysis.

For the light-curve analysis we used the program PHOEBE (Prša and Zwitter 2005), which is based on the Wilson-Devinney algorithm (Wilson and Devinney 1971). For the systems where the radial velocity (hereafter RV) study was performed the spectroscopic mass ratio $q_{\rm sp}$ was used for the LC analysis. Otherwise, after a few trials with the "q-search method" which resulted in $q_{\rm ph}=1.0$ for most cases, we chose the mass ratio equal to unity for all of the systems with unknown $q_{\rm sp}$. This is due to only negligible ellipsoidal variations outside of minima for most of the systems and difficulties with a photometric mass ratio in detached binaries as quoted *e.g.*, by Terrell and Wilson (2005). The temperature of the primary component was always fixed at a value of typical temperature for a particular spectral type (*e.g.*, Popper 1980, Harmanec 1988, or Andersen 1991). For a given mass ratio the semi-major axis was fixed at an appropriate value for the primary mass to be equal to a typical mass of a particular spectral type. With this approach besides the masses also the relative radii for both components can be roughly estimated for a prospective derivation of the internal structure constant for the individual system (see below Section 4). However, we would like to emphasize once more that these fundamental parameters are still only rough estimates and have not been derived independently from calibrations, hence should not be used as fundamental parameter sources.

3. The Individual Systems

AR CMa

AR CMa was discovered as an eclipsing variable in 1934 (van Hoof 1943). The authors mentioned its orbital period of 1.16607 day and no secondary minimum. Since then this orbital period was adopted as a correct one and no other detailed study of this system has been published.

We used the ASAS data, which cover the time epoch from 2001 to 2009. The whole light curve of AR CMa was observed in the *V* filter, and these data were used for deriving several new times of primary and secondary minima (see the Table 5 available in its entirety in electronic form from the *Acta Astronomica Archive*[2]). The Kwee and van Woerden (1956) method was used for the minima computation. We found that the orbital period is double the value presented by van Hoof (1943), while the minima are 0.77 mag and 0.71 mag deep, respectively (see Table 1).

The $O-C$ diagram of all available minima as derived from the ASAS, Rotse, and NSVS surveys is shown in Fig. 1. We followed the method of apsidal motion analysis as described in Giménez and García-Pelayo (1983). In Fig. 1 we plot the final fit with the apsidal motion hypothesis. The parameters of such fit are given in Table 2.

Table 2

The parameters of the apsidal motion fits

System	$HJD_0-2400000$	P [d]	P_a [d]	e	ω [deg]	$\dot{\omega}\left[\frac{\text{deg}}{\text{cycle}}\right]$	U [yr]	Σ res^2
AR CMa	52648.8727(32)	2.3322242(12)	2.3325597(12)	0.0094(33)	143(12)	0.052(15)	44(10)	0.00026
OZ Hya	51983.9437(72)	2.0487656(93)	2.0488637(93)	0.071(25)	234(27)	0.017(14)	117(53)	0.00267
V498 Mon	53374.8246(60)	2.4727687(14)	2.4730374(14)	0.048(7)	108(4)	0.039(3)	62(4)	0.10120
V521 Mon	53203.035(28)	2.9706724(76)	2.9707838(76)	0.186(36)	357(5)	0.013(3)	217(37)	0.16876
V684 Mon	54153.5363(24)	1.8514196(17)	1.8515456(17)	0.025(6)	190(8)	0.024(9)	74(20)	0.00085
V730 Mon	48502.744(21)	1.5723188(74)	1.5724916(74)	0.071(35)	219(21)	0.040(18)	39(12)	0.00123
GV Nor	25560.147(17)	2.9718631(38)	2.9719861(38)	0.098(23)	13(9)	0.015(8)	197(67)	0.00634
NS Nor	52258.49(13)	3.223580(124)	3.223636(12)	0.308(162)	329(45)	0.006(5)	516(230)	0.00589
TZ Pyx	53423.1493(19)	2.3185523(18)	2.3186463(18)	0.026(9)	289(10)	0.015(4)	157(37)	0.00061
V385 Sco	53268.248(81)	4.6902421(42)	4.6902734(42)	0.018(12)	143(58)	0.002(2)	1926(980)	0.00111
V629 Sco	53626.932(12)	3.2491152(41)	3.2496349(41)	0.087(31)	298(13)	0.057(26)	56(17)	0.00582
V881 Sco	52128.414(14)	2.4915700(66)	2.4916993(66)	0.106(17)	161(30)	0.019(11)	131(48)	0.00091
V1082 Sco	53454.32(54)	23.4456(28)	23.4537(28)	0.247(101)	181(63)	0.124(74)	186(280)	0.14563

The LC analysis resulted in fit presented in Fig. 2 and the final LC parameters are given in Table 3. This fit was derived assuming the primary component of A9 spectral type (as derived from the $B-V$ indices from NOMAD, Tycho, Kharchenko (2001), etc), therefore the temperature of the primary component $T_1 = 7250$ K was fixed. The derived value of internal structure constant is given below in Section 4.

[2] *ftp://ftp.astrouw.edu.pl/acta/2012/zas_97*

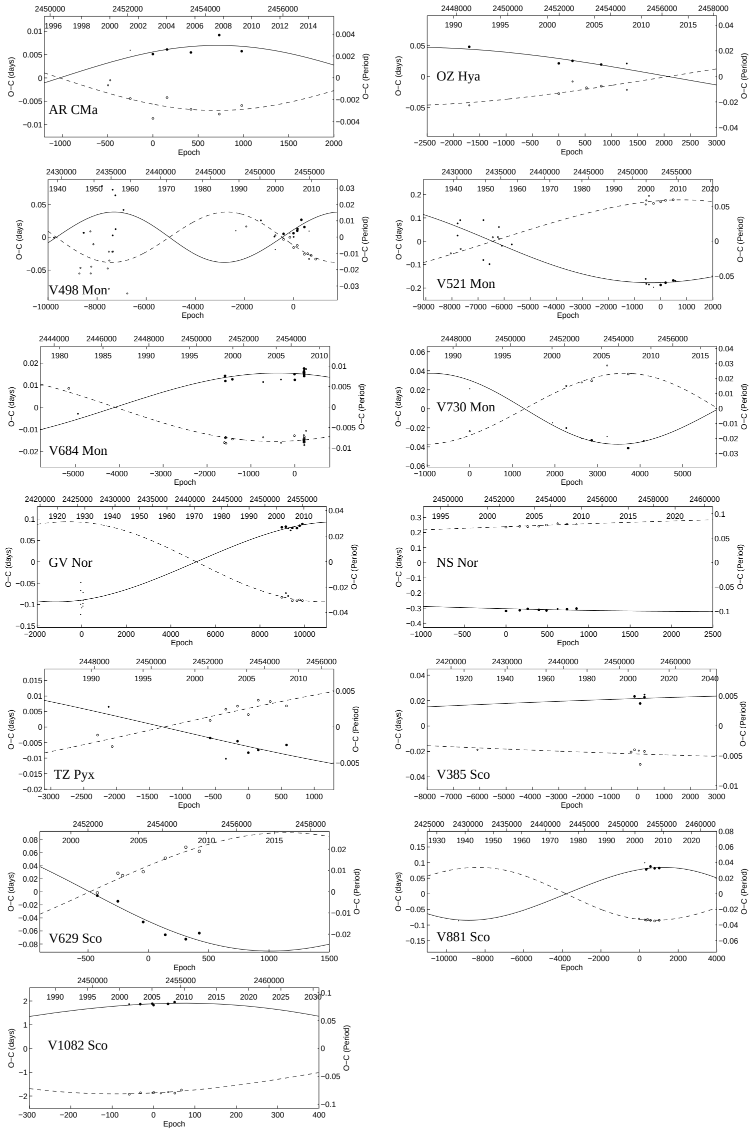

Fig. 1. $O-C$ diagrams of the studied systems. The lines represent the fit according to the apsidal motion hypothesis (see text and Table 2), solid line for the primary, while the dashed line for the secondary minima. Dots stand for the primary and open circles for the secondary minima. Bigger the symbol, higher the weight.

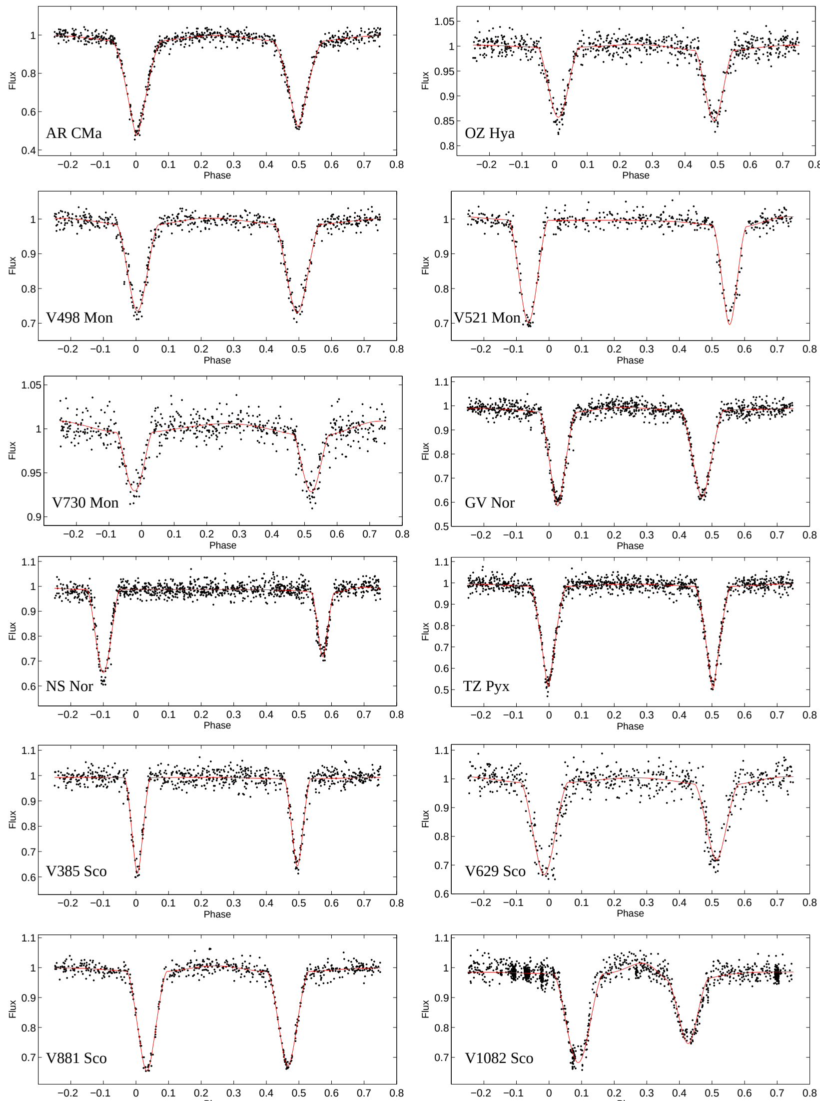

Fig. 2. The light curves of the analyzed systems. The individual points represent the ASAS data, while the lines stand for the final fits according to the parameters presented in Table 3.

Table 3

The parameters of the light curve fits (values of temperatures are only estimations)

System	i [deg]	Ω_1	Ω_2	T_1 [K]	T_2 [K]	L_1 [%]	L_2 [%]	L_3 [%]
AR CMa	91.33(22)	5.47(7)	5.30(6)	7250	7230(34)	50.29(1.06)	49.71(0.89)	0.00(0.42)
OZ Hya	79.66(36)	5.94(10)	5.42(9)	6700	7740(45)	30.07(0.94)	29.92(0.82)	40.01(1.33)
V498 Mon	79.87(20)	5.55(5)	5.81(6)	15500	16255(141)	49.92(0.98)	50.08(0.99)	0.00(0.84)
V521 Mon	82.50(28)	6.98(16)	6.55(9)	10350	13343(132)	49.80(1.30)	50.20(1.22)	0.00(1.07)
V730 Mon	72.51(39)	5.92(10)	5.42(7)	19000	19594(287)	33.32(1.01)	33.28(0.90)	33.40(3.34)
GV Nor	85.54(22)	6.42(7)	6.36(6)	13000	11382(88)	50.07(0.65)	49.93(0.78)	0.00(0.65)
NS Nor	84.24(27)	9.46(11)	7.79(11)	9400	10789(81)	50.86(1.02)	49.14(1.01)	0.00(0.99)
TZ Pyx	89.21(22)	6.84(9)	6.74(8)	9100	9102(58)	49.97(0.93)	49.96(1.04)	0.06(0.44)
V385 Sco	86.68(40)	9.11(24)	8.79(29)	10350	11953(121)	49.73(1.37)	50.27(1.29)	0.00(1.24)
V629 Sco	81.24(37)	5.91(9)	5.33(7)	8770	8926(93)	49.83(1.65)	50.17(1.73)	0.00(1.65)
V881 Sco	83.32(20)	6.22(7)	6.11(5)	9100	9249(63)	49.73(0.91)	50.27(0.94)	0.00(0.71)
V1082 Sco	79.01(14)	6.53(8)	5.33(6)	28500	33322(242)	49.81(0.87)	50.19(0.84)	0.00(0.63)

System	F_1	F_2	R_1/a	R_2/a	Σ res^2
AR CMa	1.22(54)	1.39(32)	0.227(6)	0.237(5)	0.13778
OZ Hya	1.14(65)	1.03(50)	0.202(9)	0.211(7)	0.06870
V498 Mon	1.15(21)	1.19(25)	0.224(4)	0.211(4)	0.06210
V521 Mon	1.27(51)	1.34(45)	0.176(8)	0.190(5)	0.05643
V730 Mon	0.90(76)	1.40(39)	0.207(8)	0.234(7)	0.03882
GV Nor	1.21(23)	1.12(20)	0.191(3)	0.193(4)	0.19204
NS Nor	0.77(69)	1.23(53)	0.125(3)	0.159(5)	0.24938
TZ Pyx	1.37(24)	1.09(30)	0.172(5)	0.169(5)	0.22866
V385 Sco	1.44(83)	1.20(71)	0.116(7)	0.121(8)	0.16524
V629 Sco	1.17(38)	1.21(59)	0.208(7)	0.238(7)	0.32045
V881 Sco	1.20(30)	1.20(45)	0.197(5)	0.202(4)	0.06581
V1082 Sco	1.71(43)	1.25(18)	0.198(5)	0.259(2)	0.22720

OZ Hya

OZ Hya (= HIP 49177) was discovered as a variable star by Hoffmeister (1936). It is a member of the visual double system designated as B 871, or WDS J10022-1946AB in the Washington Double Star Catalog (hereafter WDS, Mason *et al.* 2001). 15 astrometric measurements were obtained since its discovery as a double in 1927, but these data indicate no visible motion.

The spectral type of the system is listed as F2V, according to Houk and Smith-Moore (1988). We can only speculate which component this spectral type belongs to – whether the visual component or the EB pair. The star was also included into the catalog of systems located in the δ Sct region of the Cepheid instability strip (Soydugan *et al.* 2006), which are suspect to contain pulsating component. However, the quality of the ASAS data used in our analysis cannot prove or rule out this hypothesis.

Analysing all minima times (Table 5) we derived very preliminary apsidal motion parameters (Table 2 and Fig. 1). The analysis of LC yielded Fig. 2 and the parameters given in Table 3 from which the most interesting seems to be the value of the third light, which resulted in about 40% of the total luminosity of the system. This is in excellent agreement with the fact that the magnitude difference between the close visual component and the eclipsing binary itself is about 0.65 mag in the *V*-band (WDS).

V498 Mon

V498 Mon (= HD 288904) was discovered as a variable star by Wachmann (1966). Its spectral type was classified as B5 by Nesterov *et al.* (1995). For the analysis we collected old photographic minima together with new ones from NSVS and ASAS. The most recent minimum was observed in the Ondřejov observatory with 65-cm telescope equipped with the CCD camera.

As one can see from the fit in Fig. 1, the motion of line of apsides is relatively fast, with a period of about 62 years and it is evident even in the ASAS data covering about 10 years. The difference between primary and secondary minima is still increasing, reaching its maximum in 2017. The LC analysis was carried out with the assumption of the primary component's temperature $T_1 = 15\,500$ K (according to B5 spectral type).

V521 Mon

V521 Mon (= HD 292704) is an Algol-type EB, discovered also by Wachmann (1966). McCuskey (1956) presented its spectral type as A0, while Brancewicz and Dworak (1980) reported B7 spectral type, and Nesterov *et al.* (1995) lists spectrum of B9 type. On the other hand, the *UBV* and *uvby*β photometry by Lacy (1992) and Lacy (2002) indicates a bit later spectral type, about A5-A7 (according to Popper 1980).

The analysis of all available minima led to the parameters given in Table 2. The apsidal motion period is rather long, about 217 years, but about 1/3 is already covered by observations. After the subtraction of the apsidal motion term, the residuals show some additional variation, which can be caused *e.g.*, by a third body in the system. However, it still remains rather uncertain now and further observations are needed. For the LC analysis the primary component's temperature was fixed at a value of 10 350 K (sp B9). No additional third light was detected.

V684 Mon

V684 Mon (= HD 47755) was discovered by Koch *et al.* (1986). It is also a member of very young open cluster NGC 2264 (cluster age is 3–4 Myr), as well as primary of a visual double star WDS J06406+0947 (where the secondary component, about 25″ distant, is also variable V780 Mon). A detailed analysis of LC and RV curves was performed by Bradstreet *et al.* (2007). The results indicate that the system consists of two main sequence B4 stars on slightly eccentric orbit.

For our analysis we used the minima from the abovementioned analysis (Bradstreet 2011, private communication), together with the ASAS and CoRoT data.

The scatter of individual minima is caused by shallow eclipses and poor photometric data for minima computation. However, our eccentricity is very close to the one published by Bradstreet *et al.* (2007). About 1/3 of the apsidal period is already covered by observations.

V730 Mon

V730 Mon (= HD 46738 = HIP 31371) is the system with the shortest period in our sample. It is a primary component of a visual pair A 508 (or WDS J06347-0836AB), which was discovered as a double in 1903, but since then no mutual motion of the two components has been detected. Kharchenko (2001) published the only spectral classification of both visual components as B3V (component A: V730 Mon) + B4 (fainter component B).

Analysis of the new derived minima indicates that the period of apsidal motion is about 39 yr and about 1/3 is covered by observations by now. The LC analysis was carried out with the assumption of spectral types by Kharchenko (2001), *i.e.*, $T_1 = 19\,000$ K. As one can see from the individual luminosities, the triple system likely consists of three very similar stars.

GV Nor

GV Nor (= HD 146375) was discovered as a variable by Kruytbosch (1932). The only spectral classification of the star is that by Houk and Cowley (1975), who gave its spectral type B5/8, unfortunately based on poor quality spectra.

Our period analysis of GV Nor is based on 25 minima in total, resulting in apsidal period of about 200 years. After subtracting the fit, some additional variation of the minima cannot be ruled out. The LC analysis was performed under assumption that the primary component is of B7 spectral type ($T_1 = 13\,000$ K). The LC fit shows clearly defined and relatively deep eclipses, which are similar to each other.

NS Nor

NS Nor (= HD 147944) was discovered as a variable star by Hoffmeister (1963). After then Meinunger (1970) listed its type as a long-periodic with a period of about 130 days. SIMBAD lists NS Nor as a "Semi-regular pulsating Star". However, no such behavior was found in the ASAS data (also INTEGRAL/OMC and "Pi of the sky" data show no such variations). Its spectral type was classified as A0IV by Houk and Cowley (1975).

Our apsidal motion analysis is still very preliminary due to long period of NS Nor. The LC analysis was carried out with the assumption of primary temperature $T_1 = 9\,400$ K. However, we can still doubt about the initial assumption of the analysis, which is the spectral classification as a subgiant, because a more evolved star should probably be older and its orbit definitely circularized. Therefore, a detailed spectroscopic analysis is still needed.

TZ Pyx

TZ Pyx (= HIP 42619) is probably the most studied system in our sample. It was discovered as a variable one by Strohmeier (1966). The spectroscopic analysis by Duerbeck and Rucinski (2007) revealed that the system is a well-detached one and its spectral type was classified as A with both components very similar to each other (BFs, mass ratio, and depths of both minima). However, their RV study deals with one disadvantage, which is the circular orbit assumed for the analysis. Otero (2007) analysed the Hipparcos and ASAS data and found out that the system is definitely an eccentric one.

Our analysis is based on the observations after 1990's only, because the older published minima have much larger scatter than necessary for the apsidal motion analysis performed here. The apsidal motion fit is still not very convincing and would have even shorter period (the two most recent deviating points), but only further observations would confirm this hypothesis. For the LC analysis we used the assumption that the primary component is of A1 spectral type. This is based on the $B-V$ indices from different sources as well as from Ammons *et al.* (2006). Hence, we set the value of $T_1 = 9\,100$ K. Both eclipses are relatively well-covered by the data points and also the fit is satisfactory. The mass ratio q was taken from the RV analysis by Duerbeck and Rucinski (2007).

V385 Sco

The star V385 Sco (= HD 320236) was discovered as an eclipsing variable by Swope (1940), who also gave its orbital period of 2.34515 day. Its true orbital period is double, about 4.69 day. It is probably a member of open cluster Collinder 338. No detailed analysis of this system was performed, only the spectral type was estimated as B9 by Parsons *et al.* (1980).

Using all available minima we performed an apsidal motion analysis. Unfortunately, the apsidal motion is still very poorly covered by the data, however the apsidal advance is evident thanks to the one old data point. New observations are still needed. The LC analysis was done assuming the primary temperature $T_1 = 10\,350$ K.

V629 Sco

The system V629 Sco was discovered by Swope (1943), who also wrote a remark about its apsidal motion, which means that the primary and secondary minima were observed both. Unfortunately, only time of primary minimum is listed there. There is also a remark that "Further details will be published elsewhere", but no other publication about this concern was found in the literature. Svechnikov and Kuznetsova (1990) presented the spectral type (A2)+[K0IV], which is quite unreliable for the secondary, but would be more likely for the primary component.

New minima cover only a few years but even on these data there is an evident rapid apsidal motion, which has the period of about 56 years. Further observations are still needed for the parameters to be derived with higher conclusiveness. The LC analysis was carried out with the initial assumption of T_1=8 770 K. As one can see from the fit plotted in Fig. 2, the apsidal motion is so rapid that it even causes a "blurring" of a phase in the light curve (during the time epoch about 8.7 years of ASAS data the argument of periastron ω changed by about 56°). The scatter of the light curve is rather high and new more precise observations would be very welcome.

V881 Sco
V881 Sco (= HD 150384) was discovered as a variable by Strohmeier and Knigge (1973), and Houk (1982) gives its spectral classification as A1/2IV.

The apsidal motion analysis was performed and thanks to the one old minimum from 1930's there is about one half of the apsidal motion period covered now. However, due to lack of data, the analysis is still preliminary. The LC solution was done with the assumption of $T_1 = 9\,100$ K (spectral type A1 for the primary).

V1082 Sco
V1082 Sco (= HD 318015 = HIP 86163) is a member of very reddened young open cluster Trumpler 27, see The and Stokes (1970) and Moffat *et al.* (1977). Its spectrum was classified as B0.5Ia by Drilling and Perry (1981).

Available minima times show very slow apsidal motion, but only a small part of its period is covered by now and further observations are needed. The LC of rather interesting shape is plotted in Fig. 2, however there is still a place for doubts if the eclipses are total or not. Regrettably, the ASAS photometry is not precise enough for a final confirmation of this hypothesis. Secondary minimum is located near the phase $\phi_{\rm II} = 0.33$ with respect to the primary one, which indicates high value of eccentricity. This is the system which shows the largest outside-eclipse variations in our sample. We found a light curve solution (presented in Table 3) using the assumption of $T_1 = 28\,500$ K.

4. Internal Structure Constant

Thanks to the analysis of apsidal motion *via* the period changes and the light curve one is able to use the derived quantities for a rough estimation of the internal structure constants. The theoretical $\log k_{2,\rm theo}$ values are taken from Claret (2004) and the comparison with the observed ones is presented in Table 4. There are only mean values of $\log k_2$ of both components which can be derived and these are based on several assumptions. The errors were only estimated due to the fact that also the input parameters like spectral types are not known with high reliability.

The most speculative is the use of apsidal motion parameters for those systems, where only a short time interval (compared with the apsidal motion period) is covered with the data. For systems like OZ Hya, NS Nor, V385 Sco and V1082 Sco these values are still rather speculative and affected by relatively large errors because of their poor coverage of minima times. Therefore, almost the same χ^2 can be reached with slightly different values of apsidal motion rate and hence also the estimation of $\log k_2$ is still preliminary. Another possible sources of errors for the internal structure estimation are the unknown spectral types of the components, hence only rough estimation of their masses. For some systems also the interstellar reddening could play a role when the spectral type was only estimated from the $B-V$ photometric index. And finally of course the unknown value of the semimajor axis of the system (dealing with no RVs). Also better the quality of the light curves, better the result of the LC fit and the parameters derived from this fit. All of these are the possible sources of errors which affect the obtained $\log k_2$ values. However, for all systems the observed internal structure constants and the theoretical values lie within their respective error bars (Table 4 and Fig. 3).

Table 4

The internal structure constants $\log k_{2,\rm obs}$ as compared with the theoretical values from stellar evolution models together with the relativistic fraction of the total apsidal motion rate

System	$\log k_{2,\rm obs}$	$\log k_{2,\rm theor}$	$\frac{\dot\omega_{\rm rel}}{\dot\omega_{\rm total}}$	System	$\log k_{2,\rm obs}$	$\log k_{2,\rm theor}$	$\frac{\dot\omega_{\rm rel}}{\dot\omega_{\rm total}}$
AR CMa	-2.24 ± 0.20	-2.39 ± 0.05	1.3%	NS Nor	-2.45 ± 0.20	-2.30 ± 0.05	12.2%
OZ Hya	-2.47 ± 0.20	-2.30 ± 0.05	3.9%	TZ Pyx	-2.14 ± 0.20	-2.36 ± 0.05	5.5%
V498 Mon	-2.23 ± 0.20	-2.20 ± 0.05	3.2%	V385 Sco	-2.23 ± 0.20	-2.35 ± 0.05	23.8%
V521 Mon	-2.43 ± 0.20	-2.35 ± 0.05	5.9%	V629 Sco	-2.13 ± 0.20	-2.34 ± 0.05	1.1%
V684 Mon	-2.10 ± 0.05	-2.12 ± 0.05	6.9%	V881 Sco	-2.39 ± 0.20	-2.34 ± 0.05	4.2%
V730 Mon	-2.29 ± 0.20	-2.15 ± 0.05	5.4%	V1082 Sco	-2.04 ± 0.20	-1.91 ± 0.05	0.5%
GV Nor	-2.40 ± 0.20	-2.23 ± 0.05	6.4%				

Table 5

Heliocentric minima used for the analysis

System	HJD-2400000	Error	Epoch	$O-C$	Type	Filter	Reference
AR CMa	51493.2540	0.05	−495.50	−0.00158	Sec	*V*	Rotse
AR CMa	51549.22847	0.035	−471.50	−0.00049	Sec	–	NSVS
AR CMa	52063.49034	0.04664	−251.00	0.00593	Pri	*V*	ASAS
AR CMa	52064.64609	0.00625	−250.50	−0.00443	Sec	*V*	ASAS
AR CMa	52648.87782	0.01952	0.00	0.00513	Pri	*V*	ASAS
AR CMa	52650.03011	0.00322	0.50	−0.00870	Sec	*V*	ASAS

Note: Table is published in its entirety in the electronic form in the *Acta Astronomica Archive*. A portion is shown here for guidance regarding its form and content.

A direct comparison between theory and observations is still rather difficult here. As one can see from Fig. 3, the distribution of resulting $\log k_{2,\rm obs}$ values follow the predicted relation (the earlier the spectral type yields the value of $\log k_2$ closer to zero) and all thirteen values are randomly distributed around the theoretical ones. However, the error bars are still too large to do any definite finding concerning the evolutionary models. Generally we can conclude that obtaining the precise RV curves for all of these systems would be of great benefit.

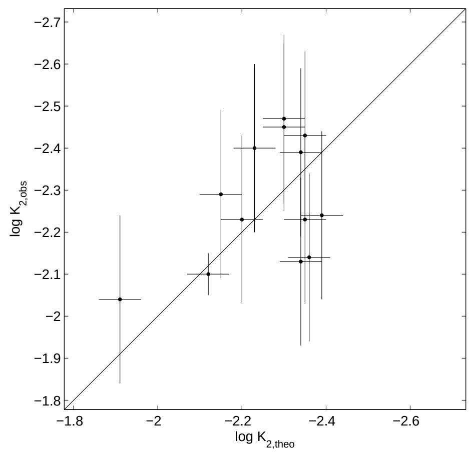

Fig. 3. Plot of internal structure constants – observed *vs.* theoretical.

5. Discussion and Conclusions

We derived preliminary apsidal motion and light curve parameters for thirteen Algol-type systems. None of these systems was studied by means of an apsidal motion hypothesis based on the minima times analysis, and the LC solution is presented here for the first time. However, the analysis still deals with several problems. The main disadvantage is that we have only very limited information about these systems and our results are based only on rough estimations. The parameters like spectral types of the components, their physical parameters (mass ratio) or the age of the system are not known (except for analyses of TZ Pyx and V684 Mon) and further more detailed study is very needed. Especially, the spectroscopic observations would be very welcome to confirm the spectral types of both components, because the rough estimations based only on the photometric indices are affected by relatively large errors (typical example is V521 Mon, where the spectral estimations are ranging between B7 and A7). Moreover, we found that the spectral estimation published by Svechnikov and Kuznetsova (1990) seems to be of little confidence in most cases.

The more detailed spectroscopic study for all of the systems would be also of great benefit for the comparison of the internal structure constants and the models. Our presented first attempt on this issue was done only on very preliminary physical parameters of the individual components and therefore our findings on the resulting $\log k_2$ constants is also affected by large errors. Also the new minima observations would be of great benefit for some of the systems, especially for those of shorter apsidal periods (such as AR CMa, V730 Mon or V629 Sco) and also for those, where we noticed some suspected additional variations potentially caused by the third components in these systems (such as V521 Mon or GV Nor). Some of the stars selected for this sample are also possible to observe from the northern hemisphere and the observations could be done rather easily (relatively high brightness, moderately deep minima and not so long orbital periods). Most of the data used for this study came from the ASAS survey, however the quality of these data is not sufficient enough for a more detailed light curve analysis in most of these systems. New more precise photometric observations in different photometric filters would be also welcome for a prospective detailed LC analysis. New times of minima, whole light curves, as well as a detailed spectroscopic analysis are still needed.

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GK Bootis and AE Fornacis: two low-mass eclipsing binaries with dwarf companions★,★★

P. Zasche[1], P. Svoboda[2], and R. Uhlář[3]

[1] Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Private observatory, Výpustky 5, Brno 614 00, Czech Republic
[3] Private Observatory, Pohoří 71, 25401 Jílové u Prahy, Czech Republic

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ABSTRACT

Context. A study of late-type low-mass eclipsing binaries provides us with important information about the most common stars in the Universe.

Aims. We obtain the first light curves and perform period analyses of two neglected eclipsing binaries GK Boo and AE For to reveal their basic physical properties.

Methods. We performed both a period analysis of the times of the minima and a BVR light curve analysis. Many new times of minima for both the systems were derived and collected from the data obtained by automatic and robotic telescopes. This allowed us to study the long-term period changes in these systems for the first time. From the light curve analysis, we derived the first rough estimates of the physical properties of these systems.

Results. We find that the analyzed systems are somewhat similar to each other. Both contain low-mass components of similar types, both are close to the Sun, both have short orbital period, and both contain another low-mass companions on longer orbits of a few years. In the case of GK Boo, both components are probably of K3 spectral type, while the distant companion is probably a late M star. The light curve of GK Boo is asymmetric, which probably causes the shift in the secondary minima in the O−C diagram. System AE For comprises two K7 stars, and the third body is a possible brown dwarf with a minimal mass of only about 47 $M_{\rm Jup}$.

Conclusions. We succeed in completing period and light curve analyses of both systems, although a more detailed spectroscopic analysis is needed to confirm the physical parameters of the components to a higher accuracy.

Key words. binaries: eclipsing – stars: fundamental parameters – stars: individual: GK Boo – stars: individual: AE For

1. Introduction

Low-mass stars are the most common stars in our Galaxy (e.g. Kroupa 2002). However, owing to their low luminosity, only these close to the Sun have been studied in detail and many of them have never been analyzed. Hence, we focused on two rather neglected low-mass eclipsing binary systems: GK Boo and AE For. Their light curves as well as their period modulation had never been studied. Some studies indicate that most late-type stars are single (e.g. Lada 2006), but the number of papers studying the multiplicity of the late-type systems is still rather limited. Therefore, the incidence of multiples in late-type stars remains unexplored.

The study of eclipsing binaries provide us with important information about the physical properties of both of their components – their radii, masses, and evolutionary status. However, when considering only with the light curve, several assumptions have to be made. For the analysis presented in this paper we also used the photometric data obtained by automatic and robotic telescopes (such as ASAS, Pi of the sky, and SWASP). Thanks to these huge databases of observations, the long-term evolution of these systems can be studied for the first time.

★ This paper uses observations made at the South African Astronomical Observatory (SAAO).
★★ Tables 8 and 9 are available in electronic form at http://www.aanda.org

2. GK Boo

2.1. Introduction

The system GK Boo (=BD+37 2556, $V_{\rm max}$ = 10.86 mag) is an Algol-type eclipsing binary with an orbital period of about 0.48 day. It is also a primary component of a visual double designated WDS J14384+3632 in the Washington Double Star Catalog (WDS[1], Mason et al. 2001). The secondary component of this double star is about 14″ distant, and is probably gravitationally bound to GK Boo itself. It is about 0.4 mag fainter, but since its discovery in 1933 there has been no detectable mutual motion of the pair, hence the orbital period is of about thousands of years (rough estimation from the Kepler's law).

The star is too faint, thus was not observed by Hipparcos satellite, and its distance is therefore rather uncertain. Kharchenko (2001) introduced the parallax 30.29 mas, which is however only an estimate. Its spectral type is also unknown, but the $B-V$ index derived from the Tycho catalogue (Høg et al. 2000), $B-V$ = 0.89 mag indicates a spectral type of about K1. On the other hand, the 2MASS infrared photometry (Cutri et al. 2003) gives $J-H$ = 0.527 mag (therefore a spectral type of K3). Finally, Ammons et al. (2006) introduced a temperature corresponding to a spectral type of about K2-3. All these rough spectral estimates were taken from Popper (1980) and Cox (2000).

[1] http://ad.usno.navy.mil/wds/

2.2. Light curve

The star was observed by the SuperWASP (Pollacco et al. 2006) project and its complete light curve (hereafter LC) is available. However, we did not use these data for the LC analysis because these were not measured in any standard photometric filter. These data were only used to derive the minima times (see below). We observed the target at the Ondřejov observatory in the Czech Republic with the 65-cm telescope equipped with the CCD camera. For the light curve analysis, only the data from two nights in May 2011 were used (see Tables 8 and 9). The remaining observations were used for the minima time derivation and to analyze the period changes in the system (see below Sect. 2.3). The observations were obtained in standard B, V, and R filters according to the specification of Bessell (1990).

At first, the complete LC was analyzed using the program PHOEBE (Prša & Zwitter 2005), which is based on the Wilson-Devinney algorithm (WD, Wilson & Devinney 1971). The derived quantities are as follows: the secondary temperature T_2, the inclination i, the luminosities L_i, the gravity darkening coefficients g_i, the albedo coefficients A_i, and the synchronicity parameters F_i. The limb darkening was approximated using a linear law, and the values of x_i were interpolated from the van Hamme's tables, given in van Hamme (1993).

At the beginning of the fitting process, we fixed the temperature of the primary component at T_1 = 4700 K (corresponding to spectral type K3, Cox 2000). In the absence of spectroscopy, the mass ratio was derived via a so-called "q-search method". This means that we tried different values of mass ratio in the range 1.5–0.5 in steps of 0.1 and tried to find the best LC fit according to the lowest value of rms. Finally, we found that the best-fit solution was reached with the value $q = M_2/M_1 = 0.9$, which agrees with both eclipses having almost equal depths. For a given mass ratio, the semi-major axis was fixed to an appropriate value for the primary mass to be equal to a typical mass of a particular spectral type (e.g. Popper 1980; Harmanec 1988; or Andersen 1991). With this approach, we were able to estimate the masses, in addition to the radii of both components in absolute units.

However, during the LC fitting process we found that the LC of GK Boo is asymmetric. In particular, the part of the LC near the secondary minimum is distorted in all BVR filters. The brightness just after the ascent from the secondary minimum (near the phase 0.6) is higher than the brightness just before the descent (phase 0.4). The difference is about 0.022 mag in B, 0.018 mag in V, and 0.017 mag in R filter, respectively.

With the PHOEBE code, we tried to fix the values of A_i and g_i to their appropriate values of 0.5 and 0.32, respectively. However, after then we also allowed these parameters to be fitted, because the fit is tighter (rms). However, probably owing to the asymmetry of the LC these quantities converged to the rather improbable values given in Table 1, and the shape of the observed LC could not be fitted properly. For the asymmetry of the curve, we also tried to introduce a star spot on either of the components. However, no acceptable solution with spot(s) was found to describe the shape of the light curve more accurately in the PHOEBE program. The parameters of the LC fit are given in Table 1, but these cannot sufficiently describe the shape of the LC.

We therefore tried a different code, called ROCHE, developed by Theo Pribulla (Pribulla 2004), which is also based on the WD code but has for instance also some other computing methods and different controlling of the calculation process. With this program, we used two star spots and similar input parameters as described above. At the beginning, the values of A_i and g_i were fixed to the appropriate values of 0.5 and 0.32, respectively. However, to achieve a tighter fit both A_i and g_i values were also varied across the range from 0 to 1 in steps of 0.05 for both components. The synchronicity parameters F_i converged to much more reliable values. The value of mass ratio was fixed to $q = 1.0$ and then also fitted as a free parameter. This was possible because there is a clear distortion of the LC outside the minima (see e.g. Terrell & Wilson 2005). For the fitting process, the two different limb darkening laws were also tried, namely a linear and logarithmic. The latter one provides a much tighter fit to our data. All of the resulting LC parameters are also given in Table 1 (together with parameters of two cooler spots located on the primary component – longitude, latitude, radius and temperature factor). As one can see, the two solutions clearly differ even outside their respective error bars for some of the parameters.

Table 1. Light curve parameters of GK Boo.

Parameter	Value PHOEBE	Value ROCHE
T_1 [K]	4700*	
T_2 [K]	4540 ± 50	4615 ± 63
q (=M_2/M_1)	0.9 ± 0.1	0.95 ± 0.12
e	0*	
i [deg]	89.83 ± 0.57	89.28 ± 0.37
g_1	0.00 ± 0.04	0.35 ± 0.05
g_2	0.00 ± 0.03	0.35 ± 0.05
A_1	0.00 ± 0.08	0.80 ± 0.05
A_2	1.00 ± 0.08	0.80 ± 0.05
F_1	1.892 ± 0.107	1.131 ± 0.096
F_2	1.866 ± 0.116	1.295 ± 0.108
L_1 (B) [%]	54.8 ± 1.9	52.4 ± 1.1
L_2 (B) [%]	45.2 ± 1.8	47.6 ± 1.0
L_1 (V) [%]	53.5 ± 1.5	51.6 ± 1.2
L_2 (V) [%]	46.5 ± 1.3	48.4 ± 1.1
L_1 (R) [%]	52.1 ± 1.4	51.1 ± 1.1
L_2 (R) [%]	47.9 ± 1.3	48.9 ± 1.0
Spots:		
l_1 [deg]	–	287.2 ± 7.9
b_1 [deg]	–	60.5 ± 3.2
r_1 [deg]	–	37.9 ± 2.0
k_1	–	0.75 ± 0.04
l_2 [deg]	–	63.3 ± 7.4
b_2 [deg]	–	47.4 ± 12.8
r_2 [deg]	–	28.7 ± 4.1
k_2	–	0.76 ± 0.04
Derived quantities:		
R_1 [$R_\odot$]	0.83 ± 0.18	0.89 ± 0.15
R_2 [$R_\odot$]	0.86 ± 0.18	0.86 ± 0.14
M_1 [$M_\odot$]	0.73 ± 0.06	0.73 ± 0.06
M_1 [$M_\odot$]	0.66 ± 0.06	0.70 ± 0.06

Notes. (*) Fixed.

The individual errors in the parameters were not taken from the WD code, but derived in the following way. We computed a range of solutions for GK Boo, which were then used for its error estimation. All solutions with χ^2 value close to the minimal one (5% from our final solution) were taken and the resultant values of parameters were used to compute the differences between the parameters. The errors in the individual parameters were then computed as a maximum difference and their individual WD errors, given by $\max(a_i - a_{\min}) + \delta a_i + \delta a_{\min}$.

This solution obtained with the ROCHE program provides a much closer fit to the observed data and is the fit plotted in Fig. 1. The value of the eccentricity was fixed at 0 (for a discussion about possible eccentricity see below). Our resultant parameters indicate that both the components are still located on

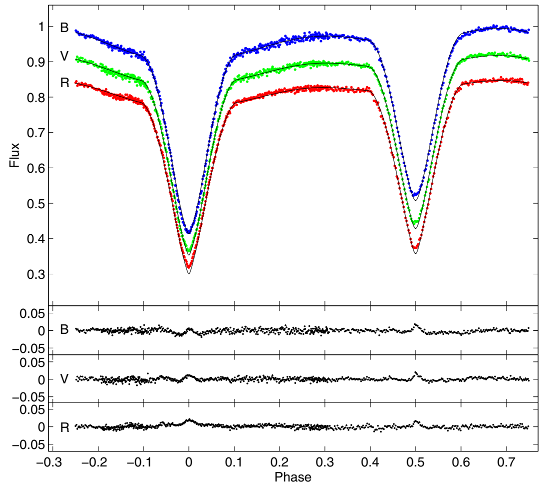

Fig. 1. Light curves in *BVR* filters for GK Boo, the solid lines represent the final fit. The residuals after the fit are plotted below. The curves are shifted along *y*-axis for reasons of clarity.

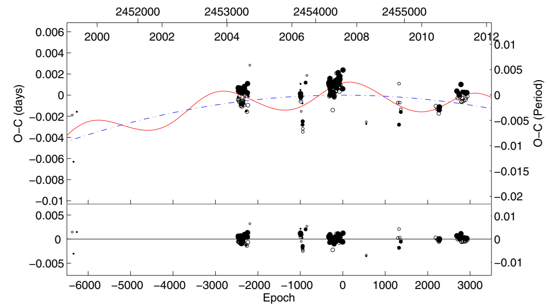

Fig. 2. Periodic modulation of period GK Boo. Blue dashed line represents quadratic ephemeris, while red solid line stands for the LITE hypothesis. Residuals are plotted in the bottom plot. The larger the symbol, the higher the weight (higher the precision).

Table 2. Final parameters of the long orbit for GK Boo.

Parameter	Value
HJD_0	2454305.4570 ± 0.0006
P [day]	0.47777174 ± 0.00000022
p_3 [day]	1472.7 ± 170.0
p_3 [yr]	4.032 ± 0.450
A [day]	0.0126 ± 0.0012
T_0	2454263.3 ± 1108.3
ω_3 [deg]	56.54 ± 15.0
e_3	0.084 ± 0.267
Q [$\times 10^{-10}$]	–1.071 ± 0.206
$f(M_3)$ [$M_\odot$]	0.000633 ± 0.000002
$M_{3,\min}$ [$M_\odot$]	0.115 ± 0.001
$M_{3,60}$ [$M_\odot$]	0.134 ± 0.002
$M_{3,30}$ [$M_\odot$]	0.242 ± 0.005
$a_{12} \sin i$ [AU]	0.217 ± 0.108
a_3 [mas]	88.7 ± 9.8

the main sequence, (as required because the age of the Universe does not allow low-mass stars to have evolved from the main sequence). If we follow the assumption of a K3V primary, then the secondary is also of K3V spectral type. These are consistent with the photometric indices presented above, as well as with the individual masses and radii for these types of stars (e.g. Harmanec 1988). An undetectable value of the third light was also resulted derived by this analysis. The presence of photospheric spots on both components of such a late spectral type star is also foreseeable.

2.3. Period analysis

To monitor the detailed long-term evolution of the system or its short-period modulation, we collected all available published minima observations. Photometry from the SWASP (Pollacco et al. 2006), ASAS (Pojmanski 2002), and PiOfTheSky (Burd et al. 2005) projects were used to derive many new minima times for GK Boo. All of these data are given in Table 8. The method of Kwee & van Woerden (1956) was used. Some of the data were of poor quality, but most were accurate enough to perform a detailed period analysis of the system. The range of these data is about 12 years.

We used these data to analyze the period modulation and found some interesting results. Applying the hypothesis of a third body in the system (the so-called LIght-Time Effect, hereafter LITE, described e.g. by Irwin 1959), we found a weak period modulation with a period of about four years. The final fit to the data together with the theoretical curve is shown in Fig. 2. As one can see, there is also some long-term period evolution of the orbital period (the blue dashed line), which was described as a quadratic term in ephemerides. It can be understood as a slow period decrease caused by the mass loss from the system or mass flow between the components (or even momentum loss, magnetic breaking, etc.). Another explanation is that this is only part of the long-term period modulation, although we have only limited data coverage.

A more interesting finding is that of a period of about 4 years. Applying the LITE hypothesis, we obtained a final set of parameters given in Table 2, namely the period of the third body p_3, the semi-amplitude of the effect A, the time of periastron passage T_0, the argument of periastron ω_3, and the eccentricity e_3. Despite the low amplitude (about only 1.8 min) of the LITE, most of the observed minima times are of higher precision and the modulation is clearly visible. Table 2 also provides the mass function of the third body $f(M_3)$, which helps us to estimate its predicted mass.

Having no information about the inclination between the orbits of the eclipsing pair and the hypothetical third body, we plotted Fig. 3, where a plot mass versus inclination is shown. Assuming the coplanar orbits (i.e. $i_3 = 90° \rightarrow M_3 = M_{3,\min}$), the resulted minimum mass of the third body is only about 0.116 $M_\odot$, which places this body at the lower end of stellar masses, hence we can rule out the hypothesis of a brown dwarf or even an exoplanet. Despite of there being no upper limit to this mass (it goes to infinity with $i_3 \rightarrow 0°$), we can estimate a lower limit to the mass. Taking into account that no third light is detected in the LC solution, e.g. $L_3/(L_1 + L_2) < 0.01$ and assuming a main-sequence star, we can estimate its mass to be lower than 0.22 $M_\odot$, which is shown in Fig. 3 as a gray area. Further observations are still needed to confirm this hypothesis with higher conclusiveness.

If we assume the parallax of GK Boo as given by Kharchenko (2001), π = 30.29 mas, we are also able to compute

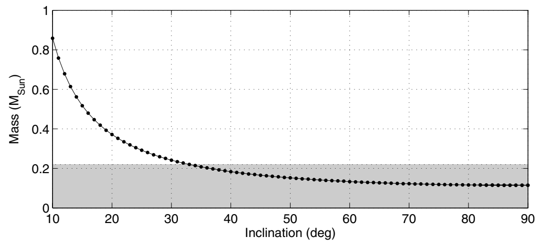

Fig. 3. GK Boo: mass of the third body based on from the LITE hypothesis with respect to the inclination between the orbits.

Table 3. Apsidal motion parameters for GK Boo.

Parameter	Value
e	0.0944 ± 0.0068
ω [deg]	268.9 ± 2.5
$\dot{\omega}$ [deg/cycle]	0.00026 ± 0.00001
U [yr]	1790 ± 50

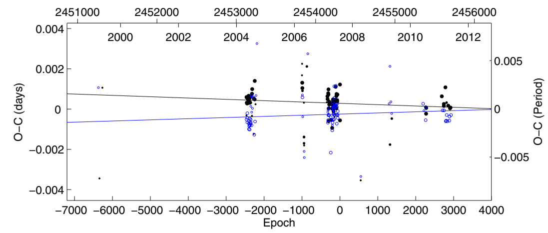

Fig. 4. O−C diagram of GK Boo with the apsidal motion hypothesis, black color is for primary minima, while blue one for secondary.

Table 4. Methods of minima fitting for GK Boo.

Method of minima fitting	rms	BIC
Linear ephemeris:	0.00151	23.5
Quadratic ephemeris:	0.00119	29.2
LITE and linear ephemeris:	0.00080	51.0
LITE and quadratic ephemeris:	0.00074	56.4
LITE, quadratic ephemeris and apsidal motion:	0.00060	72.6

the angular distance of a hypothetical body to be about 89 mas. This separation of components is well above the limit for modern stellar interferometers. However, there is a problem with the brightness of the third component, which was found to be about more than five magnitudes fainter than the eclipsing pair itself. With the brightness of about 11 mag for the system, this makes a detection impossible. The magnitude difference of the third body with respect to the close pair also clarify why no third light was detected in the LC solution.

Another interesting result was a detection of displaced secondaries. This can be clearly seen in more precise data points (SWASP and our new observations). That secondary minima occur at a different phase of $\phi_2 \neq 0.5$ from the primary usually indicates that the system is on an eccentric orbit. GK Boo is a well-detached system, so the eccentric orbit cannot be ruled-out easily. Therefore, we assumed an apsidal motion hypothesis for our data set of minima times. We followed a procedure described by e.g. Giménez & García-Pelayo (1983) or Giménez & Bastero (1995) and obtained a set of apsidal motion parameters. The plot of residuals (after subtraction of the LITE fit) with the apsidal motion fit is shown in Fig. 4. It is obviously very slow because the position of secondaries versus primaries changes only very slowly. The resultant values of apsidal motion parameters are given in Table 3.

However, we have to rule out this hypothesis because it lead to unacceptable results. With some information about the physical parameters of both components, we can use the apsidal motion parameters to estimate the internal structure constant. The theoretical log $k_{2,\rm theor}$ value taken from Claret (2004) should range from −1.35 to −1.65. However, the mean value of log k_2 of both components that can be derived from our solution is very different, even when $k_2 < 0$, which is unacceptable. Thus, the system is very probably on a circular orbit.

We may ask why the secondary minima deviate from the 0.5 phase. We published a finding that the displaced secondary minima can also be present in contact binaries where no eccentric orbit is possible (Zasche 2011), so one cannot perform an apsidal motion analysis based only on the minima times of a particular system. Some studies found that the secondary minimum is displaced because of the distortion of the LC, thus any standard routine for deriving the time of minimum (e.g. Kwee-van Woerden, bisector chord method or polynomial fitting) cannot be used properly because these consider symmetric minima only. When using these methods to determine minima where both ascending and descending branches have different slopes, we recover only a "false eccentricity".

One can also ask about a significance of the fits presented in Figs. 2 and 4. For this comparison, we summarized different approaches in Table 4. In addition to the rms values, we also provide the values of BIC (Bayesian Information Criterion, see e.g. Liddle 2007), which show the significance of the fit. According to this method, the smaller the rms value, the tighter the fit. To conclude, our final fit provides the smallest rms, but its significance is low and still highly speculative. This is also caused by the poor data coverage, and large scatter in the minima and their low accuracy. Determinations of new more precise minima are therefore needed to confirm or exclude this hypothesis.

3. AE For

3.1. Introduction

The Algol-type system AE For (=HIP 14568, $V_{\max}$ = 10.22 mag) is also a poorly studied binary. Its published spectral types range from K4 to M0, with the most probable one being K7V as derived by (Torres et al. 2006). The system was presented as a wide double with the star HD 19632 based on their similar parallaxes and proper motions (see Poveda et al. 1994).

Neither the light curve nor the radial velocity curve of AE For have been studied. The star was observed by the Hipparcos satellite and a few times also for the minima observations. It was also continuously monitored with automatic photometric systems such as PiOfTheSky and ASAS. However, the quality of these data do not allow us to use them for a LC analysis. The distance to the system was derived from the Hipparcos data to be d = 31.5 pc.

3.2. Light curve

We observed the star from the South African Astronomical Observatory (SAAO) in 2010, using the classical one-channel photoelectric photometer mounted on the 50-cm telescope. All

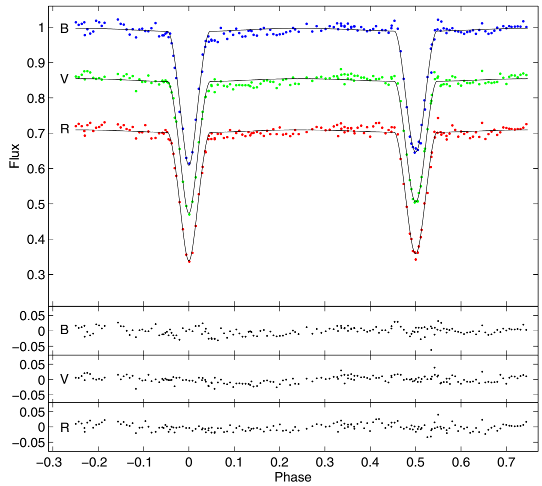

Fig. 5. Light curve in *BVR* filters for AE For, the solid line represents the final fit. The curves are shifted along the y-axis for greater clarity.

Table 5. Light curve parameters of AE For.

Parameter	Value
T_1 [K]	4100*
T_2 [K]	4065 ± 48
q (=M_2/M_1)	1.0*
e	0*
i [deg]	86.51 ± 0.31
$g_1 = g_2$	0.32*
$A_1 = A_2$	0.50*
$F_1 = F_2$	1.000*
L_1 (B) [%]	63.2 ± 1.3
L_2 (B) [%]	36.8 ± 1.0
L_1 (V) [%]	63.1 ± 1.2
L_2 (V) [%]	36.9 ± 1.0
L_1 (R) [%]	62.6 ± 1.4
L_2 (R) [%]	37.4 ± 1.0
Derived quantities:	
R_1 [$R_\odot$]	0.66 ± 0.10
R_2 [$R_\odot$]	0.52 ± 0.08
M_1 [$M_\odot$]	0.50 ± 0.05
M_1 [$M_\odot$]	0.50 ± 0.05

Notes. $^{(*)}$ Fixed.

measurements were carefully reduced to the Cousins E-region standard system (Menzies et al. 1989) and corrected for differential extinction.

Thanks to its orbital period close to one day, its complete light curve was observed once in standard *BVR* filters, with some overlapping points (about 170 data points in each filter were obtained). Unfortunately, the quality of the data acquired for several nights was not very good, hence the scatter in the curve is affected by these conditions. Two secondary and one primary minima were observed (see below).

We analyzed our data using the same computational procedure as for GK Boo. The primary temperature was fixed to the appropriate value of 4100 K (sp K7V), the eccentricity was fixed to 0, the values of gravity darkening coefficients were fixed at 0.32, and the albedo coefficients to 0.5 (as recommended for stars with convective envelopes), while the limb darkening coefficients were interpolated from values given in van Hamme (1993). The computational approach was different for the mass ratio q, which was fixed to $q = 1.0$ because of the weak outside-eclipse ellipsoidal variations and its detached configuration. In addition, the synchronicity parameters F_i were set to values of 1.0 for both components. The program ROCHE was used and the resulting LC parameters are given in Table 5, while the final solution is presented in Fig. 5.

One can see that the secondary temperature T_2 is close to the value of T_1, indicating that the components are similar. Thus, the estimated spectral types of both stars are probably K7V + K7V. Both components are still located on the main sequence and their properties are in agreement with the typical values of K7V stars (as presented by e.g. Harmanec 1988). The third light was also not detected here in any filter. In contrast to GK Boo, the LC of AE For seems to be symmetric.

3.3. Period analysis

Similarly to GK Boo, we tried to perform the period analysis of all available minima. The collection of minima is much smaller, but thanks to the first observation by Hipparcos (Perryman et al. 1997) these cover a longer time span than for GK Boo. Several

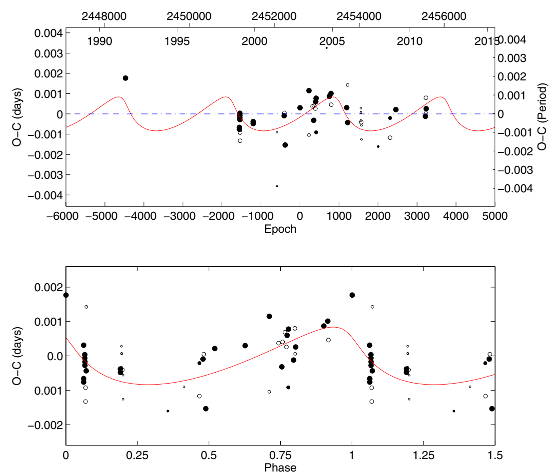

Fig. 6. O−C diagram of AE For. *up*: with linear ephemeris. *Bottom*: with respect to the phase. The data points are fitted with the curve representing the third body hypothesis (see the text for details).

new minima were derived based on our new observations from SAAO as well as those from the ASAS and PiOfTheSky surveys.

The same hypothesis as for GK Boo was applied to the data points here. All of the minima times used for the analysis are summarized in Table 9. As one can see from Fig. 6, there is a clear variation in the minima times. We used the same third-body hypothesis (LITE) as for GK Boo, deriving a final fit to the data given by the parameters in Table 6. The LITE hypothesis resulted in a rather eccentric orbit, although the result is affected by a relatively large error, hence maybe the e_3 value should be lower. Only additional observations would help us confirm or refute this hypothesis, refine the period, and possibly detect some long-term evolution of the period similar to that in GK Boo, because the first observation from Hipparcos deviates significantly from the fit. With the same procedure as for GK Boo, we computed the significance of the fits according to the BIC criterion (see Table

Table 6. Final parameters of the long orbit for AE For.

Parameter	Value
HJD_0	2452605.97070 ± 0.00035
P [day]	0.91820943 ± 0.00000012
p_3 [day]	2524.6 ± 149.6
p_3 [yr]	6.912 ± 0.409
A [day]	0.00083 ± 0.00032
T_0	2453548.8 ± 413.1
ω_3 [deg]	146.2 ± 57.8
e_3	0.601 ± 0.414
$f(M_3)$ [$M_\odot$]	0.000098 ± 0.000001
$M_{3,\min}$ [$M_\odot$]	0.047 ± 0.001
$M_{3,60}$ [$M_\odot$]	0.055 ± 0.001
$M_{3,30}$ [$M_\odot$]	0.098 ± 0.003
$a_{12} \sin i$ [AU]	0.167 ± 0.064
a_3 [mas]	117.2 ± 8.3

Table 7. Methods of minima fitting for AE For.

Method of minima fitting	rms	BIC
Linear ephemeris:	0.000255	24.4
LITE and linear ephemeris:	0.000163	44.8

7). As one can see, the fit is still very poor and highly speculative. However, using only the linear ephemeris, there remains a clear quasi-sinusoidal variation, which needs some physical explanation.

From the LITE parameters, we were able to calculate the minimal mass of the third body (i.e. coplanar orbits), which we found to be only about 47 $M_{\rm Jup}$, which is even lower than the limit of stellar masses. Therefore, if the orbits were coplanar (which only would be our assumption, because the process of tidal coplanarization is very slow), the third body would very probably be a brown dwarf (exoplanets have masses about one half of this value). With such a body, we reach minimal masses that can be detected by this method, because the amplitude of LITE is comparable to the typical precision of individual minima-time measurements. Whatever applies to the possible interferometric detection of GK Boo companion also applies here, because its luminosity is too low.

4. Discussion and conclusions

We have derived preliminary light-curve solutions and period analyses of the poorly studied Algol-type eclipsing binaries GK Boo and AE For, which we have found to have several interesting and similar features. Since both of them are low-mass stars of very similar types (K3+K3 for GK Boo, and K7+K7 for AE For), both of them have short orbital periods. Moreover, both are relatively close to the Sun and also appear to contain third bodies in their systems, which cause a periodic modulation of the orbital periods of both systems. Assuming a coplanar orbit, for AE For this third body appears to be a brown dwarf, which makes this system even more interesting. However, more photometric and spectroscopic observations are needed to confirm or refute this hypothesis.

The system GK Boo has an asymmetric light curve, which is the probably accounts for the shift in the secondary minimum in phase with the primary one. The apsidal motion hypothesis cannot explain this discrepancy.

In general, if the third body hypothesis as proposed based on the period analysis is found to be the correct one, here we have considered quite curious examples of hierarchical quadruple systems of low masses. As far as we know, there are only a few similar multiple late-type systems for which one of the components is an eclipsing binary (e.g. BB Scl or MR Del).

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THE PERIOD ANALYSIS OF V418 AQL, SU BOO, RV CVn, CR CAS, GV CYG, V432 PER, AND BD+42 2782

P. Zasche[1], M. Wolf[1], R. Uhlař[2], and H. Kučáková[1,3]
[1] Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic
[2] Private Observatory, Pohoří 71, CZ-254 01 Jílové u Prahy, Czech Republic
[3] Johann Palisa Observatory and Planetarium, Technical University Ostrava, CZ-708 33 Ostrava, Czech Republic
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ABSTRACT

The minimum timings of eclipsing binaries V418 Aql, SU Boo, RV CVn, CR Cas, GV Cyg, V432 Per, and BD+42 2782 were collected and analyzed. Their long-term behavior was studied via period analysis, revealing a periodic term in eclipse times. We derived 576 new times of minimum. Hence, to describe the periodic variation, a third-body hypothesis was proposed and the resulting orbital periods are as follows: 70, 7.4, 53, 37, 27, 53, and 18 yr, respectively. For the system V432 Per an additional 9.5 yr variation was also found. The predicted minimum masses of these distant bodies were calculated and their detectability discussed. The light curves of SU Boo and RV CVn were analyzed using the PHOEBE program, resulting in physical parameters of the components. New variable stars in the field of V418 Aql were discovered.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual (V418 Aql, SU Boo, RV CVn, CR Cas, GV Cyg, V432 Per, BD+42 2782)

Online-only material: color figures, machine-readable and VO table

1. INTRODUCTION

After more than a century of intensive study of eclipsing binaries (hereafter EBs), these objects still represent the best method to derive the masses, radii, and luminosities of the stars. Moreover, discovering additional components in these systems is also rather straightforward using the precise times of minimum and analyzing the period variation of the eclipsing pair, a so-called light–time effect (hereafter LITE; Irwin 1959; Mayer 1990).

The period analysis method, despite its classical nature and many decades of usage (about 250 such systems are known nowadays; see, e.g., Zakirov 2010), still provides us with an efficient method of discovering the hidden components in eclipsing systems. Its main advantage is its ease of use because huge data sets of eclipse times exist. The other benefit is that this method is able to reveal the hidden components that are otherwise hardly detectable: the short-periodic ones can be easily detected via spectroscopy, while the long-period ones are visual or interferometric doubles. Hence, the period gap in between can be harvested via period analysis in these systems—it is adequately sensitive to relatively low masses, independent of luminosities of the third bodies, and also only mildly dependent on the orbit orientations (only the body orbiting perpendicular to the EB orbit cannot be detected). Finally, its usefulness with huge photometric databases was also shown (e.g., by Rappaport et al. 2013).

2. METHODS

For a brief reminder of the method of period analysis using the LITE hypothesis,

$$\tau = \frac{A}{\sqrt{1-e^2\cos^2\omega}}\left[\frac{(1-e^2)\cdot\sin(\nu+\omega)}{1+e\cos\nu} + e\sin\omega\right] \quad (1)$$

is the light–time orbit delay as the body moves around a common barycenter (see, e.g., Mayer 1990 for an explanation of the individual parameters). This delay is periodically changing with respect to the current orbital phase, hence the times of minimum for a particular system are being observed earlier and later than predicted from the linear ephemerides. For some of the systems the quadratic term in ephemerides was also used. Hence another parameter of a rate of period change q was introduced. This continuous period change is often attributed to the mass transfer between the close eclipsing components. Mass transfer is slowly moving the barycenter of the double and hence also the period of the pair itself. Using a hypothesis of conservative mass transfer (i.e., no mass loss from the system), the well-known equation introduced, e.g., by Hilditch (2001) can be used to compute the estimated rate of mass transfer:

$$\frac{1}{P}\frac{dP}{dt} = 3\,\frac{M_1 - M_2}{M_1 M_2}\,\frac{dM_1}{dt}, \quad (2)$$

where M_i are the masses of the primary and secondary components, respectively.

There are still many eclipsing systems lacking a detailed period analysis despite the fact that their observations exist in various databases. For example, the automatic photometric projects (like ASAS (Pojmanski 2002), Super WASP (Pollacco et al. 2006), "Pi of the sky" (Burd et al. 2005), NSVS (Woźniak 2004), OMC (Mas-Hesse et al. 2004), and others) monitor the sky continuously, and the data are publicly available. These data points can be used either for deriving the times of minimum, or for the complete light curve (hereafter LC) analysis. For our study we have chosen several rather neglected eclipsing binaries on the northern sky for their availability from our observatories.

3. NEW PHOTOMETRIC OBSERVATIONS

New observations were mostly obtained at Ondřejov Observatory in the Czech Republic, using the 65 cm reflector equipped with the MI G2-3200 CCD camera. The standard R photometric filter was used, while the exposing times were chosen according to the brightness of the target (usually 10–90 s). The only exception was the star BD+42 2782, which is too bright for this telescope, and hence was observed by one of the authors (R.U.)

Table 1
Final Parameters of the LITE Orbits

Parameter	V418 Aql	SU Boo	RV CVn	CR Cas	GV Cyg	BD +42 2782
JD_0	2451276.4853 (106)	2453142.5733 (18)	2444374.6415 (16)	2440529.0619 (96)	2450283.4500 (45)	2444423.3372 (19)
P (days)	2.23490129 (168)	1.56125039 (20)	0.26956736 (3)	2.84019694 (262)	0.99066628 (56)	0.37015161 (9)
p_3 (day)	25548.4 (953.1)	2709.1 (24.8)	19397.8 (852.3)	13553.0 (789.6)	9847.1 (442.9)	6470.60 (67.49)
p_3 (yr)	69.95 (2.61)	7.42 (0.07)	53.1 (2.3)	37.1 (2.2)	27.0 (1.2)	17.7 (0.2)
A (day)	0.0453 (96)	0.0076 (5)	0.0074 (9)	0.0451 (32)	0.0079 (8)	0.0099 (5)
T_0	2430626.6 (760.0)	...	2453523.1 (892.0)	...	...	2490833.6 (133.6)
ω (deg)	27.9 (15.8)	...	131.5 (31.9)	...	...	85.5 (6.8)
e	0.658 (0.305)	0.000 (0.001)	0.413 (0.014)	0.000 (0.001)	0.000 (0.001)	0.546 (0.090)
q (10^{-10} d)	...	1.695 (0.001)	0.024 (0.001)	24.04 (0.01)	0.693 (0.003)	...
$f(m_3)$ ($M_\odot$)	0.184 (56)	0.045 (0.002)	0.001 (0.001)	0.347 (0.015)	0.004 (0.001)	0.016 (0.001)
$M_{3,\min}$ ($M_\odot$)	1.1 (0.3)	0.97 (0.05)	0.17 (0.07)	6.63 (0.89)	0.29 (0.08)	0.51 (0.05)
$\dot{M}$ ($M_\odot$ yr^{-1})	...	1.8×10^{-7}	9.9×10^{-8}	3.2×10^{-6}	9.4×10^{-9}	...

with small 34 mm and 200 mm telescopes at a private observatory in Jílové u Prahy in the Czech Republic. The observations were obtained using the standard R filter, or without any filter.

All of the observations were routinely reduced in a standard way, using dark frames and flat fields. The resulting photometry was used for deriving the times of minimum for a particular system. The standard Kwee–van Woerden procedure (Kwee & van Woerden 1956) was used for the derivation of the times of minimum. Finally, the heliocentric correction was applied to the data points. All of the data points used for the analysis are stored in Table 4 below. All of these times of minimum are heliocentric (HJD). The accuracy of particular minima are also given in the tables, for our newly derived ones as well as for the already published ones (if available).

4. THE INDIVIDUAL SYSTEMS UNDER ANALYSIS

In the present analysis we included only the systems that satisfy all of the following criteria.

1. A northern-sky eclipsing binary in the range of 9–15 mag and an orbital period of up to 3 days.
2. The times-of-minimum data set is sufficiently large for a period analysis.
3. The variation in the $O - C$ diagram shows periodic variation and at least one period of such variation is covered recently.
4. The system was not studied before, or a new solution significantly differs from the published one.
5. At least a few new minimum time observations were obtained by the authors during the last few years.

Using these criteria, seven systems were found to be suitable for the analysis.

4.1. V418 Aql

V418 Aql (=AN 115.1930, $V = 11.6$ mag) was discovered as a variable star by Guthnick & Schneller (1939), who also correctly classified the star as an Algol type. However, since then only a few studies on this star were published, and no detailed photometric or spectroscopic study was performed. The spectral type was classified as F8III (Halbedel 1984), but based on only fair quality spectrograms. Later, Locher (1987b) published his finding on the duration of the total primary eclipse of about 2 hr, which is only a bit longer than that derived from our new observations (1^h43^m). Moreover, the system V418 Aql comprises two components; see the Washington Double Star Catalogue (Mason et al. 2001). The secondary component is about 17″ distant.

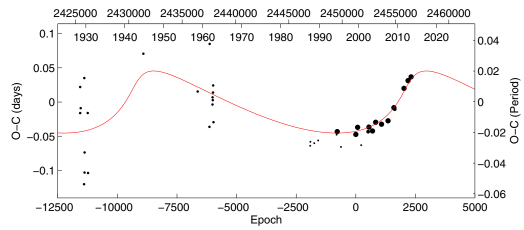

Figure 1. Period analysis of V418 Aql. The individual times of minimum are plotted as dots; the bigger the symbol, the larger the weight, while the continuous curve represents the final fit. See the text for details.

(A color version of this figure is available in the online journal.)

We collected all available times of minimum of V418 Aql; see Table 4. For deriving new times of minimum we also used the publicly available photometry obtained for the ASAS survey (Pojmanski 2002), NSVS survey, and the OMC camera on board the *INTEGRAL* satellite. Two new minima were also observed during the last year by the authors. The data were analyzed applying the LITE hypothesis. See Figure 1 for the final results; the parameters of the LITE orbit are given in Table 1. In this table we present all the fitted parameters from the LITE hypothesis together with their respective errors. However, it is necessary to emphasize that these errors are only formal errors as resulting from the fitting procedure (for the estimation of errors from the covariance matrix, see, e.g., Press et al. 1986). Hence, these mathematical errors can sometimes be two to five times lower than more reliable physical uncertainties of the individual parameters. As one can see, the periodic variation is clearly visible, its period is about 70 yr, and the periastron passage will occur in upcoming years. Hence, new observations would be very welcome.

One can argue that the whole analysis and our solution is based on one crucial point only, the one near the last periastron in 1944. However, this is not true. We tried to perform a similar analysis using only the data after 1950, and using only the quadratic term in ephemerides with no LITE variation. But this approach did not lead to a better result due to the fact that the curvature of the points is not symmetric for a parabola and some of the points significantly deviate.

From the LITE hypothesis, we know that the mass function of the third hidden body is about 0.2 $M_\odot$, hence one can speculate about its nature. Using the easiest assumption about the coplanarity of both orbits (and using the total mass of the

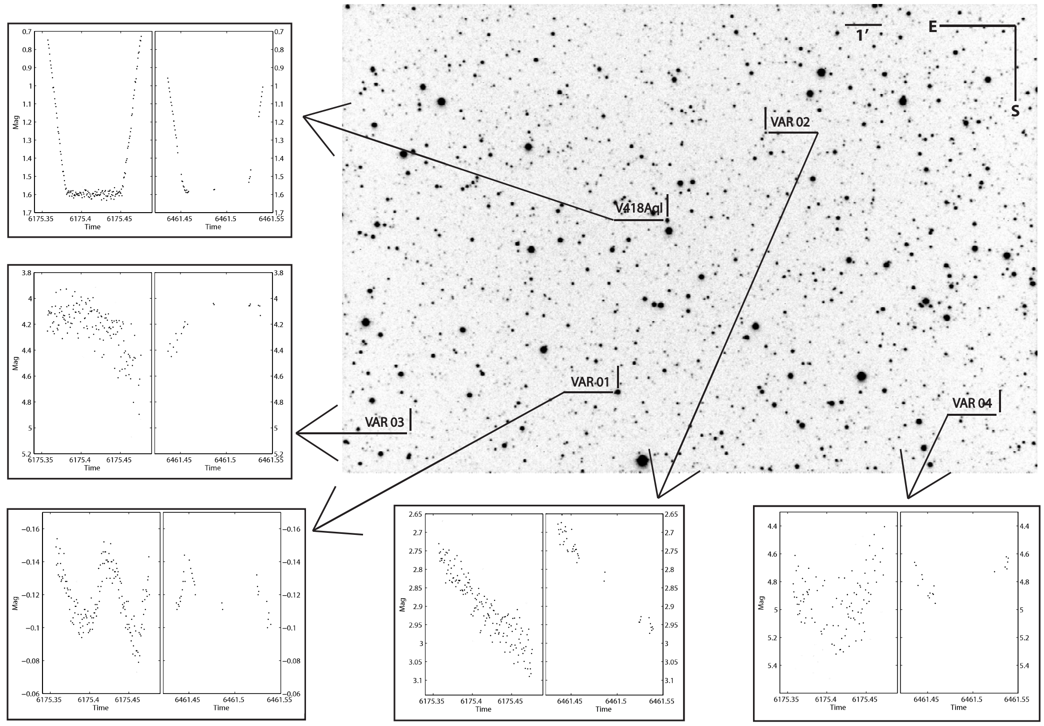

Figure 2. Identification chart for the field of V418 Aql and the surrounding new variables; see the text for details.

eclipsing pair, about 1.6 $M_\odot$), we found a minimal mass of the third body of about 1.1 $M_\odot$. Such a component should be easily detectable in the light curve solution and should also be visible in the spectra of the system. A new detailed analysis is hence needed. Finally, this third component is different than the one observed visually; hence, we are dealing with at least a quadruple stellar system.

One can also ask whether such a picture of the system is self-consistent with the individual luminosities. Using a spectral type of F8III as derived by Halbedel (1984), its absolute bolometric magnitude is about 3 mag brighter than normal main sequence F8 stars (see, e.g., Cox 2000). About the same spectral type was also derived using the photometric indices $(V - K)$ and $(J - H)$ of V418 Aql observed by the Two Micron Sky Survey (2MASS) (Skrutskie et al. 2006). According to our observations, the primary minimum is about 2.36 mag deep, while the secondary about 0.04 mag only. Hence, the primary giant component contributes about 90% of the total luminosity of the system and is the absolutely dominant source. This is also the reason that the observed combined spectral type F8III is mainly the spectral type of the primary component. We tried to find out the individual properties of the three components in the system from our (poorly covered) light curve. We found that the secondary is probably a subgiant with a spectral type of about M1IV. Hence, the total mass of the eclipsing binary is about $1.2 + 0.4 = 1.6\, M_\odot$. From the fitting procedure we also derived that the value of the third light is about 4% of the total light. The light contribution of the third body with a mass of 1.1 $M_\odot$ (i.e., about G5V spectral type) as derived from the LITE analysis is about 3.5%, which is in excellent agreement.

Moreover, during the observations of V418 Aql we discovered several new variable stars in the field. See Figure 2 for the identification chart and position of the new variables near V418 Aql. Our two nights of observations are plotted for each of these stars. The brightest one (designated as VAR 01) is the star GSC 0048604545 (=2MASS 19364467+0352167, R.A. $19^h36^m44\overset{s}{.}70$, decl. $+03°52'16\overset{''}{.}3$). It is a rapidly pulsating star, probably of δ Scuti type. Its variations are about 0.07 mag in the R filter, while the period of pulsations is about 1.5 hr. The second star (VAR 02) is 2MASS 19362870+0359267 (R.A. $19^h36^m28\overset{s}{.}73$, decl. $+03°59'27\overset{''}{.}0$), but its type is unknown, having an amplitude of at least 0.35 mag. The two other new variables (VAR 03 = 2MASS 19370740+0351051, R.A. $19^h37^m07\overset{s}{.}40$, decl. $+03°51'05\overset{''}{.}17$ and VAR 04 = 2MASS 19360258+0351466, R.A. $19^h36^m02\overset{s}{.}58$, decl. $+03°51'46\overset{''}{.}64$) are rather faint, but their variations are still visible in the data; see Figure 2.

4.2. *SU Boo*

Another star in our sample is SU Boo (=AN 78.1914, $V = 11.9$ mag). It was discovered as a variable by Beljawsky (1914), while later Broglia (1960) performed the first analysis of its light curve. It is a classical Algol-type binary with deep primary and shallow secondary minima, its orbital period is about 1.5 days, and its spectral type was derived to be A3V/A4V

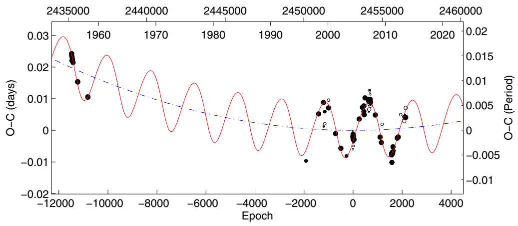

Figure 3. Period analysis of SUBoo. The open circles stand for the secondary, while the filled dots for the primary minima. The blue dash–dotted line represents the quadratic term in ephemerides.

(A color version of this figure is available in the online journal.)

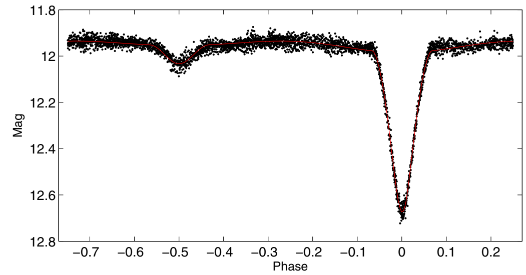

Figure 4. Light curve of SU Boo from the WASP survey and our final fit.

(A color version of this figure is available in the online journal.)

(Hill et al. 1975). The inclination of the system is about 81$^\circ\!\!.$5 according to Broglia (1960); however, Mardirossian et al. (1980) later published the value $i = 86^\circ\!\!.3$. Therefore, such a large discrepancy is noteworthy and a new LC analysis would be useful.

We collected all available times of minimum published since its discovery. These are given in Table 4, including our six new measurements. Most of the data points used for the analysis were derived using the WASP (Pollacco et al. 2006) photometry, the NSVS photometry (Woźniak 2004), and two from the CRTS data (Drake et al. 2009). The resulting $O - C$ diagram is plotted in Figure 3, where the periodic variation is clearly visible, covering several cycles. We used the same approach as for V418 Aql and the LITE hypothesis to analyze the period variations. The parameters of the LITE fit are in Table 1. The period of LITE variation is only about 7.4 yr, which makes this system even more interesting. Moreover, we also detected a slow steady increase in the period of the eclipsing pair (see the blue dash–dotted line in Figure 3), probably caused by a mass transfer between the close components. If we use Equation (2), we can estimate its rate to be about $2 \times 10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, which is quite a realistic value for a conservative mass transfer in an eclipsing binary.

We used the WASP data for the LC analysis. Despite having no spectroscopy and radial velocities (RVs), some of the parameters have to be fixed or only estimated. At first, the ephemerides were fixed according to the period analysis. Secondly, the albedo and gravity darkening values were kept fixed at their suggested values for stars with radiative envelopes (i.e., $A_i = 1$, $g_i = 1$, $i = 1, 2$). The temperature of the primary component was kept fixed at a value of $T_1 = 8450$ K, in agreement with its spectral type (Harmanec 1988). We used the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson–Devinney algorithm (Wilson & Devinney 1971) and its later modifications. For the whole computation process the eccentricity was fixed at zero. The limb-darkening coefficients were automatically interpolated from the van Hamme tables (van Hamme 1993).

During the fitting process, we found why there was such a large discrepancy between the two inclination angles previously published. Starting with equal components ($q = 1$), the inclination results in $i = 81^\circ\!\!.5$, while if we fit the mass ratio, it decreases and hence the inclination increases. We get the smallest possible chi-square value when the value of $q = 0.85$ and the inclination is about $i = 83^\circ\!\!.2$. Moreover, the solution presented by Broglia (1960) is doubtful because of $q > 1$, which is rather improbable. For our final solution see Figure 4 and the parameters of the light curve given in Table 2. As one can see, the primary component dominates the system luminosity and also the mass.

Table 2
The Parameters of the Light Curves of SU Boo and RV CVn as Derived from the Analysis

Parameter	SU Boo		RV CVn	
	Value	Error	Value	Error
T_1 (K)	8450 (fixed)		6100 (fixed)	
T_2 (K)	5090	60	5564	75
i (deg)	83.18	0.14	84.75	0.25
Ω_1	5.075	0.013	3.039	0.013
Ω_2	5.717	0.020	...	...
L_1 (%)	94.5	0.7	50.1	0.5
L_2 (%)	5.5	0.2	49.9	0.5
r_1/a	0.239	0.007	0.482	0.005
r_2/a	0.184	0.006	0.481	0.005
$q = M_2/M_1$	0.852	0.005	0.93	0.03
e	0.00 (fixed)		0.00 (fixed)	
$F_1 = F_2$	1.00 (fixed)		1.00 (fixed)	
$A_1 = A_2$	1.00 (fixed)		0.50 (fixed)	
$g_1 = g_2$	1.00 (fixed)		0.32 (fixed)	

The resulting mass function of the predicted third body (see Table 1) yields a minimal mass of such component of about 1 $M_\odot$ (with the assumption that the orbits are coplanar and the masses of the eclipsing components are 1.95 and 1.66 $M_\odot$). It is noteworthy that no additional third light was detected in the LC solution. Assuming a normal main sequence star, then such a component should contribute about 3% to the total light, which probably should be detectable. More precise observations are needed. However, one can also speculate about an underluminous or even binary nature of the third star. From the estimated luminosities of all components, the photometric distance to the system was derived to be about 1.5 kpc.

4.3. RV CVn

RV CVn (=AN 4.1921, $V = 14.9$ mag) is another seldom investigated eclipsing binary system. It is a W UMa-type star, discovered as a variable by Larink (1921). Its spectral type was derived as F8, according to Schilt (1927). In the latter paper, Schilt stated that the star is of W UMa type, but no reliable LC solution was given. Moreover, there was a discussion about its membership to the cluster NGC 5272 (=M 3), which seems nowadays rather improbable. Another paper by Hoffmann (1981) also presented only the light curves, but no LC solution to the data. Since then, many new observations of times of

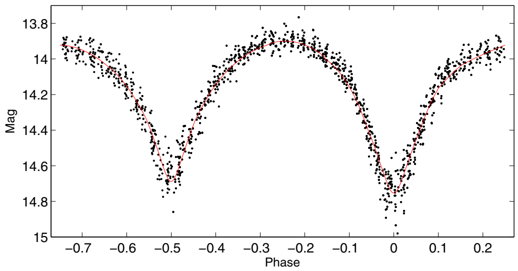

Figure 5. Light curve of RV CVn from the WASP data.
(A color version of this figure is available in the online journal.)

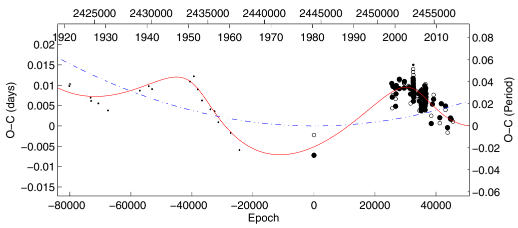

Figure 6. Period analysis of RV CVn.
(A color version of this figure is available in the online journal.)

minimum have been published; however, no reliable LC solution was available until now.

Hence, we collected all the minimum observations for a period analysis as well as the data obtained within the WASP survey project for the LC analysis. For the LC analysis, we used an approach similar to that used for SU Boo: the primary temperature was fixed at a value of 6100 K (i.e., spectral type F8), and a circular orbit. The relevant light curve quantities are given in Table 2. As one can see, both components are similar to each other; the LC fit is plotted in Figure 5. The contact configuration of the system is obvious, as is usual for these types of compact W UMa-type systems.

The set of times of minimum is rather huge nowadays: 153 new minima were derived from the WASP photometry, 6 new ones from the LINEAR data (Sesar et al. 2011), and 10 from the CRTS survey. Eight new observations were obtained by the authors. All of the minima used are given in Table 4. The periodic variation is clearly visible, despite a rather large scatter of the older visual or photographic observations (we believe all published data are trustworthy due to rather deep eclipses, so all of them were used for the analysis). Hence, we followed the same procedure as for the previous systems, and the LITE hypothesis was used. The resulting fit is plotted in Figure 6, while its parameters are written in Table 1. Besides the 52 yr LITE variation we also detected a steady period increase. However, it is rather slow, so the mass transfer between the components is only about $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. Such a value is reliable for a contact binary like RV CVn.

From the resulting mass ratio from the LC analysis ($q = 0.93$), and using the assumption of a main sequence primary component, we can estimate the mass of the secondary. With this mass, using the LITE hypothesis one can also calculate the mass function of the third hidden component, which leads to the minimal mass (i.e., $i_3 = 90°$) of the third body $M_{3,\mathrm{min}} = 0.17\,M_\odot$.

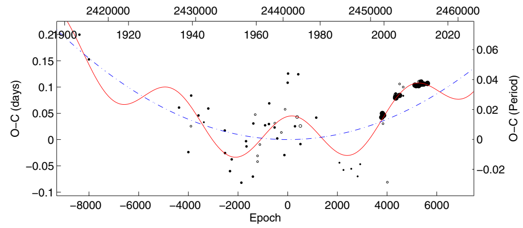

Figure 7. Period analysis of CR Cas.
(A color version of this figure is available in the online journal.)

Therefore, if such a body orbits on a coplanar orbit with the eclipsing pair, then its light contribution to the total luminosity of the binary should be negligible. This is also the result of our LC analysis, where no additional third light was found. Also, the interferometric detection is inapplicable because of its low luminosity.

4.4. CR Cas

The system CR Cas (=AN 450.1934, $V = 11.70$ mag) was discovered to be a variable star by Nielsen (1935). Later (Guthnick & Schneller 1939), it was classified as an Algol type with an orbital period of about 1.42 days, half of the correct value. Its spectral type according to the SIMBAD database is K8, which is definitely wrong. The precise *UBV* photometry outside of eclipse published by Lacy (1992) was used to derive the unreddened index $(B-V)_0 = -0.27$mag. Almost the same value of $(B-V)_0$ was derived using the Strömgren magnitudes by Clement & Fabregat (1998; following the method described in Harmanec & Božić 2001). This $(B-V)_0$ index corresponds to a spectral type of B0.5V–B1V (Popper 1980). Later, Popper (1996) gives a type of B. The most detailed analysis of the star was published by Clement & Fabregat (1998). They obtained the *uvby* photometry and the consequent analysis yielded that the components are probably of B0.5V and B1V spectral types, but located away from the Sun (more than 3.5 kpc, the reddening of the system is $E(b-y) = 0.621$). Moreover, our observations show that the system has total eclipses (lasting about 45 minutes).

We collected all available published times of minimum for the period analysis. Moreover, 14 new minima were derived from the NSVS and OMC photometry, and a few other minima were observed by the authors. All of these data are stored in Table 4. The same period analysis was used as in the previous cases, yielding a set of LITE parameters given in Table 1. As one can see from Figure 7, the periodic variation is clearly visible nowadays, even despite a rather large scatter in the older visual observations. Moreover, we also detected a rather rapid period increase (i.e., fitting also the quadratic term in ephemerides). Clement & Fabregat (1998) speculated about the emission-type secondary component, which probably should be connected with the rapid mass transfer between the components. From our analysis we found about $3 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$, which is the largest mass transfer in our sample. Nevertheless, as noted, e.g., by Hilditch (2001), such a value is still possible on a thermal timescale in binaries. On the other hand, without the detailed spectroscopic analysis, this is still only a hypothesis.

From the third-body fit, we can also derive the mass function ($f(m_3) = 0.347 \pm 0.015\,M_\odot$), from which we find the minimum mass of the third body to be about $6.6\,M_\odot$. Hence, we can

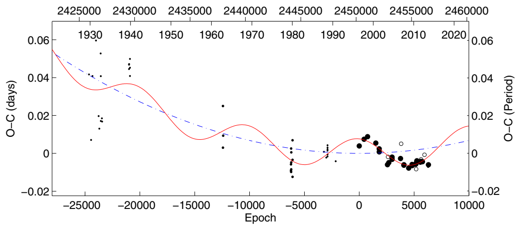

Figure 8. Period analysis of GV Cyg.
(A color version of this figure is available in the online journal.)

speculate about its detectability in the LC solution performed by Clement & Fabregat (1998). The third light fraction resulted in more than 6% of the total light, which should be detectable. However, the authors did not test the presence of additional light in their LC solution. We can also compute the predicted angular separation of the third component assuming the coplanar orbits and using the photometric distance as derived by Clement & Fabregat (1998). This resulted in about $a = 9.4$ mas, which is within the capabilities of modern stellar interferometers; however, its low luminosity makes it probably undetectable with current facilities.

4.5. GV Cyg

The system GV Cyg (=AN 354.1929, $V = 13.2$ mag) is the least studied system in our sample. It is an Algol-type eclipsing binary with an orbital period of about 0.99 day. It was discovered as a variable by Hoffmeister (1930). The first brief analysis and the LC of the system were published by Ahnert et al. (1941), which revealed a rather deep primary eclipse of about 2 mag, and probably a rather shallow secondary. The updated ephemerides were presented by Wood & Forbes (1963), while its spectral type was estimated to be about A5 by Brancewicz & Dworak (1980). However, no detailed LC and RV analyses exist and the papers published during the last two decades only contain new times of minimum observations.

Hence, we collected all available minimum timings, as well as a few of our new observations, for a period analysis. Our complete data set consists of more than 70 observations spanning over 80 yr. All of the data points are stored in Table 4. As one can see from Figure 8, the periodic variation is clearly visible, especially with the more precise observations obtained during the last two decades.

The LITE hypothesis applied to the data points led to the parameters presented in Table 1. The period of the LITE variation is about 27 yr, while the amplitude is about 11 minutes. Using the very rough parameters of the system as published by Budding et al. (2004), we can calculate the predicted minimal mass of the third component. This resulted in about 0.3 $M_\odot$ (hence an M dwarf), which should contribute only a negligible and hardly detectable portion to the total luminosity. Only a detailed spectral analysis would detect such a body in the system via spectral disentangling. The quadratic term in ephemerides shows some indication of a slow mass transfer between the eclipsing components; the smallest in our sample is only about $9 \times 10^{-9}\, M_\odot\, \mathrm{yr}^{-1}$.

4.6. V432 Per

The system V432 Per (=GSC 02856-01647 = TYC 2856-1647-1, $V = 11.2$ mag) is probably the most often studied system in our sample. It is relatively bright, with a short orbital period (about 0.4 day), deep minima (about 0.7 mag), and high declination, which all make it an ideal target for observers from the northern hemisphere. Its first photoelectric light curves in BV filters were published by Agerer (1992); later, Yang & Liu (2002) published the first LC solution of the system, revealing its asymmetric shape (O'Connell effect) and contact W UMa-type configuration. More recently, Lee et al. (2008) published their photometric study of the star, where they presented spectral types for the primary and secondary components of G4 and G8–9. Moreover, they also found a periodic modulation of minimum timings, which led to a period of about 35 yr, which could be caused by a hidden M-type component. Finally, the most recent paper on the star by Odell et al. (2009), which benefits from a few spectral observations, more or less affirms the results published by Lee et al. (2008).

Table 3
Final Parameters of the Two LITE Orbits of V432 Per

Parameter	Value
JD_0	2448601.3757 ± 0.0020
P (days)	0.38330916 ± 0.00000013
p_3 (day)	19125.4 ± 927.5
p_3 (yr)	52.36 ± 2.54
A (day)	0.0324 ± 0.0022
T_0	2439151.2 ± 781.3
ω (deg)	180.9 ± 14.7
e	0.459 ± 0.141
p_4 (day)	3490.0 ± 150.9
p_4 (yr)	9.55 ± 0.41
A_4 (day)	0.0038 ± 0.0015
$T_{0,4}$	2451167.5 ± 182.7
ω_4 (deg)	127.3 ± 10.4
e_4	0.014 ± 0.008
$f(m_3)$ ($M_\odot$)	0.092 ± 0.001
$M_{3,\min}$ ($M_\odot$)	0.81 ± 0.01
$f(m_4)$ ($M_\odot$)	0.003 ± 0.001
$M_{4,\min}$ ($M_\odot$)	0.28 ± 0.01

Since its discovery, about 200 times of minimum have been published. Despite the fact that the set of minima is quite large and several studies on period changes were published, we still believe that its true nature is different than the already published one. The problem with the interpretation of the $O - C$ diagram is that if we collect all available times of minimum and use the LITE hypothesis as presented in published papers, there still remains an unexplainable variation in the residuals. Hence, we believe that one has to use two LITE terms to describe the data in detail.

Therefore, we applied a double LITE hypothesis; hence, twelve parameters were fitted in total. The list of all available data found in the literature is given in Table 4, while our results are written in Table 3. The final fit is presented in Figure 9, where both LITE terms are plotted to the available data points. Despite a rather large scatter of the older visual and photographic minima, the most recent data obtained during the last decade clearly shows the additional variation superimposed on the third-body LITE orbit. However, such an approach is nothing novel: the double periodic LITE hypothesis was used for several eclipsing systems; see, e.g., Borkovits & Hegedüs (1996).

We can only speculate about the nature of these variations. Lee et al. (2008) find that the period modulation is most probably caused by the third body orbiting around the EB pair, and the third light contribution found in the LC solution originates from

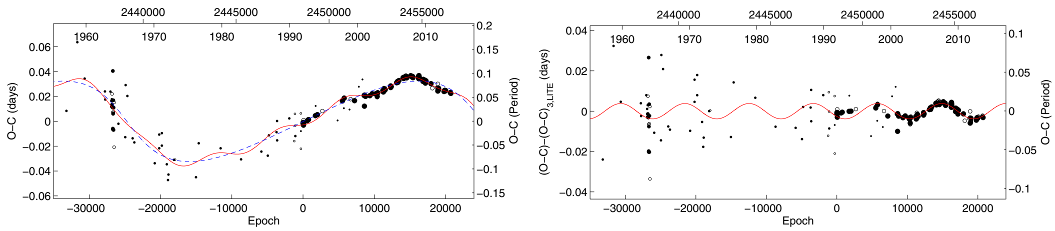

Figure 9. Period analysis of V432 Per. The blue dashed line stands for the third body, while the red solid one is for the final fit of both LITE terms. The right panel shows the analysis after subtraction of the third-body LITE term.

(A color version of this figure is available in the online journal.)

Table 4
The Minimum Times Used for the Analysis

System	HJD-2400000	Error	Filter	Type	Reference
V418 Aql	52503.4095	0.0003	*C*	Prim	Agerer & Hübscher (2003)
V418 Aql	52838.63898	0.00286	*V*	Prim	ASAS—This paper
V418 Aql	53138.12852	0.00159	*V*	Prim	ASAS—This paper
V418 Aql	53685.67644	0.00344	*V*	Prim	ASAS—This paper
V418 Aql	54298.04441	0.00974	*V*	Prim	ASAS—This paper
V418 Aql	54845.61447	0.01468	*V*	Prim	ASAS—This paper
V418 Aql	54930.53848	0.00626	*V*	Prim	OMC—This paper
V418 Aql	55795.4758	0.0035	*I*	Prim	Hübscher & Lehmann (2012)
V418 Aql	56175.42018	0.00006	*R*	Prim	This paper
V418 Aql	56461.49308	0.00022	*R*	Prim	This paper

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

this component. However, in our case the problem is more complicated due to two other components. Their total luminosity has to be lower than the detected l_3 in the LC solution presented by Lee et al. (2008); however, disentangling their individual contributions is impossible. Moreover, using the distance to the system as presented in Lee et al. (2008), we can compute the predicted angular separation of the third and fourth body in the system for a prospective interferometric detection. For the third body we found a separation of about 68 mas, and for the fourth body about 23 mas. The hope of finding these bodies is diminished due to rather low brightness of the system. Hence, spectroscopic detection via disentangling currently seems to be the best method to solve this problem.

4.7. BD +42 2782

BD +42 2782 (=TYC 3080-1410-1, $V = 9.5$ mag) is the brightest star in our sample, and also the system studied in the most detailed analysis. It was discovered as a variable by Sokolovsky & Antipin (2005). A detailed LC and RV analysis of the star was performed by Lu et al. (2007). They derived that the system is in contact, its curve is of W UMa-type, and it has a cool spot on the primary component, which is surprisingly underluminous. Its spectrum is probably about F5 and its distance was derived to be about 124 pc. Moreover, there is also a visual component about 3.″5 distant, which contributes about 6.5% to the total light of the system.

Despite having a huge set of photometric observations from the WASP survey covering the whole LC, we decided not to perform the LC analysis due to a more detailed LC+RV analysis published by Lu et al. (2007) based on precise observations obtained in two filters. However, the WASP data were used for the minimum time derivation, and hence the collection of minima (see Table 4) is rather large. Moreover, we also derived new minima from the discovery paper by Sokolovsky & Antipin (2005), from *Tycho* (Perryman et al. 1997), from NSVS, and from our recent observations. However, we find two major problems. At first the amplitude of photometric variations is about 0.25 mag, while the precision of individual photometric observations published by Sokolovsky & Antipin (2005) is 0.01 mag. We find a similar problem with the data sampling (it is the sparse photometry; two subsequent data points are separated by more than 24 minutes, which is about 1/20 of the orbital period). All of these make the scatter of the older observations rather large.

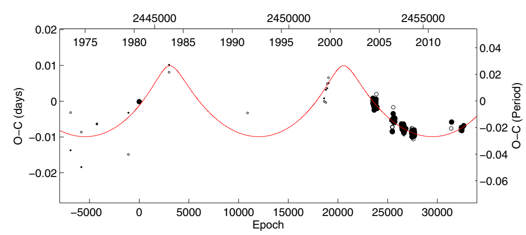

Figure 10. Period analysis of BD +42 2782.

(A color version of this figure is available in the online journal.)

As one can see from Figure 10, the periodic variation is currently pretty well covered. Applying the LITE hypothesis to the data, we get the parameters given in Table 1. There are only two cycles covered by the observations; however, the variation is evident, mainly during the last two decades. One can ask how reliable the fit presented in Figure 10 is, but the lack of other observations prevents us from doing more analysis. The period of LITE was derived relatively well, but the amplitude should be a bit different because of poor coverage near both periastron passages.

From the LITE hypothesis we find that the predicted minimal mass of the third body should be about 0.5 $M_\odot$, which should be detectable in the LC solution. However, dealing with the visual component and also this predicted third one, we cannot disentangle the third light into the contributions from the individual components. Hence, we also deal with a quadruple system. Using the distance to the system as derived by Lu et al. (2007), we can also estimate the predicted angular separation of the third component from the eclipsing pair. This value resulted in about $a = 78 \pm 10$ mas, which should be easily detectable with current stellar interferometers. However, there arises a problem with its luminosity. It should be more than 3 mag fainter than the eclipsing pair (which itself is rather faint for interferometry), so its detection is right on the limit of current technique.

5. CONCLUSION

We performed a period analysis of times of minimum for seven rather seldom investigated eclipsing systems, where a third component orbiting around the EB pair was suggested as a realistic hypothesis. For some of these systems, the periods are adequately short for the third body to be discovered via spectroscopic monitoring during several seasons. For others, the third light contribution to the total light in the LC solution was discussed as a more promising technique of detection. We also discussed the possibility of interferometric detection of the additional components, but this was mostly ruled out due to their low luminosities. Moreover, for the prediction of angular separation of the third components, the distance of the systems from the Sun is needed, which is still unavailable for some of the systems.

The most interesting system in our sample is probably CR Cas, being the most distant and also the most massive system in our sample. Moreover, besides a proposed third body orbiting around the EB pair with period of about 37 yr, we derived a rather rapid mass transfer between the eclipsing components. Hence, the system might be in an interesting evolutionary stage. Another noteworthy system is also SU Boo, having the shortest third body period in our sample, only about 7.4 yr, and also significant mass transfer.

One can also ask whether such periodic variation is presented in a specific kind of EB, or if it is a quite common phenomenon. Most of the early-type stars are multiples (e.g., Chini et al. 2012), hence the LITE should also be detected for many of them. Usually, there is a problem with an insufficient data set for such an analysis. On the other hand, there are many EBs observed for decades, where no period variation was detected. Such systems are, e.g., AA And, AE Cyg, ER Vul, and many others. For a catalog of available $O - C$ diagrams of EBs, see Paschke & Brát (2006) or Kreiner et al. (2001).

The benefit of such period analyses for the stellar multiplicity studies in general is undisputed. There exist a few hundred LITE systems, and their period variation is still being monitored. Hence, on longer timescales one can still hope to find some dynamical effects due to third bodies. All of our systems are certainly stable (from the ratio of periods), but generally the orbits of both inner and outer bodies are not stable and are subject to long-term precession, which can be studied in the future.

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TEN *KEPLER* ECLIPSING BINARIES CONTAINING THE THIRD COMPONENTS

P. Zasche[1], M. Wolf[1], H. Kučáková[1], J. Vraštil[1], J. Juryšek[1,2], M. Mašek[2], and M. Jelínek[3]
[1] Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, CZ-180 00 Praha 8, V Holešovičkách 2, Czech Republic
[2] Institute of Physics of the Czech Academy of Sciences, CZ-182 21 Praha 8, Na Slovance 1999/2, Czech Republic
[3] Instituto de Astrofísica de Andalucía, P.O. Box 03004, E-18080 Granada, Spain
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ABSTRACT

Analyzing the available photometry from the *Kepler* satellite and other databases, we performed detailed light curve modeling of 10 eclipsing binary systems that were found to exhibit a periodic modulation of their orbital periods. All of the selected systems are detached Algol type, with orbital periods from 0.9 to 2.9 days. In total, 9448 times of minimum for these binaries were analyzed in an attempt to identify the period variations caused by the third bodies in these systems. The well-known method of the light-travel time effect was used for the analysis. The orbital periods of the outer bodies were found to be between 1 and 14 years. This hypothesis makes such systems interesting for future prospective detections of these components, despite their low predicted masses. Considering the dynamical interaction between the orbits, the system KIC 3440230 seems to be the most interesting, in which one would expect the detection of some effects (i.e., changing the inclination) even after a few years or decades of observations.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual (KIC 2305372, KIC 3440230, KIC 5513861, KIC 5621294, KIC 7630658, KIC 8553788, KIC 9007918, KIC 9402652, KIC 10581918, KIC 10686876)

Supporting material: machine-readable and VO table

1. INTRODUCTION

Eclipsing binaries (EBs) provide us with an excellent method for deriving the basic physical properties of the two eclipsing components (their radii, masses, and temperatures). Moreover, they can also serve as independent distance indicators: one can study the dynamical evolution of the orbits, test the stellar structure models, or discover additional components in these systems (see e.g., Guinan & Engle 2006). On the other hand, the *Kepler* satellite (Borucki et al. 2010) provides us with unprecedented accuracy of photometric data. From this huge set of observations, 1879 EBs were detected after the first data release (Prša et al. 2011), which was later extended to 2165 (Slawson et al. 2011).

Such a huge database of EBs observed with superb precision and monitored continuously over a period of four years encouraged several teams to look for a periodic modulation of data, indicative of triple systems. The use of such a method and its limitations are described elsewhere (e.g., Irwin 1959, or Mayer 1990). For example, Gies et al. (2012) presented 41 suspected triples, while Conroy et al. (2014) listed 236 potential triples. More will be published in the future by J. A. Orosz (see Conroy et al. 2014). Moreover, Rappaport et al. (2013) presented 39 dynamically interesting systems, where the third-body periods are short enough (if compared with the binary period) that some interaction between the orbits is expected or even observed (e.g., changing of the inclination). On the other hand, most of the triples listed in Conroy et al. (2014) have periods of the order of hundreds or even thousands of days, so long periods were usually only estimated (due to limited coverage of the *Kepler* data) or were influenced by large errors.

For this reason we decided to perform a similar analysis to detect third-body signals for other systems, but based on a larger data set if available. For some of the systems we tried to observe additional ground-based observations. These were done quite recently, so even a single point can help us to better constrain the third-body period. Finally, we also tried to find photometry from other sources, like the survey data from SuperWASP (Pollacco et al. 2006), NSVS (Woźniak et al. 2004), ASAS (Pojmanski 2002), and others. These (mostly rather scattered) points help us to prove the long-term stability of the orbital period of the close pair or its evolution (e.g., the quadratic ephemeris).

2. SELECTION PROCESS FOR THE BINARIES

All the studied systems were chosen according to their remarkable variations in the $O-C$ diagrams. Such systems naturally complete a set of triple systems as presented by Gies et al. (2012) and Conroy et al. (2014). However, these two published studies only presented binaries in which the third-body variations are visible in the *Kepler* data set, and those with longer periodic modulation were omitted or only briefly mentioned. This is the main impact of this paper. We decided to include in our study those systems where the orbital periods of the third bodies are longer, and we also harvested for such an analysis the ground-based surveys and our new photometric data. Obviously, this also leads to the conclusion that the multiplicity fraction should be even higher than that from the previous studies because a non-negligible number of triples have a third-body orbital period of the order of years, decades, or even longer.

For the systems under our analysis we have chosen only those systems that fulfill the following criteria. All of them are Algol-type detached binaries with circular orbits. This information was taken from visual inspection of the *Kepler* EB catalog.[4] All have remarkable curvatures in their $O-C$ diagrams, which was considered on the basis of the Gies et al. (2012) and Conroy et al. (2014) minimum times plotted in the

[4] http://keplerebs.villanova.edu/

$O-C$ diagrams in the $O-C$ gateway[5] (Paschke & Brát 2006). None of these systems was studied before concerning the third-body orbits (not counting a brief remark in Gies et al. 2012 with no orbital solution). For each of them some additional photometry also exists (older or more recent) besides the *Kepler* data. At this point it is worth mentioning that two of the analyzed systems (KIC 7630658 and KIC 9007918) were not included in the previous work on *Kepler* triples detected using eclipse timings by Gies et al. (2012). Therefore, we have to emphasize that due to these rather limited selection mechanisms our study does not aim to present a complete sample for any statistical analysis of *Kepler* EBs. As a by-product some systems were found to exhibit no visible variation or yielded rather spurious results; see below.

3. PHOTOMETRY AND LIGHT CURVE (LC) MODELING

The analysis of the LCs based on *Kepler* photometry was carried out using the program PHOEBE (Prša & Zwitter 2005) for all of the systems. This program is based on the Wilson–Devinney algorithm (Wilson & Devinney 1971) and its later modifications. However, some of the parameters have to be fixed during the fitting process. The limb-darkening coefficients were interpolated from van Hamme's tables (van Hamme 1993). The albedo coefficients A_i, the gravity-darkening coefficients g_i, and the synchronicity parameters F_i were also computed during the fitting process due to the high quality of the photometry. The same applies for the value of the third light, which was also considered to be a free parameter and has been fitted (in agreement with our third-body hypothesis). The temperature of the primary component was kept fixed according to the T_1 value as given in the *Kepler* catalog[6] (Brown et al. 2011), while only the secondary temperature was fitted. In our final solution we only present a ratio of the temperatures T_2/T_1 for higher robustness due to (sometimes) problematic values of the T_1 from the *Kepler* catalog. An issue with the mass ratio was solved by fixing $q = 1$ because no spectroscopy for these selected systems exists, and for detached EBs the LC solution is almost insensitive to the photometric mass ratio (see, e.g., Terrell & Wilson 2005).

The quality of the LC fit is even noticeable by the naked eye; see Figure 1. The automatic routines as used, e.g., by Slawson et al. (2011) are definitely better for reducing huge data sets of hundreds of binaries; however, the codes sometimes produce spurious results. If we analyze this particular system in more detail, we are able to get a better fit to the data, lower residuals, and hence also parameters with lower errors. The automatic pipelines may not even compute parameters like albedos, gravity brightening, and third light. All of these parameters can also be fitted with the *Kepler* data and help us to obtain a better fit to the data.

However, it is necessary to admit that some of the parameters can correlate with each other during the fitting process (this especially applies for luminosity and temperature, inclination and the third light for partially eclipsing systems, etc.). This problem was avoided by checking whether or not there is a value in the correlation matrix higher than 0.8, and if so, such a fit was not accepted. Another iteration with a different parameter set was used, and all systems were analyzed this way, yielding the results presented below.

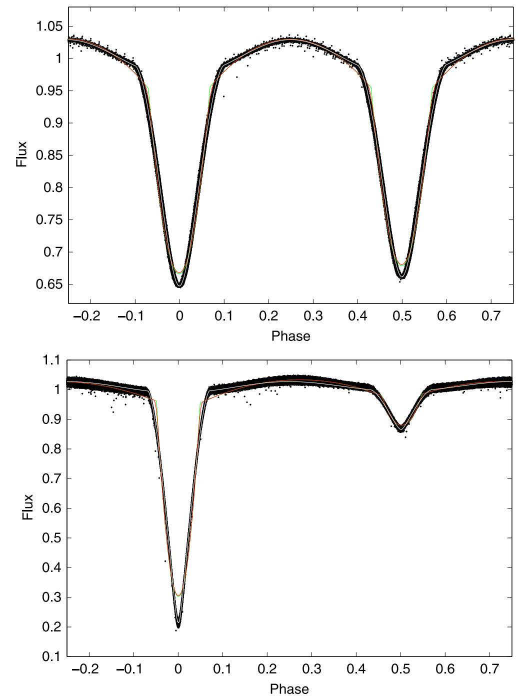

Figure 1. Illustrative example of the light curves of KIC 09402652 (upper plot) and KIC 10581918 (lower plot) together with their respective fits from Slawson et al. (2011) plotted in red and green, and our new fit plotted in white.

4. THE TIMES OF MINIMUM LIGHT

CCD follow-up observations of selected *Kepler* targets were mostly carried out at the Ondřejov Observatory in the Czech Republic (labeled as OND in the tables with minimum times), and a few new observations were also obtained remotely with the BOOTES-1A and BOOTES-2[7] telescopes located in Spain (labeled as BOO-1 and BOO-2 in the tables with minimum times). The new times of primary and secondary minima and their respective errors were determined using the classical Kwee & van Woerden (1956) method or our new approach (see below). All the times of minima used for the analysis are given in the appendix Table 5.

For the analysis of minimum times and variation of the orbital period caused by the third body, one needs the minimum times to be as precise as possible. For some of the *Kepler* targets, the times of minima exist and were even published several times; see, e.g., Gies et al. (2012) or Conroy et al. (2014). However, their published times of minima differ significantly—sometimes more than their respective errors. One possible explanation is that the abovementioned teams included or did not include the error in the barycentric times of

5 http://var.astro.cz/ocgate/
6 http://archive.stsci.edu/kepler/data_search/search.php
7 http://bootes.iaa.es/

the *Kepler* data, which was first mentioned in *Kepler* Data Release 19.[8]

For this reason, we have proceeded in the following way. First, the times of minima published by Gies et al. (2012) were taken and plotted in the $O - C$ diagram. The same was done with the data by Conroy et al. (2014), and the $O - C$ diagrams were analyzed to check whether some periodic modulation due to the third body was present. Then, the original data from the *Kepler* archive were downloaded and analyzed. Such an analysis was done in several steps. First, from the original raw `fits` files the photometry was extracted, the flux converted into magnitudes, and the individual LCs in different quarters of data were analyzed and the theoretical LCs were constructed. Let us call this Method 1. In Method 2 we used the data downloaded from the EB catalog[9] by Slawson et al. (2011), which were already detrended and the normalized flux versus BJD was provided. These LCs were analyzed and used to construct the theoretical LC (but from the whole *Kepler* mission).

The theoretical LCs were used to derive the times of minima following the AFP method as described in Zasche et al. (2014). Using the LC templates from Method 1 and 2 and also the times of minima from Gies et al. (2012) and Conroy et al. (2014), we have four different sets of times of minima for the analysis (the disadvantage of the Gies et al. 2012 data is the fact that only a portion of the *Kepler* data was provided: those obtained after reducing only the first 9 quarters). These four data sets sometimes differed significantly and the best one (with the lowest scatter) was used for the subsequent analysis of a particular system. Usually, the best one was the data set obtained using Method 2.

However, it is natural that some of the limitations of the method play a role. The most critical issue is the fact that for deriving the times of minima we always use the same LC template. However, in some cases the shape of the LC varies during the *Kepler* mission and the difference is sometimes visible even by the naked eye (see comments below for particular systems). This problem can be avoided using the different LC templates for data obtained during the different time epochs. However, it is questionable whether using five or a hundred different LC templates for the whole *Kepler* data set would provide a better result. Hence, we solved this problem using a slightly different template for each *Kepler* quarter.

If we compare both minimum derivation methods, we find some aspects of the problem. The classical Kwee & van Woerden (1956) method was used only for recent observations due to the fact that only small parts of the minima were observed and the whole LC cannot be fitted. On the other hand, the AFP method can provide us with a much more precise result even with a lower number of observations, but one needs the complete LC template, and hence the complete observed LC. Generally, the individual errors from the AFP method are a bit lower (but not 10 times lower) than the classical errors from the Kwee & van Woerden (1956) method and are not affected by any observational biases, incorrect reductions, poor conditions, etc. as can be true for the ground-based ones.

[8] https://archive.stsci.edu/kepler/release_notes/release_notes19/DataRelease_19_20130204.pdf
[9] http://keplerebs.villanova.edu/

5. THE PERIOD CHANGES

For the analysis of period changes in these binaries, we used a well-known method introduced by Irwin (1959). It resulted in a set of parameters of the third-body orbit: the period of the third body P_3, eccentricity e, semi-amplitude of the variation A, time of periastron passage T_0, and longitude of periastron ω. The input values for the analysis were the ephemerides (HJD_0, P) given by Slawson et al. (2011), and these ephemerides were also recomputed. If necessary, the quadratic term of the ephemerides was also used (attributed to the mass transfer between the components). The solutions presented below were found using Monte Carlo simulations and the simplex algorithm. However, the individual errors of the parameters are taken from the code and may be too optimistic for some of the systems.

All the new precise CCD times of minima from the *Kepler* satellite were used with a weight of 10 in our computation; some of the less precise measurements were weighted by a factor of five, while the poorly covered minima were given a weight of 1. This applies mostly for the minimum times derived from other sources of photometry (like ASAS, SuperWASP, etc.), which were derived using the same method as the *Kepler* ones, but using a different LC template. The weights were used instead of the uncertainties due to the fact that for the older published minima any information about their accuracy is missing.

Because we only studied the period changes due to the third-body orbit and all of the systems are circular, for most of the systems only the deeper (primary) minimum was used to detect the period changes.

6. INDIVIDUAL SYSTEMS

In the following section we present the results of our analysis for all of the systems. The whole procedure is described in detail for the first binary, and the others are only briefly discussed due to the similarity of the analysis to the first one. Table 1 summarizes basic information about the stars, their cross-identification, magnitudes, and photometric indices. As one can see from the $(J - H)$ index, most of the stars are of F and G spectral type.

6.1. KIC 2305372

The first system in our sample is the star KIC 2305372, which was first recognized as a variable by the Hatnet (Hartman et al. 2004) and ASAS (Pigulski et al. 2009) surveys in the pre-*Kepler* era. After that, it was included in the catalog of EBs in the *Kepler* field (Slawson et al. 2011). The times of minima were published by Gies et al. (2012) and later by Conroy et al. (2014). However, Gies et al. (2012) presented the system as a candidate triple, while Conroy et al. (2014) roughly estimated a period of about 3700 days. No spectral analysis was carried out, and hence we can only estimate that it is probably a system of G spectral type (from the $J - H$ photometric index).

The LC analysis was carried out from the *Kepler* detrended data, and its parameters are given in Table 2. As one can see, both components are rather different, and no third light was detected during the LC solution. The final LC fit is presented in Figure 2, where the shape of the LC is clearly seen to be a classical Algol shape. However, the LC shape seems to be slightly asymmetric (see the outside-eclipse curvature). This LC template was also used to derive the times of minima (using

Table 1
Relevant Information for the Analyzed Systems

System	Other ID	R.A.	Decl.	KEP_{max} [a]	$(J-H)$(mag) [b]	$(B-V)$(mag) [c]	Sp. Type [c]
KIC 2305372	2MASS J19275768+3740219	$19^h27^m57^s.7$	$+37°40'21''.9$	$13^m.82$	0.364	⋯	⋯
KIC 3440230	2MASS J19215310+3831428	$19^h21^m53^s.1$	$+38°31'42''.8$	$13^m.64$	0.317	⋯	⋯
KIC 5513861	TYC 3123–2012-1	$18^h57^m24^s.5$	$+40°42'52''.9$	$11^m.64$	0.238	0.448	wF8V
KIC 5621294	2MASS J19285262+4053359	$19^h28^m52^s.6$	$+40°53'36''.0$	$13^m.61$	0.143	⋯	⋯
KIC 7630658	2MASS J19513965+4315224	$19^h51^m39^s.6$	$+43°15'22''.3$	$13^m.89$	0.389	⋯	⋯
KIC 8553788	2MASS J19174291+4438290	$19^h17^m42^s.9$	$+44°38'29''.1$	$12^m.69$	0.120	0.537	A7V
KIC 9007918	TYC 3541–2296-1	$19^h04^m02^s.0$	$+45°21'21''.7$	$11^m.66$	0.135	0.155	F5IV
KIC 9402652	V2281 Cyg	$19^h25^m06^s.9$	$+45°56'03''.1$	$11^m.82$	0.154	0.470	F8V
KIC 10581918	WX Dra	$18^h52^m10^s.5$	$+47°48'16''.7$	$12^m.80$	0.186	⋯	⋯
KIC 10686876	TYC 3562–961-1	$19^h56^m13^s.6$	$+47°54'33''.7$	$11^m.73$	(−0.041)	0.204	F0V

Notes.
[a] *Kepler* database.
[b] 2MASS catalog; Skrutskie et al. (2006).
[c] Based on the Tycho catalog; Pickles & Depagne (2010).

Table 2
Light Curve Parameters for the Analyzed Systems as Resulting from PHOEBE

System	$T_2/T1$	i (deg)	Ω_1	Ω_2	L_1 (%)	L_2 (%)	L_3 (%)
KIC 2305372	0.6637 (0.0152)	79.92 (0.27)	5.431 (0.035)	4.134 (0.059)	82.70 (0.90)	17.30 (0.80)	0
KIC 3440230	0.6082 (0.0085)	81.63 (0.82)	6.278 (0.692)	5.114 (0.192)	87.02 (0.83)	12.98 (0.47)	0
KIC 5513861	0.9891 (0.0115)	79.37 (0.08)	5.393 (0.012)	5.773 (0.024)	55.10 (0.23)	43.97 (0.27)	0.94 (0.55)
KIC 5621294	0.5620 (0.0096)	72.32 (0.73)	4.182 (0.084)	4.255 (0.106)	82.85 (0.35)	8.86 (3.02)	11.29 (0.99)
KIC 7630658	0.9635 (0.0004)	79.76 (0.02)	7.660 (0.005)	7.646 (0.007)	51.66 (0.02)	43.26 (0.02)	5.07 (0.02)
KIC 8553788	0.6385 (0.0022)	69.72 (0.22)	5.351 (0.025)	5.106 (0.057)	80.15 (0.71)	13.27 (0.15)	6.56 (0.60)
KIC 9007918	0.6289 (0.0008)	72.83 (0.05)	5.479 (0.006)	5.781 (0.016)	79.06 (0.05)	6.36 (0.02)	14.58 (0.05)
KIC 9402652	0.9956 (0.0033)	79.61 (0.07)	4.386 (0.007)	4.357 (0.004)	50.01 (1.68)	49.99 (1.44)	0
KIC 10581918	0.6813 (0.0126)	88.53 (0.42)	5.595 (0.058)	5.751 (0.050)	86.68 (0.67)	13.32 (0.50)	0
KIC 10686876	0.6532 (0.0048)	88.35 (0.06)	6.976 (0.030)	16.290 (0.123)	92.32 (3.41)	2.76 (0.11)	4.92 (3.08)

the method as described above). For the period analysis we collected the Hatnet, ASAS, SuperWASP, and *Kepler* data points and derived more than 800 times of primary minima for this star. One new minimum was also observed by the authors at Ondřejov Observatory in the Czech Republic.

This data set was analyzed and the method of Irwin (1959) was used. The results are given in Table 3 and the final fit is also plotted in Figure 3. In these plots only the new post-*Kepler* data and the isolated measurements (groups of up to three data points) are plotted with their respective error bars for clarity. Plotting the error bars for all the data would diminish the readability of the graphs (however, for some observations their respective error bars are too small and are plotted almost inside the individual dots). We are aware of the fact that only a few poor-quality points define the shape of the third-body variation and its period P_3 in the $O-C$ diagram. However, the parabolic fit is not able to describe the data in such detail. From the parameters of the third body one is also able to compute the mass function of the third body in the system, which is also given in Table 3. As one can see, its value is rather high, so the third component should also be detected in the LC solution as a third light contribution. However, no such value was detected during the LC fitting. This still remains an open question; however, we also have to mention that the shape of the LC varies over time and the LC fit in different quarters of the data differs a bit. This can also influence our result and the minimum precision, LC modeling, and third light detection. Regrettably, with no information about the masses of the eclipsing components, one cannot easily set a tighter limit to the mass of the predicted third body.

6.2. KIC 3440230

KIC 3440230 was discovered by Slawson et al. (2011), and later Gies et al. (2012) included the star in the group of tertiary candidates. However, there was also a remark about the flux variation and possible pulsations (Gies et al. 2012). This is the star with the longest orbital period in our sample.

The same method as for the previous star was used. We were not able to fit the outside-eclipse curvature of the *Kepler* LC (due to asymmetry of the LC), but the primary minimum was fitted pretty well. Therefore, the LC template was used to derive the minimum times used for a subsequent period analysis. Besides the *Kepler* data, a few SuperWASP minima were also derived. However, these were not used in the analysis due to their large scatter. The long-term period decrease is also visible in the *Kepler* data with no need to spread the time interval with these scattered data points. From the third-body orbit fitting there resulted a very small mass function value

$$f(m_3) = \frac{(m_3 \sin i)^3}{(m_1 + m_2 + m_3)^2} = \frac{1}{P_3^2} \cdot \left[\frac{173.15 \cdot A}{\sqrt{1 - e^2 \cos^2 \omega}} \right]^3,$$

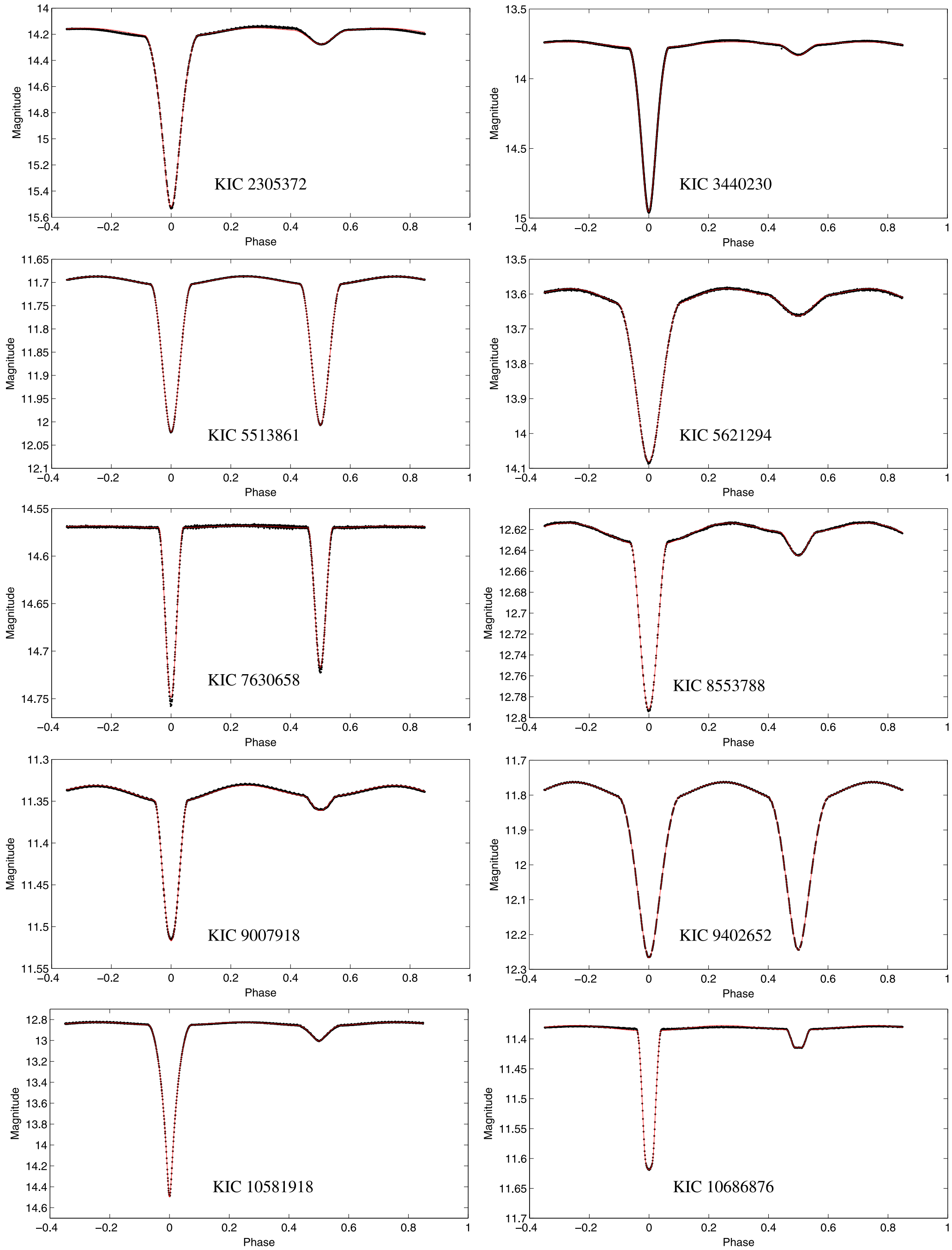

Figure 2. *Kepler* light curves of all studied systems. The red curves show the final fit, and the dots show the observations.

Table 3
The Parameters of the Third-body Orbits for the Individual Systems

System	HJD_0 (2450000+)	P (days)	A (days)	ω (deg)	P_3 (year)	T_0 [HJD] (2400000+)	e	$f(m_3)$ ($M_\odot$)	P_3^2/P (year)
KIC 2305372	4965.9539 (8)	1.4047173 (15)	0.0211 (13)	86.9 (4.7)	10.36 (0.16)	54532 (62)	0.625 (66)	0.4543 (18)	27919
KIC 3440230	5687.5150 (3)	2.8811052 (38)	0.00060 (25)	111.3 (17.5)	1.04 (0.13)	55818 (32)	0.264 (98)	0.0010 (1)	137
KIC 5513861	4955.0004 (9)	1.5102096 (10)	0.00831 (73)	27.2 (7.4)	5.94 (0.18)	56347 (139)	0.135 (89)	0.0861 (39)	8540
KIC 5621294	4954.5109 (2)	0.9389102 (3)	0.00024 (5)	133.9 (11.7)	2.70 (0.10)	56124 (28)	0.654 (175)	0.000014 (2)	2843
KIC 7630658	5003.2780 (2)	2.1511554 (4)	0.00393 (3)	145.9 (1.1)	2.53 (0.01)	67358 (17)	0.680 (10)	0.0875 (33)	1085
KIC 8553788	4954.9856 (13)	1.6061776 (17)	0.00802 (114)	237.3 (8.6)	9.09 (0.08)	56430 (59)	0.764 (93)	0.0429 (50)	18787
KIC 9007918	4954.7485 (2)	1.3872066 (2)	0.00048 (4)	94.6 (9.2)	1.30 (0.08)	56721 (14)	0.662 (170)	0.00034 (4)	445
KIC 9402652	4954.2856 (2)	1.0731067 (2)	0.00427 (17)	266.9 (4.9)	4.08 (0.05)	56343 (11)	0.757 (37)	0.0242 (10)	5670
KIC 10581918	2829.3696 (3)	1.8018668 (34)	0.00209 (58)	0.1 (8.3)	14.05 (0.47)	53244 (530)	0.254 (88)	0.00027 (9)	40023
KIC 10686876	4953.9490 (45)	2.6184137 (50)	0.00563 (189)	280.5 (28.4)	6.72 (0.96)	56990 (442)	0.464 (157)	0.0207 (19)	6302

which is mostly caused by the small amplitude of the variation. The potential third body would probably be a late-type dwarf star.

On the other hand, what makes this system the most interesting is the fact that the period P_3 is rather short, and hence one can hope to detect some dynamical interaction between the orbits (see, e.g., Söderhjelm 1975; Rappaport et al. 2013). The nodal period can be computed from the equation

$$P_{\rm nodal} = \frac{4}{3}\left(1 + \frac{m_1 + m_2}{m_3}\right) \times \frac{P_3^2}{P}\left(1 - e_3^2\right)^{3/2}\left(\frac{C}{G_2}\cos j\right)^{-1},$$

where the subscripts 1 and 2 stand for the EB components and 3 stands for the third distant body, the term G_2 stands for the angular momentum of the wide orbit, C is the total angular momentum of the system, and j stands for the mutual inclination of the orbits. For this system the ratio of periods P_3^2/P resulted in a surprisingly low value of only about 137 years. Hence, one can hope to detect some changes in the binary orbit even after a few years of observations. The most promising is the inclination change, because it is rather easily detectable. Due to its deep eclipses a change in the inclination angle should also be detected in ground-based data of modest quality. However, the amplitude of any such change is also strongly dependent upon a third-body mass and the orientation of its orbit. For the derivation of these quantities, precise interferometry or spectroscopy would be very useful. However, one cannot hope to obtain these observations easily for a 14 mag star.

6.3. KIC 5513861

The star KIC 5513861 (also TYC 3123-2012-1) was first mentioned as a variable by Pigulski et al. (2009) from the ASAS data. Later, Gies et al. (2012) reported its curvature in the $O - C$ diagram, which was probably caused by a third body. Also mentioned were the pulsations and rapid flux variability. Conroy et al. (2014) published preliminary results from the *Kepler* data estimating that the third body should have a period of ≈1800 days. This is the first system in our sample of stars, which was included in the work by Pickles & Depagne (2010), who used Tycho photometry for estimating the spectral type of the star; see Table 1.

The same approach was used for the analysis: the LC was fitted and the final plot was then used as a template to derive the precise times of minima. The final $O - C$ diagram is plotted in Figure 3, where some minima as derived from the ASAS (Pojmanski 2002) and SuperWASP (Pollacco et al. 2006) surveys were also included together with our three new observations (one from Ondřejov Observatory in the Czech Republic, two from the BOOTES-1A and BOOTES-2 telescopes in Spain). All of the data clearly define the third-body variation with a period of about 6 years and yield a moderate value of the mass function. However, the fraction of the third light is rather lower than anticipated from the third-body mass function. With the available data we are not able to find the problem, and the nature of the third body still remains an open question.

6.4. KIC 5621294

The system KIC 5621294 was discovered from the *Kepler* data (Slawson et al. 2011). Later, the times of minima were published by Gies et al. (2012), who also included a remark about a possible parabolic trend in the $O - C$ diagram, starspots, and pulsations.

The LC was fitted and analyzed, resulting in the largest difference between the primary and secondary temperatures of the eclipsing components in our sample of stars. From the LC parameters in Table 2 one can see a non-negligible value of the third light and only a very weak contribution of the secondary component to the total light. On the other hand, the times of minima as derived from the *Kepler* data show a significant period decrease (described via parabolic ephemerides); see Figure 3. Moreover, superposed over the parabola, a small periodic variation is also visible, with period of about 2.7 years and the lowest amplitude in our sample (only about 21 s); see Figure 4. This small amplitude also yielded a small value of the predicted third light value, and hence a third light contribution as detected during the LC solution should probably be attributed to another body in the system or a close visual component. However, it is still rather premature to speculate that we are dealing with a real quadruple system. Such a low amplitude of the variation in the $O - C$ diagram could also serve as a test example of what can be discovered from the *Kepler* data using these classical techniques with EBs: assuming component masses $M_1 = M_2 = 1\,M_\odot$, then the

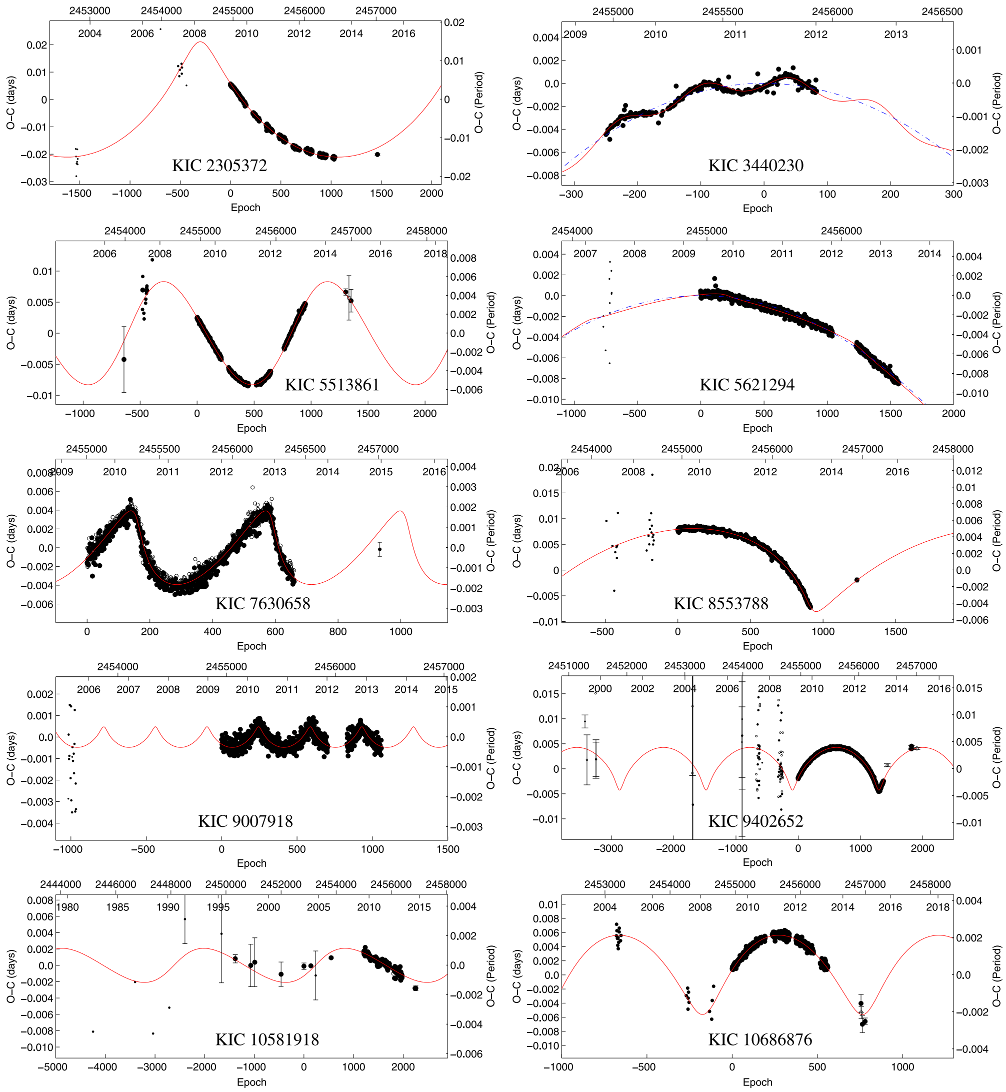

Figure 3. $O-C$ diagrams of all studied systems. The red curves present the final fit, the blue dash–dotted curves the quadratic ephemerides. The dots stand for the primary minima and open circles for the secondary minima, and the bigger the symbol, the higher the weight in our computation (the oldest visual observations are plotted as small dots and their respective errors were even not published, but we estimate their precision to be up to 5–15 minutes).

minimum third-body mass (i.e., assuming $i = 90°$) resulted in $M_{3,\min} = 0.039\ M_\odot$, a typical brown dwarf mass.

6.5. *KIC 7630658*

The system KIC 7630658 was discovered by Slawson et al. (2011) from the *Kepler* data. No other analysis was carried out and our knowledge about the system is very limited. It is the faintest star in our sample.

The shape of the LC as obtained by the *Kepler* satellite clearly shows two well-defined minima, and hence the derivation of the times of minima was rather straightforward. The final parameters are given in Table 2, where one can see that both components are similar to each other and only a small fraction of the third light was detected. Variation with a period of about 2.5 years is clearly visible in the data; however, our last observation slightly deviates from the prediction. This can be caused by long-term modulation of the orbital period

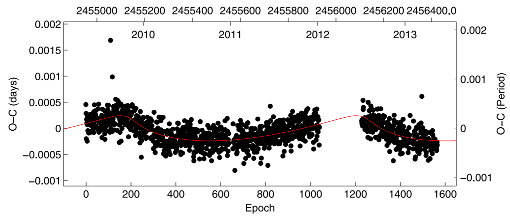

Figure 4. $O - C$ diagram of the *Kepler* minimum times of the system KIC 5621294 after subtraction of the quadratic ephemerides.

(quadratic ephemerides), but this has to be tested in upcoming years with new observations.

6.6. KIC 8553788

The star KIC 8553788 was first mentioned as an EB by Pigulski et al. (2009). Later, only the results from the *Kepler* data analysis were published: Slawson et al. (2011), Prša et al. (2011), and Gies et al. (2012). The latter paper gives some information about possible pulsations, starspots, and a possible third body. This system seems to be of the earliest spectral type in our sample of stars (see Table 1).

Our analysis using the *Kepler* data yielded an LC solution showing that the primary is the dominant object in the system, and hence only the primary minima were used for the $O - C$ diagram analysis. The nine-year variation is clearly visible in the plot despite the fact that the orbital period is still determined only by the last observation from the Ondřejov Observatory. The older observations from the ASAS and SuperWASP surveys only slightly follow the predicted fit, but have quite a large scatter. Our fit of the minimum times yielded a rather high value of eccentricity; however, the minimal third-body mass as resulted from the mass function is somewhat lower than the masses of the eclipsing components. Its light contribution hence should probably be higher than resulted from our LC fit.

6.7. KIC 9007918

The star KIC 9007918 (also TYC 3541-2296-1) was first detected as a variable by Devor et al. (2008) on the basis of the TRES survey data. Later, the star was included in the catalog of *Kepler* EBs (Slawson et al. 2011; Prša et al. 2011).

Some variations were detected in the LC during the *Kepler* mission, and the whole LC is not perfectly symmetric. This can also play a role in the precision of the derived times of minima from the LC template. As one can also see from the LC, the secondary minimum is very shallow, and hence we used only the primary ones to analyze the period changes in this binary. Together with the old (and rather scattered) photometry from the TRES survey we were able to detect periodic variations with a period of about 1.3 years and an amplitude of only about 41 s. The other interesting issue is the value of the period for a possible dynamical interaction between the orbits of $P_3^2/P \sim 445$ years. Hence, we can hope to find some changes after several decades of observations.

6.8. KIC 9402652

The star KIC 9402652 (also V2281 Cyg) was already discovered as a variable in the pre-*Kepler* era and a few observations of the minima of this star were published. It was mentioned in the list of stars observed by the ROTSE survey (Diethelm 2001), Pigulski et al. (2009) later included the star in their ASAS observations of the *Kepler* fields, and the times of minima were published by Gies et al. (2012) and Conroy et al. (2014).

As one can see, the system consists of two almost identical stars with practically the same temperatures and luminosities. For this reason, both minima are also very similar, and hence both the primary and secondary were used for the period analysis. We also collected the older published minima together with the photometry from the NSVS, SuperWASP, and ASAS surveys. Thanks to the large data set of available times of minimum observations, this system seems to be the richest one in our sample of stars (and with the data coverage ranging over more than 15 years). The $O - C$ diagram together with our new observations clearly show a four-year variation, but with rather high eccentricity.

6.9. KIC 10581918

The system KIC 10581918 (also WX Dra) was discovered to be a variable as early as 1960 by Tsesevich (1960). Since then a few observations of the minima were published, but no LC nor spectroscopic analysis of the system. Due to a very deep primary eclipse of this star (1.67 mag), the older visual and photographic observations can also be reliable in the analysis of the period changes. The very first preliminary results were recently published in conference proceedings (Wolf et al. 2015).

As one can see from the results of our analysis, the period of the third body is of about 14 years (the longest one in our sample) and is now well covered, but its amplitude is only poorly defined with our data. New minimum time observations in the upcoming years can help us to better derive the amplitude of variations. However, the predicted mass function of the third body resulted in a rather low value, and hence a non-detection of the third light in the LC solution is also something to be expected.

6.10. KIC 10686876

The EB KIC 10686876 was first mentioned by Devor et al. (2008) based on the TRES survey data. Later, the star was included in the *Kepler* EB database, Prša et al. (2011), and Slawson et al. (2011). Gies et al. (2012) published the minimum times for the system, but no other information or analysis was obtained or performed.

The star seems to be the only system in our sample that shows a total eclipse. For this reason the error of the inclination from the LC fit is already very small. On the other hand, the secondary component is probably a very small star and the primary is the dominant one. As one can also see, the primary eclipses are rather deep and provide us with much better times of minima than the secondaries. Hence, analyzing the available minima from *Kepler*, TRES, SuperWASP, and our new data (two from Ondřejov and two from the BOOTES-1A and BOOTES-2 telescopes in Spain), we obtained a set of third-body parameters given in Table 3 and the final fit presented in Figure 3. The variation with a period of about 6.7 years is now clearly visible in the current data set, and the shape of the $O–C$ variation should easily be confirmed and the parameters improved by a few new observations obtained during the upcoming years.

Table 4
Other Analyzed Systems

System	Other ID	Remark
KIC 04245897	V583 Lyr	some variation with period about 50 years found, but based only on older photographic data
KIC 06187893	TYC 3128-1653-1	quadratic ephemerides or third body with long period, not very convincing, new data needed
KIC 06852488	2MASS J19135355+4222482	some variation detected, but period still uncertain, more data needed
KIC 07258889	2MASS J18510630+4248400	some variation found, but showing rather non-periodic modulation
KIC 07938468	V481 Lyr	quadratic ephemerides based also on older photographic data
KIC 08552540	V2277 Cyg	no variation found
KIC 09101279	V1580 Cyg	some variation found, but not very convincing, older data too scattered
KIC 09602595	V0995 Cyg	variation with period 13.3 years found, but the data before 1970 are in contradiction
KIC 09899416	BR Cyg	no variation found
KIC 10736223	V2290 Cyg	quadratic ephemerides only, based on older visual data
KIC 11913071	V2365 Cyg	no variation found
KIC 12071006	V379 Cyg	some variation detected only on the *Kepler* data, older measurements too scattered

Table 5
List of the Minimum Timings Used in the Analysis

Star	BJD—2400000	Error (day)	Type	Filter[a]	Source / Observatory
KIC 2305372	52802.67112	0.08710	Prim	I	Hatnet
KIC 2305372	52806.88251	0.07516	Prim	I	Hatnet
KIC 2305372	52809.68474	0.02068	Prim	I	Hatnet
KIC 2305372	52813.90357	0.06025	Prim	I	Hatnet
KIC 2305372	52816.71288	0.02019	Prim	I	Hatnet
KIC 2305372	52820.92775	0.03789	Prim	I	Hatnet
KIC 2305372	52823.74173	0.04552	Prim	I	Hatnet
KIC 2305372	52827.95039	0.03124	Prim	I	Hatnet
KIC 2305372	52830.76181	0.10454	Prim	I	Hatnet
KIC 2305372	53986.89162	0.00559	Prim	I	ASAS
KIC 2305372	54349.28814	0.00479	Prim	I	ASAS
KIC 2305372	54232.70365	0.04672	Prim	W	SuperWASP

Notes.
[a] W and K stand for the special filters used for SuperWASP and *Kepler*.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)

7. DISCUSSION AND CONCLUSIONS

Ten selected binaries were found to be worth studying due to the presence of the distant components, which cause a periodic modulation of their eclipsing periods. The periods of the third bodies (from 1 to 14 years) are usually adequately covered by the *Kepler* and ground-based data, so the variation is certain nowadays. However, its origin is still questionable in several cases. This especially applies to systems where the predicted mass function of the third body and the non/detected third light from the LC solution contradict each other. However, this could be caused by the following reasons: (1) an imperfect LC fit (for those binaries with slightly asymmetric LCs), (2) not very well-defined third-body variation in the *O–C* diagram (especially in those cases where the variation is mostly determined by the older scattered ground-based data), (3) the variation in the *O–C* diagram being incorrectly described (i.e., missing a quadratic term or a fourth-body variation), (4) an exotic object as the distant body (or also as a binary, hence having a much lower luminosity), or (5) some other phenomena modulating the period variation in the *O–C* diagram (such as magnetic or other activity of the components). As a by-product of our analysis, we found a few more systems where the *O–C* variation was not found, or is still questionable. These are summarized in Table 4. Regrettably, this sample is still too limited to do a reliable statistical analysis of the incompleteness of triple systems found in the *Kepler* data.

At this point it would be useful to mention that when using Method 1 as introduced in Section 3, some of the systems also have short-cadence data in the *Kepler* photometric database. Using the short-cadence data produces a much more precise minimum derivation (these minimum times are labeled as "*Kepler* SC" in Table 5), but can also reveal some other phenomena that are not detectable in the long-cadence data. This happened for KIC 8553788 and KIC 10686876, for which short time variation was detected in the short-cadence data (probably δ Sct pulsations) that was not visible in the long-cadence data. However, such additional variation also influences the LC fitting and its precision.

One also has to consider the limitations of the method used for the analysis. The LC fit is a crucial issue because it is used to derive the minimum times for a subsequent analysis. However, the LC fits can also be a problematic issue because we are dealing with pure photometry with no information about the individual masses of the components. Hence, fixing the mass ratio value to $q = 1$ is in fact only the first rough simplification. Therefore, with no information about the individual masses, the mass function of the third body provides only very preliminary information about such objects. For this reason and because of the unknown distance, the angular separation of the third component cannot be computed for a prospective interferometric detection. However, it should probably be hard to detect such bodies due to the relative faintness of most of the stars using this technique.

To conclude, only dedicated high-dispersion, high signal-to-noise ratio spectroscopic observations and a subsequent analysis can tell us something more about these objects and reveal their true nature. Moreover, new photometric observations in the upcoming years would be of great benefit, especially in systems where the period variation is still not very certain and for the dynamically interesting systems like KIC 3440230.

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APPENDIX
TABLES OF MINIMA

Table 5 presents the times of minimum light for all of the analyzed systems.

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Apsidal motion and absolute parameters for five LMC eccentric eclipsing binaries⋆,⋆⋆

P. Zasche and M. Wolf

Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz

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ABSTRACT

Aims. As part of our observational projects at the La Silla Danish 1.54-meter telescope, we aim to measure the precise times of minimum light for eccentric eclipsing binaries in the Large Magellanic Cloud, needed for accurate determination of apsidal motion. Many new times of minima were derived from the photometric databases OGLE and MACHO. Several new minima were also observed. Five early-type and eccentric-orbit eclipsing binaries: HV 982 ($P = 5\overset{d}{.}34$, $e = 0.15$), HV 2274 ($5\overset{d}{.}73, 0.17$), MACHO 78.6097.13 ($3\overset{d}{.}11, 0.05$), MACHO 81.8881.47 ($3\overset{d}{.}88, 0.22$), and MACHO 79.5377.76 ($2\overset{d}{.}64, 0.06$) were studied.

Methods. The O–C diagrams of the systems were analysed using all reliable timings found in the literature, and new or improved elements of apsidal motion were obtained. Light and radial velocity curves of MACHO 81.8881.47 and MACHO 79.5377.76 were analysed using the program PHOEBE.

Results. We derived for the first time or significantly improved the relatively short periods of apsidal motion of 211 (12), 127 (8), 48 (13), 103 (20), and 42 (19) years, respectively. The internal structure constants, log k_2, were found to be –2.37, –2.47, –2.17, –2.02, and –1.86 respectively, under the assumption that the component stars rotate pseudosynchronously. The relativistic effects are weak, up to 6% of the total apsidal motion rate. The masses for MACHO 81.8881.47 resulted in 5.51 (0.21) and 5.40 (0.19) $M_{\odot}$, while for MACHO 79.5377.76 the masses are 11.26 (0.35) and 11.27 (0.35) $M_{\odot}$, respectively.

Key words. binaries: eclipsing – stars: early-type – stars: general – stars: fundamental parameters – Magellanic Clouds

1. Introduction

Eccentric eclipsing binaries (EEB) with an apsidal motion can provide us with an important observational test of theoretical models of stellar structure and evolution. A long-term collecting the times of minima of EEBs observed throughout the apsidal motion cycle and consecutive detailed analysis of the period variations of EEB can be performed, yielding both the orbital eccentricity and the period of rotation of the apsidal line with high accuracy (Giménez 1994). Many different sets of stellar evolution models have been published in recent years, e.g. Maeder (1999), Claret (2004), or Claret (2006); however, to distinguish between them and to test which one is more suitable is still rather difficult. The internal structure constants as derived from the apsidal motion analysis could serve as one independent criterion. On the other hand, to discriminate between the models only stellar parameters for EEBs with an accuracy of 1% can be used.

The Magellanic Clouds are of prime importance in the context of stellar evolution theory. However, the chemical composition of the Magellanic Clouds differs from that of the solar neighborhood (e.g. Ribas 2004) and the study of these massive and metal-deficient stars in the LMC checks our evolutionary models for these abundances. All eclipsing binaries analysed here have properties that make them important astrophysical laboratories for studying the structure and evolution of massive stars (Ribas 2004).

Here we analyse the observational data and rates of apsidal motion for five LMC detached eclipsing systems. All these systems are early-type objects known to have eccentric orbits and to exhibit apsidal motion. Similar studies of LMC EEBs have been presented by Michalska & Pigulski (2005, hereafter MP05) and Michalska (2007).

2. Observations of minimum light

The monitoring of faint EEBs in external galaxies requires only moderate telescopes in the 1–2 m class range equipped with a modern CCD camera. However, a large amount of observing time is needed, which is unavailable at larger telescopes. During past observational seasons, we accumulated over 1600 photometric observations at selected phases during primary and secondary eclipses and derived 16 precise times of minimum light for selected eccentric systems. New CCD photometry was obtained at the La Silla Observatory in Chile, where the 1.54 m Danish telescope (hereafter DK154) with the CCD camera and *RI* filters was used.

All CCD measurements were dark-subtracted and then flat-fielded using sky exposures taken at either dusk or dawn. Several comparison stars were chosen in the same frame as the variables. A synthetic aperture photometry and astrometry software developed by Velen and Pravec called A   , was routinely used for data obtained. No correction for differential extinction was

⋆ Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 68.A-0223(A), and on data collected with the Danish 1.54 m telescope at the ESO La Silla Observatory.

⋆⋆ Appendices are available in electronic form at http://www.aanda.org

Table 1. Apsidal motion elements for HV 982, HV 2274, MACHO 78.6097.13, MACHO 81.8881.47, and MACHO 79.5377.76.

Element [Unit]	HV 982	HV 2274	MACHO 78.6097.13	MACHO 81.8881.47	MACHO 79.5377.76
T_0 [HJD]	2 449 340.5146 (195)	2 448 099.8540(9)	2 452 424.6888 (78)	2 452 282.2431 (178)	2 452 262.6776 (67)
P_s [days]	5.3352210 (97)	5.7259971 (8)	3.1070278 (104)	3.8818717 (32)	2.6365767 (79)
P_a [days]	5.3355902 (97)	5.7267045 (8)	3.1075678 (104)	3.8822732 (33)	2.6370342 (79)
e	0.149 (0.033)	0.1252 (39)	0.0459 (139)	0.217 (23)	0.0574 (160)
$\dot{\omega}$ [deg cycle^{-1}]	0.0249 (0.0014)	0.0445 (29)	0.0633 (264)	0.03723 (606)	0.0625 (194)
$\dot{\omega}$ [deg yr^{-1}]	1.705 (0.095)	2.84 (0.20)	7.44 (3.1)	3.50 (0.57)	8.65 (2.68)
ω_0 [deg]	221.2 (0.7)	71.9 (2.9)	27.9 (4.0)	95.9 (8.6)	31.57 (4.20)
U [yr]	211 (12)	126.9 (7.9)	48.4 (12.5)	102.8 (20.0)	41.6 (18.8)

applied because of the proximity of the comparison stars to the variable and the resulting negligible differences in air mass and their similar spectral types.

The new times of primary and secondary minima and their errors were determined by the classical Kwee-van Woerden (1956) algorithm. All new times of minima are given in Table A.1, where epochs are calculated from the ephemeris given in Table 1; the other columns are self-evident.

3. Photometry

For all of the systems we harvested the M (Faccioli et al. 2007) and O (Graczyk et al. 2011) photometry available online. These photometric data were used both for minima times analysis as well as for light curve analysis.

The analysis of the light curves for two of the systems was carried out using the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson-Devinney algorithm (Wilson & Devinney 1971) and its later modifications, but some of the parameters had to be fixed during the fitting process. The albedo coefficient remained fixed at value 1.0 and the gravity darkening coefficients $g = 1.0$. The limb darkening coefficients were interpolated from the van Hamme tables (van Hamme 1993). A problem emerged with the synchronicity parameters (F_i) due to poor coverage of the RV data near the eclipses and low quality of the light curves used for the LC analysis, hence we fixed these values at $F_i = 0$. The temperature of the primary component was derived from the $V - I$ photometric index, from MP05 and from the resulting masses derived from the combined LC+RV analysis.

4. Spectroscopy

The spectroscopic data for two of the systems (MACHO 81.8881.47, MACHO 79.5377.76) were found in the ESO Archive of the UV-Visual Echelle Spectrograph (UVES) at the Very Large Telescope (VLT). The spectra were obtained during the ESO Period 68 program "*Precise distances to the LMC and SMC from double-lined eclipsing binaries*"; the PI of the project was A. Clausen. Typical exposure times were about 1500 seconds, while the spectra typically have a signal-to-noise ratio (S/N) of about 50. The original data were reduced using the standard ESO routines. The final radial velocities (hereafter RV) used for the analysis were derived via a manual cross-correlation technique (i.e. the direct and flipped profile of spectral lines manually shifted on the computer screen to achieve the best match) using program SPEFO (Horn et al. 1996; Škoda 1996) on several absorbtion lines in the measured spectral region (usually H_β to H_ϑ). The derived radial velocities are given in Table B.1. We estimate the error of individual data points to be about 5 km s^{-1}.

5. An approach for the analysis

For the analysis we used the approach presented below. For the systems where the inclination of the orbit is known, the first two steps can be skipped.

- First, all of the available photometric data were analysed, resulting in a set of minima times. Preliminary apsidal motion parameters were derived (with the assumption $i = 90°$).
- Second, the eccentricity (e), argument of periastron (ω), and apsidal motion rate ($\dot{\omega}$) derived from the apsidal motion analysis were used for the preliminary light curve (hereafter LC) analysis.
- Third, the inclination (i) from the LC analysis was used for the final apsidal motion analysis.
- And finally, the resulting e, ω, and $\dot{\omega}$ values from the apsidal motion analysis were used for the final LC + RV analysis.

6. Apsidal motion analysis

The apsidal motion in all eccentric systems was studied by means of an O–C diagram analysis. All available times of minima, both published in the literature and newly measured, were analysed using the method presented by Giménez & García-Pelayo (1983). This is a weighted least-squares iterative procedure, including terms in the eccentricity up to the fifth order. There are five independent variables ($T_0, P_s, e, \dot{\omega}, \omega_0$) determined in this procedure. The periastron position ω is given by the linear equation

$$\omega = \omega_0 + \dot{\omega}\, E$$

where $\dot{\omega}$ is the rate of periastron advance, and the position of periastron for the zero epoch T_0 is denoted as ω_0. The relation between the sidereal and the anomalistic period, P_s and P_a, is given by

$$P_s = P_a\,(1 - \dot{\omega}/360°),$$

and the period of apsidal motion by

$$U = 360° P_a/\dot{\omega}.$$

All new precise CCD times of minima were used with a weight of 10 or 20 in our computation. Some of our less precise measurements were weighted by a factor of 5, while the earlier visual and photographic times (esp. the times of the mid-exposure of a photographic plate) were given a weight of one or nought because of the large scatter in these data.

7. Analysis of the systems

7.1. HV 982

The detached eclipsing binary HV 982 (also known as MACHO 82.8043.26, LMV110; $V_{\rm max} = 14^{\rm m}.65$; Sp. B5V) is a relatively well-known LMC binary with an eccentric orbit ($e = 0.15$) and a moderate orbital period of 5.3 days. It was discovered to be a variable star by Gaposhkin (1970), who published the first photographic light curve.

Pritchard et al. (1994, 1998) in their photometric study derived high surface temperatures (∼28 000 K) and masses (∼8 $M_\odot$) of components. They also derived the apsidal motion period $U = 205 \pm 7$ years. The precise stellar parameters of components of HV 982 were derived spectroscopically by Fitzpatrick et al. (2002), who found components with similar mass and size,

$$M_1 = 11.28 \pm 0.46\, M_\odot,\ M_2 = 11.61 \pm 0.47\, M_\odot,$$
$$R_1 = 7.15 \pm 0.12\, R_\odot,\ R_2 = 7.92 \pm 0.13\, R_\odot.$$

The following linear light elements were given in that paper:

Pri. Min. = HJD 2 449 $340^{\rm d}.7172 + 5^{\rm d}.33522 \times$ E.

Using the complete analyses of HV 982 they also found the distance to the center of the LMC $d_{\rm LMC} = 50.7 \pm 1.2$ kpc. Later, Clausen et al. (2003) presented a new accurate CCD *uvby* light curve obtained at the Danish 1.54 m telescope at La Silla and derived the precise photometric elements with apsidal motion period $U = 208 \pm 15$ years.

All CCD times of minimum light given in Pritchard et al. (1998) and Clausen et al. (2003) were incorporated into our analysis. Using M (Faccioli et al. 2007) and O (Graczyk et al. 2011) photometry, we were able to derive additional times of minimum light. A total of 68 times of minimum light were used in our analysis (see Table A.1). The orbital inclination adopted was $i = 89^\circ.3$, based on the analysis of Fitzpatrick et al. (2002). The computed apsidal motion parameters and their internal errors of the least-squares fit are given in Table 1. In this table, $P_{\rm s}$ denotes the sidereal period, $P_{\rm a}$ the anomalistic period, e represents the eccentricity, and $\dot\omega$ is the rate of periastron advance (in degrees per cycle and in degrees per year). The zero epoch is given by T_0, and the corresponding position of the periastron is represented by ω_0. The O–C residuals for all times of minimum with respect to the linear part of the apsidal motion equation (Min = $T_0 + P \times E$) are shown in Fig. 1. The non-linear predictions, corresponding to the fitted parameters, are plotted for primary and secondary eclipses.

7.2. HV 2274

The detached and double-lined eclipsing binary HV 2274 (also known as MACHO 19.3577.7, 2MASS J05024076-6824212, LMV 182, FL 3556; $V_{\rm max} = 14^{\rm m}.13$; Sp. B1-2 IV-III) is a relatively bright and well-studied LMC eclipsing binary with an eccentric orbit ($e = 0.17$) and a moderate orbital period of 5.7 days. It was discovered to be a variable star by Leavitt (1908). Later, Shapley & Nail (1953) recognized its eclipsing nature and classified it as a β Lyrae type. The eccentric orbit and apsidal motion of HV 2274 was first announced by Watson et al. (1992), who obtained the $BVI_{\rm c}$ CCD photometry at the Mount John University Observatory. See also the history of HV 2274 in the last paper mentioned. Later Claret (1996) found the masses and evolutionary status of this system:

Pri. Min. = HJD 2 448 $099^{\rm d}.818 + 5^{\rm d}.726006 \times$ E.

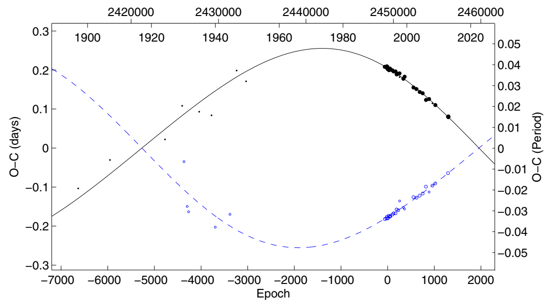

Fig. 1. O–C diagram for the times of minima of HV 982. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by dots and open circles, respectively. Larger symbols correspond to the photoelectric or CCD measurements that were given higher weights in the calculations.

The fundamental properties of HV 2274 were most recently given in Ribas et al. (2000) who determined the precise absolute parameters of both eclipsing components to be

$$M_1 = 12.2 \pm 0.7\, M_\odot,\ M_2 = 11.4 \pm 0.7\, M_\odot,$$
$$R_1 = 9.86 \pm 0.24\, R_\odot,\ R_2 = 9.03 \pm 0.24\, R_\odot.$$

They also derived the improved apsidal motion period $U = 123 \pm 3$ years and the value of internal structure constant log $k_{2,\rm obs} = -2.56$. Since the above-mentioned papers were published, new times of minima have been obtained, which allowed us to reduce the uncertainties in the derived parameters. We collected all times of minimum light given in the literature together with new ones derived from M , O , and our new photometry obtained in Chile. All of these values are listed in Table A.1. In total, 58 precise times of minimum light were used in our analysis, including 29 secondary eclipses. The orbital inclination adopted was $i = 89^\circ.6$, based on the analysis of Ribas et al. (2000).

Analysing the available data using the apsidal motion hypothesis, we found an additional variation superimposed on the apsidal motion. Hence, we used a different code computing the apsidal motion parameters together with the third-body orbit (a so-called light travel time effect), see e.g. Irwin (1959). Altogether, ten parameters were fitted (five from apsidal motion, five from the third body hypothesis), thus this approach led to an acceptable solution. The resulting parameters of the fit are given in Tables 1 and 2, the complete O–C diagrams are shown in Figs. 2 and 3. From the third-body parameters we were also able to compute the mass function of the distant component, which resulted in $f(m_3) = 0.053 \pm 0.008\, M_\odot$. From this value, we calculated the predicted minimal mass of the third body (i.e. assuming coplanar orbits $i_3 = 90^\circ$), which resulted in $m_{3,\rm min} = 3.4\, M_\odot$. If we propose this body in the system, one can ask whether it is detectable somehow in the already-obtained data. The period is rather long for continuous monitoring of the radial velocity changes, but detecting the third light in the light curve solution is difficult. Assuming a normal main sequence star, its luminosity is about only 1% of the total system luminosity. Such a weak third light could be detectable only in extremely precise photometric data for the light curve solution.

Table 2. Third-body orbit parameters for HV 2274.

Element [Unit]	Value
p_3 [yr]	98.2 ± 14.3
A_3 [day]	0.045 ± 0.009
T_3 [HJD]	2 456 205 ± 5033
e_3	0.654 ± 0.047
ω_3 [deg]	251.1 ± 7.1

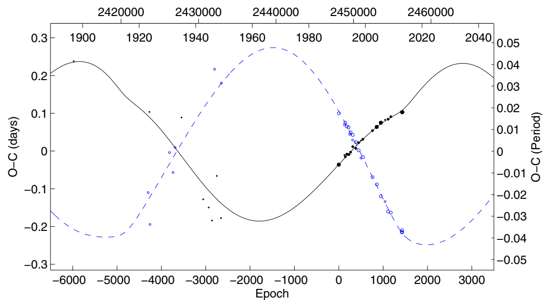

Fig. 2. O–C diagram for the times of minima of HV 2274. See legend to Fig. 1. The final fit is composed from two effects: the apsidal motion together with the third-body hypothesis.

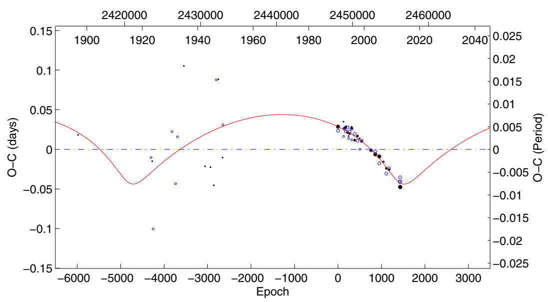

Fig. 3. O–C residuals for HV 2274 after subtraction of the apsidal motion term. Only the third body effect is plotted.

7.3. MACHO 78.6097.13

The detached eclipsing binary MACHO 78.6097.13 (also known as OGLE J051804.81-694818.9, LMC MP#5; $V_{\rm max}$ = $14^{\rm m}.37$, sp O9V+O9V) is an eccentric binary system (e = 0.046) with a short orbital period (P = 3.1 d) discovered by MP05 in the O field LMC-SC7.

Our analysis gives the following ephemeris:

Pri. Min. = HJD 2 452 424$^{\rm d}$.6888 + 3$^{\rm d}$.1070278 × E.

The most detailed analysis of the system was published by González et al. (2005), which was based on the ESO spectral observations together with the MACHO data. They also derived the masses and radii of both components that were used in the present analysis. Both components are of O9 spectral types, which makes this system the earliest in our sample.

Our new times of minimum light, as well as the timings derived from M and O photometry are given in Table A.1. All of these data (31 minima times) were used in our calculations. Using the parameters presented by González et al. (2005), we analysed the system on apsidal motion, deriving the parameters given in Table 1. As one can see, this system has the lowest eccentricity in our sample and the apsidal advance is rather fast: almost one half of the period has been covered with observations so far.

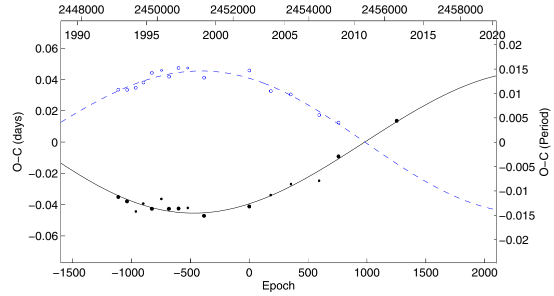

Fig. 4. O–C graph for the times of minimum of MACHO 78.6097.13. See legend to Fig. 1.

7.4. MACHO 81.8881.47

The detached eclipsing binary MACHO 81.8881.47 (also known as OGLE J053517.75-694318.7, LMC MP#7; $V_{\rm max}$ = $14^{\rm m}.9$; Sp. B) is a relatively bright binary system with an eccentric orbit (e = 0.2) and a moderate orbital period $P \simeq 3.9$ days. Its variability was discovered by MP05 in the OGLE field LMC-SC16. Most recently, Graczyk et al. (2011) included this star in their catalogue of eclipsing binaries in the LMC. They also gave the preliminary ephemeris:

Pri. Min. = HJD 2 453 571$^{\rm d}$.1063 + 3$^{\rm d}$.881980 × E.

Using O and M photometry, we were also able to derive additional times of minimum light; two more minima were derived from our observations. Only 30 times of minimum light were used in our analysis (see Table A.1). As one can clearly see from the shape of the light curve and the different duration of both the primary and secondary eclipse, this is the system with the highest value of eccentricity in our sample.

We used the ESO data for deriving the radial velocities of the components. Ten UVES spectra were found, of which nine were usable for the analysis. The derived RVs of both components are given in Table B.1. Together with these radial velocities, the MACHO light curve was used for the subsequent combined LC+RV analysis. The final parameters of the solution are given in Table 3, while the fits are plotted in Figs. 5 and 6. Our results show the rather noticeable property that the more massive component (the primary) is smaller and less luminous (i.e. has a lower temperature). However, this is still a preliminary result based on only nine RVs and a poor fit. Although the scenario is possible, the more probable explanation is that the mass ratio is inverse, and the primary and secondary components are interchanged. This can be allowed for within the uncertainties of the mass ratio. A more detailed analysis is needed, based on more precise spectral observations. The orbital inclination was about i = 84°.2, which was later used for the apsidal motion analysis. The resulting parameters of apsidal motion are found in Table 1, and the current O–C diagram is shown in Fig. 7. As one can see, the period is rather long and only about 1/5 has been covered so far.

Table 3. Light and radial velocity curve fit parameters for MACHO 81.8881.47 and MACHO 79.5377.76.

Parameter	MACHO 81.8881.47	MACHO 79.5377.76
T_1 [K]	17 200 (fixed)	27 500 (fixed)
T_2 [K]	18 420 (360)	26 710 (470)
i [deg]	84.20 (0.27)	87.22 (0.44)
Ω_1	7.067 (0.115)	5.774 (0.085)
Ω_2	6.365 (0.102)	6.264 (0.098)
$q = M_2/M_1$	0.981 (0.030)	1.00 (0.02)
a [$R_\odot$]	23.04 (0.12)	22.65 (0.07)
v_γ [km s^{-1}]	272.6 (1.6)	250.0 (1.0)
L_1 [%]	41.4 (1.2)	57.2 (1.5)
L_2 [%]	58.6 (1.4)	42.8 (1.1)

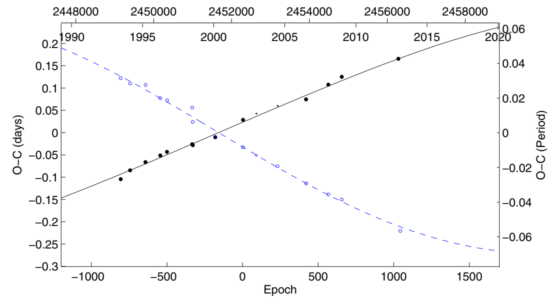

Fig. 7. O–C graph of MACHO 81.8881.47. See legend for Fig. 1.

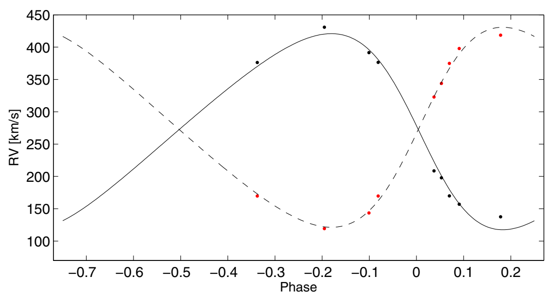

Fig. 5. Radial velocity curve for MACHO 81.8881.47.

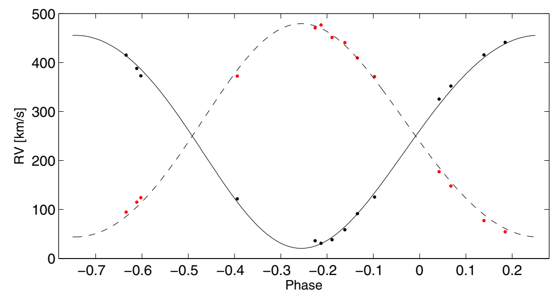

Fig. 8. Radial velocity curve for MACHO 79.5377.76.

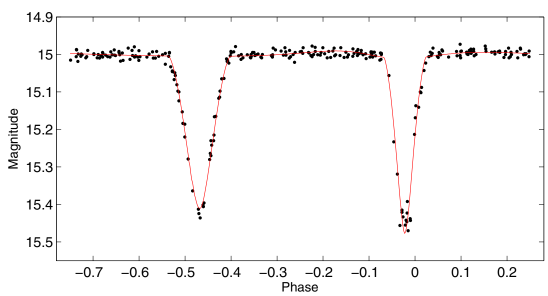

Fig. 6. Light curve for MACHO 81.8881.47.

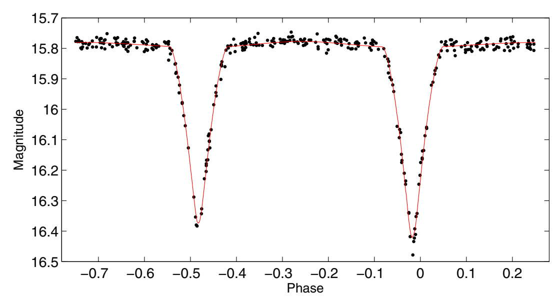

Fig. 9. Light curve for MACHO 79.5377.76.

7.5. MACHO 79.5377.76

The detached eclipsing binary MACHO 79.5377.76 (also known as OGLE J051323.98-692249.2, $V_{\max} = 15^{\rm m}8$; Sp. B) is a fairly neglected binary system with a moderate eccentric orbit (e = 0.06) and a short orbital period ($P \simeq 2.64$ day):

Pri. Min. = HJD 2 452 262$^{\rm d}$6776 + 2$^{\rm d}$6365767 × E.

We used the MACHO and OGLE photometry together with our new observations from Chile to derive the times of minima, the ESO spectral observations to derive the radial velocities, and the MACHO photometry to model the light curve of the system. Our results are plotted in Figs. 8 and 9. The resulting parameters are given in Table 3. As one can see, both components are of equal mass and their spectral type was estimated to be about B0-B1. Radial velocities used for our analysis are also given in Table B.1. The coverage of the radial velocity curve is better than for MACHO 81.8881.47; however, it was rather difficult to derive the synchronicity parameters F_i, and so we fixed them at $F_i = 0$. A total of 34 reliable times of minimum light were used in our analysis including 16 secondary eclipses (see tables in the Appendices). The final apsidal motion elements are given in Table 1, and the O–C graph is shown in Fig. 10. The apsidal period is the shortest among systems studied here, only 42 years.

8. Discussion

The detection of apsidal motion in EEB provides the opportunity to test models of stellar internal structure. The internal structure constant (ISC) $k_{2,\rm obs}$ is related to the variation in the density inside the star and can be derived using the expression

$$k_{2,\rm obs} = \frac{1}{c_{21} + c_{22}} \frac{P_{\rm a}}{U} = \frac{1}{c_{21} + c_{22}} \frac{\dot{\omega}}{360}, \quad (1)$$

Table 4. Basic physical properties of HV 982, HV 2284, MACHO 78.6097.13, MACHO 81.8881.47, and MACHO 79.5377.76 and their internal structure constants.

Parameter	Unit	HV 982	HV 2274	MACHO 78.6097.13	MACHO 81.8881.47	MACHO 79.5377.76
M_1	$M_\odot$	11.28 (0.46)	12.2 (0.7)	11.76 (0.48)	5.51 (0.21)	11.26 (0.35)
M_2	$M_\odot$	11.61 (0.47)	11.4 (0.7)	10.51 (0.40)	5.40 (0.19)	11.27 (0.35)
r_1		0.194 (0.003)	0.255 (0.013)	0.258 (0.021)	0.169 (0.008)	0.212 (0.004)
r_2		0.214 (0.003)	0.234 (0.012)	0.206 (0.020)	0.192 (0.010)	0.190 (0.004)
Source		Clausen et al. (2003)	Ribas et al. (2000)	González et al. (2005)	This paper	This paper
$\dot{\omega}_{\rm rel}$	deg cycle^{-1}	0.0015	0.0014	0.0020	0.0011	0.0023
$\dot{\omega}_{\rm rel}/\dot{\omega}$	%	5.9	3.2	3.24	3.06	3.65
log $k_{2,\rm obs}$		–2.371 (0.10)	–2.470 (0.15)	–2.174 (0.35)	–2.017 (0.18)	–1.859 (0.17)
log $k_{2,\rm theo}$		–2.32	–2.45	–2.19	–2.01	–1.90

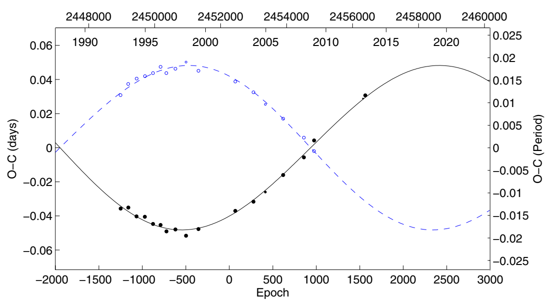

Fig. 10. O–C diagram for MACHO 79.5377.76. See legend to Fig. 1.

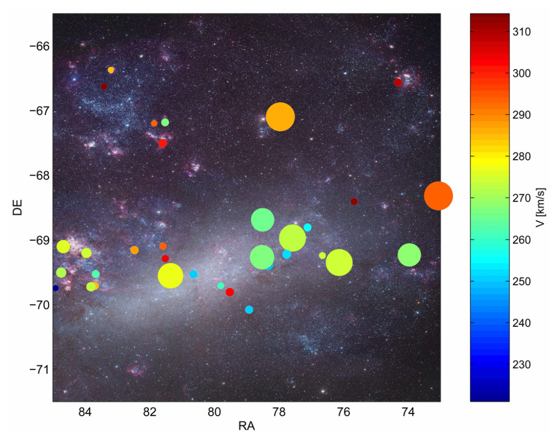

Fig. 11. Position and systemic velocities (see the colour scale on the *right*) of eclipsing binaries located in the LMC and its vicinity, see Table 5. The larger the symbol, the higher the precision. The background image of the LMC is used with the permission of the author Robert Gendler (`http://www.robgendlerastropics.com`).

where c_{21} and c_{22} are functions of the orbital eccentricity, fractional radii, the masses of the components, and the ratio between rotational velocity of the stars and Keplerian velocity (Kopal 1978). We also assume that the component stars rotate pseudosynchronously with the same angular velocity as the maximum orbital value at periastron (see e.g. Kopal 1978). Another possible approach is to use the value of $v \sin i$ as derived from the combined LC+RV analysis published earlier. However, there could be a problem with the inclination of the rotation axis (as in the case of DI Her) and, moreover, the error of the internal structure constants is by far dominated by the term r_i^5 in the equations. In addition to the classical Newtonian contribution, the observed rate of rotation of the apses includes the contribution from General Relativity (Giménez 1985),

$$\dot{\omega}_{\rm rel} = 5.45 \times 10^{-4} \, \frac{1}{1-e^2} \left(\frac{M_1 + M_2}{P} \right)^{2/3}, \quad (2)$$

where M_i denotes the individual masses of the components in solar units and P is the orbital period in days.

The values of $\dot{\omega}_{\rm rel}$ and the resulting mean internal structure constants $k_{2,\rm obs}$ for the systems studied are given in Table 4. Theoretical values $k_{2,\rm theo}$ according to available theoretical models for the internal stellar structure computed by Claret (2006) for given masses of components are presented in Table 4.

We tried to compare our resulting systemic velocities with other published values of eclipsing binaries in the LMC, see Table 5 and Fig. 11. There are still only a few such systems studied in detail (i.e. LC+RV analysis). Therefore, reliable analysis of different velocities within the LMC is still very difficult. We can only compare our Fig. 11 with other kinematic studies of the LMC published earlier, e.g. that by Reid & Parker (2006) or Rohlfs et al. (1984), that were based on much larger radial-velocity data sets. Nevertheless, we can conclude that our two new systemic velocities roughly fit the overall picture and the total velocity dispersion within the LMC is more than 30 km s^{-1}.

9. Conclusions

The apsidal motion in EEB has been used for decades to test evolutionary stellar models. This study provides accurate information on the apsidal motion rates of five main-sequence early-type binary systems in the LMC: HV 982, HV 2274, MACHO 78.6097.13, MACHO 81.8881.47, and MACHO 79.5377.76. In our Galaxy there are known a few hundreds of apsidal motion EEBs, however in the LMC there are still only a few dozen of these systems (Michalska & Pigulski 2005). Hence this study still presents an important contribution to the topic. The relativistic effects are weak, being up to 6% of the total apsidal motion rate. For the systems MACHO 79.5377.76 and MACHO 81.8881.47, their light and radial velocity curves were analysed for the first time yielding the stellar parameters of both components given in Table 4. Moreover, when the MACHO 79.5377.76 internal structure constant and the

Table 5. Radial velocities of eclipsing binaries in the LMC derived from various analyses.

System	RA [h m s]	DE [° ′ ″]	P [d]	RV [km s^{-1}]	Reference
MACHO 47.1884.17	04 52 15.29	–68 19 10.55	251.0068	293.44 ± 0.04	Pietrzyński et al. (2013)
MACHO 18.2475.67	04 55 51.48	–69 13 47.99	150.0198	267.68 ± 0.08	Pietrzyński et al. (2013)
HV 2241	04 57 15.74	–66 33 54.20	4.342635	307.9 ± 3	Ostrov et al. (2001)
HV 2274	05 02 40.80	–68 24 21.02	5.726006	312 ± 4	Ribas et al. (2000)
MACHO 1.3926.29	05 04 32.88	–69 20 50.99	189.8215	274.32 ± 0.05	Pietrzyński et al. (2013)
MACHO 1.4290.113	05 06 37.80	–69 14 22.98	2.273210	274.2 ± 4.5	González et al. (2005)
MACHO 1.4539.37	05 08 28.10	–68 48 26.02	2.995450	255.6 ± 3.1	González et al. (2005)
OGLE LMC-ECL-9114	05 10 19.65	–68 58 12.0	214.1707	272.04 ± 0.05	Pietrzyński et al. (2013)
MACHO 79.5017.83	05 11 02.80	–69 13 09.01	2.152915	252.0 ± 2.0	González et al. (2005)
MACHO 52.5169.24	05 11 49.45	–67 05 45.20	167.6350	286.24 ± 0.04	Pietrzyński et al. (2013)
MACHO 79.5377.76	05 13 23.91	–69 22 48.90	2.636577	250.0 ± 1.0	This paper
MACHO 2.5509.50	05 14 01.91	–68 41 18.41	117.8708	265.10 ± 0.08	Pietrzyński et al. (2013)
MACHO 79.5500.60	05 14 05.95	–69 15 56.83	771.7806	266.38 ± 0.07	Pietrzyński et al. (2013)
MACHO 6.5730.3092	05 15 41.50	–70 04 39.00	1.761014	250.9 ± 2.6	González et al. (2005)
MACHO 78.6097.13	05 18 04.70	–69 48 19.02	3.107023	301.7 ± 2.4	González et al. (2005)
HV 12012	05 19 11.78	–69 42 24.38	2.727125	261.4 ± 4.6	Ribas et al. (2002)
MACHO 78.6827.66	05 22 35.00	–69 31 44.01	2.183358	250.8 ± 3.0	González et al. (2005)
MACHO 77.7311.102	05 25 25.55	–69 33 04.49	157.3243	276.66 ± 0.06	Pietrzyński et al. (2013)
MACHO 80.7436.52	05 26 04.40	–69 17 10.99	1.664135	303.2 ± 3.8	González et al. (2005)
TYC 8891-3349-1	05 26 06.15	–67 10 56.98	3.30161	267 ± 3	Ostrov & Lapasset (2003)
MACHO 80.7438.42	05 26 21.60	–69 05 45.00	1.505947	292.7 ± 4.4	González et al. (2005)
[L72] LH 54-425	05 26 24.25	–67 30 17.19	2.24741	300.9 ± 2.3	Williams et al. (2008)
HV 2543	05 27 27.40	–67 11 54.55	4.829046	293.2 ± 6	Ostrov et al. (2000)
HV 982	05 29 53.00	–69 09 22.99	5.335220	287.8 ± 2.5	Fitzpatrick et al. (2002)
LMC X-4	05 32 49.54	–66 22 13.30	1.40830	284.0 ± 7.0	Hutchings et al. (1978)
HV 5936	05 33 39.03	–66 37 39.61	2.805068	314.3 ± 5.8	Fitzpatrick et al. (2003)
MACHO 81.8881.21	05 34 48.14	–69 42 36.30	4.250806	284 ± 3	Bonanos (2009)
MACHO 81.8763.8	05 34 41.30	–69 31 39.01	1.404740	263.1 ± 3	Ostrov (2001)
MACHO 81.8881.47	05 35 17.57	–69 43 18.90	3.881872	272.6 ± 1.6	This paper
MACHO 82.9010.36	05 35 50.79	–69 12 00.44	2.762456	273.8 ± 1.2	Massey et al. (2012)
[HSH95] 38	05 38 42.10	–69 06 07.79	3.39	275.3 ± 0.5	Massey et al. (2002)
[HSH95] 39	05 38 42.49	–69 06 01.29	4.06	266.9 ± 0.5	Massey et al. (2002)
[HSH95] 42	05 38 42.18	–69 06 02.38	2.89	272.0 ± 0.5	Massey et al. (2002)
[HSH95] 77	05 38 42.56	–69 06 04.39	1.88	275.2 ± 0.5	Massey et al. (2002)
LMC X-3	05 38 56.63	–64 05 03.30	1.7049	310.0 ± 7.0	Cowley et al. (1983)
[M2002] LMC 172231	05 38 58.10	–69 30 11.31	3.225414	271.5 ± 1.2	Massey et al. (2012)
LMC X-1	05 39 38.84	–69 44 35.70	4.2288	221.0 ± 6.0	Hutchings et al. (1987)

theoretical model are compared the system appears to be very young ($\sim 2 \times 10^6$ yr).

In spite of the considerable amount of observational data that has been collected for decades, the absolute dimensions of massive binary components are only known with an accuracy of about 1–3% (e.g. Clausen 2004). More detailed study based on more precise radial velocities would be very profitable to derive the physical properties of components with higher accuracy. The most promising system for further detailed analysis seems to be HV 2274 because of the putative third component in the system. We still know only a few such systems nowadays, see e.g. Bozkurt & Değirmenci (2007), while HV 2274 is the first to be discovered out of our Galaxy. Only precise spectral observations and their disentangling should reveal its true nature.

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Apsidal motion and a light curve solution for eighteen SMC eccentric eclipsing binaries⋆,⋆⋆

P. Zasche[1], M. Wolf[1], J. Vraštil[1], J. Liška[2], M. Skarka[2], and M. Zejda[2]

[1] Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Department of Theoretical Physics and Astrophysics, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

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ABSTRACT

Aims. The Danish 1.54-meter telescope at the La Silla observatory was used for photometric monitoring of selected eccentric eclipsing binaries located in the Small Magellanic Cloud. The new times of minima were derived for these systems, which are needed for accurate determination of the apsidal motion. Moreover, many new times of minima were derived from the photometric databases OGLE and MACHO. Eighteen early-type eccentric-orbit eclipsing binaries were studied.

Methods. Their O–C diagrams of minima timings were analysed and the parameters of the apsidal motion were obtained. The light curves of these eighteen binaries were analysed using the program PHOEBE, giving the light curve parameters. For several systems, the additional third light also was detected.

Results. We derived for the first time and significantly improved the relatively short periods of apsidal motion from 19 to 142 years for these systems. The relativistic effects are weak, up to 10% of the total apsidal motion rate. For one system (OGLE-SMC-ECL-0888), the third-body hypothesis was also presented, which agrees with high value of the third light for this system detected during the light curve solution.

Key words. binaries: eclipsing – stars: early-type – stars: general – stars: fundamental parameters – Magellanic Clouds

1. Introduction

Other galaxies have become the most prominent battlefields in current astrophysical research, mainly due to the large and long-lasting photometric surveys. These surveys like MACHO or OGLE have discovered thousands of new eclipsing binaries in the Magellanic Clouds, hence, we know only about twice more eclipsing binaries in our own Milky Way than in other galaxies (see Pawlak et al. 2013; or Graczyk et al. 2011).

On the other hand, the chemical composition of the Magellanic Clouds differs from that of the solar neighborhood (e.g. Ribas 2004), and the study of the massive and metal-deficient stars in the Small Magellanic Cloud (SMC) checks our evolutionary models for these abundances. All eclipsing binaries analysed here have properties that make them important astrophysical laboratories for studying the structure and evolution of massive stars (Ribas 2004).

Eccentric eclipsing binaries (EEBs) with an apsidal motion can provide us with an important observational test of theoretical models of stellar structure and evolution. A long-term collection of the times of EEBs minima observed for several years throughout the apsidal motion cycle and a consecutive detailed analysis of the period variations of EEB can be performed, yielding both the orbital eccentricity and the period of rotation of the apsidal line with high accuracy (Giménez 1994). Many different sets of stellar evolution models have been published in recent years, such as for Maeder (1999), or Claret (2005); however, to distinguish between them and to test, which one is more suitable, it is still rather difficult. The internal structure constants, as derived from the apsidal motion analysis, could serve as one independent criterion. On the other hand, only stellar parameters for EEBs with an accuracy of 1% can be used to discriminate between the models.

Here, we analyse the observational data and rates of apsidal motion for eighteen SMC detached eclipsing systems. All these systems are early-type objects, having eccentric orbits, which also exhibits an apsidal motion. Similar studies of Large Magellanic Cloud (LMC) EEBs have been presented by Michalska & Pigulski (2005), by Michalska (2007), and recently also by Zasche & Wolf (2013). As far as we know, only several eclipsing binaries with apsidal motion were analysed in SMC galaxy until now: SC3 139376, SC5 311566 (Graczyk 2003), and nine other systems by North et al. (2010).

2. Observations of minimum light

Monitoring of faint EEBs in external galaxies became almost routine nowadays with quite moderate telescopes of 1–2 m class, which are equipped with a modern CCD camera. However, a large amount of observing time is needed, which is usually unavailable at larger telescopes. During the last two observational seasons, we have accumulated 2660 photometric observations and derived 29 precise times of minimum light for selected eccentric systems. New CCD photometry was obtained at the

⋆ Based on data collected with the Danish 1.54-m telescope at the ESO La Silla Observatory.

⋆⋆ Table A.1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/572/A71

La Silla Observatory in Chile, where the 1.54-m Danish telescope (hereafter DK154) with the CCD camera and *R* filter was used (remotely from the Czech Republic).

All CCD measurements were reduced in a standard way using the bias frames and then the flat fields. The comparison star was chosen to be close to the variable one and with similar spectral type. A synthetic aperture photometry and astrometry software developed by Velen and Pravec A , was routinely used for reducing the data. No correction for differential extinction was applied because of the proximity of the comparison stars to the variable and the resulting negligible differences in air mass and their similar spectral types.

The new times of primary and secondary minima and their respective errors were determined by the classical Kwee & van Woerden (1956) method or by our new approach (see Sect. 4.2). All new times of minima are given in Table A.1.

3. Photometry and light curve modelling

The core of our analysis lies on the huge photometric data sets, as obtained during the M (Faccioli et al. 2007), O II (Wyrzykowski et al. 2004), and O III (Graczyk et al. 2011) surveys. These photometric data were used both for minima time analysis and for light curve analysis. The method of how the individual times of minima for the particular system were computed is presented in Sect. 4.2. Our new observations obtained at the Danish 1.54-m telescope were used only for deriving the times of minima for the selected targets.

The analysis of the light curves (LC) for the systems was carried out using the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson-Devinney algorithm (Wilson & Devinney 1971) and its later modifications, but some of the parameters have to be fixed during the fitting process. The albedo coefficients A_i remained fixed at value 1.0, the gravity darkening coefficients g_i = 1.0. The limb darkening coefficients were interpolated from the van Hammes tables (van Hamme 1993), and the synchronicity parameters (F_i) were also kept fixed at values of $F_i = 1$. The temperature of the primary component was derived from the photometric indices or other sources (see below). The problematic issue of the mass ratio was solved by fixing $q = 1$ because no spectroscopy for most of these selected systems exists, and for detached eclipsing binaries the LC solution is almost insensitive to the photometric mass ratio (see e.g. Terrell & Wilson 2005).

4. Methods used for the analysis

4.1. Apsidal motion analysis

For the analysis, we used the approach as presented below.

1. At the beginning, all of the available photometric data were analysed, resulting in a set of minima times. Preliminary apsidal motion parameters were derived (with the assumption $i = 90°$).
2. Secondly, the eccentricity (e), argument of periastron (ω), and apsidal motion rate ($\dot{\omega}$) that resulted from the apsidal motion analysis were used for the preliminary light curve analysis.
3. As the third step, the inclination (i) from the LC analysis was used for the final apsidal motion analysis.
4. Finally, the resulted e, ω, and $\dot{\omega}$ values from the apsidal motion analysis were used for the final LC analysis.

Moreover, this simple approach was a bit complicated because the minima times were also derived using the light curve template (see the AFP method in Sect. 4.2). Hence, the LC solution from step 2 allows us to derive the better times of minima for the step 3. The whole process run iteratively until the changes are negligible (usually it was enough to run these four steps two times).

The O–C diagrams of all available times of minima were analysed using the method presented by Giménez & García-Pelayo (1983). This is a weighted least-squares iterative procedure, including terms in the eccentricity up to the fifth order. There are five independent variables ($T_0, P_s, e, \dot{\omega}, \omega_0$) determined in this procedure. The periastron position ω is given by the linear equation

$$\omega = \omega_0 + \dot{\omega}\, E,$$

where $\dot{\omega}$ is the rate of periastron advance, E is the epoch, and the position of periastron for the zero epoch T_0 is denoted as ω_0. The relation between the sidereal and the anomalistic period, P_s and P_a, is given by

$$P_s = P_a\,(1 - \dot{\omega}/360°)$$

and the period of apsidal motion by $U = 360° P_a/\dot{\omega}$.

All new precise CCD times of minima were used with a weight of 10 in our computation; some of our less precise measurements were weighted by a factor of five, while the poorly covered minima were given a weight of 1.

4.2. Method of minima fitting

We developed and routinely used a method for deriving the times of minima for selected stars observed during the MACHO and OGLE surveys. This semi-automatic fitting procedure (hereafter AFP) has harvested the fact that the number of data points obtained during these two photometric surveys is large (typically thousands of data points) but obtained during many orbital revolutions of the close pair (a so-called sparse photometry).

Therefore, we can construct the phased light curve of the eclipsing binary in different time epochs. If the apsidal motion is prominent in the system, the shape of the light curve also slightly varies between the different epochs.

The first step is to divide the whole data set of photometry into several different "subsets", which are used for constructing the individual light curves. Then, we usually choose the data set closest to the half of the time interval covered with observations and use these data points for constructing the light curve to be analysed.

Then, this light curve is analysed using the PHOEBE code, and the theoretical light curve template is being constructed. This LC model is then being used for deriving the individual times of minima easily by fitting this phased light curve to the phased light curves for the individual data sets. The best fit is obtained with the simplex algorithm and the least squares fitting method by only shifting the theoretical and observed light curve in two axis (phase and magnitude). If the star has constant magnitude over the whole time range of our data, there is no need to fit the magnitude shift, and only one free parameter is computed. When we find the best fit, then the times of minima are computed easily according to the ephemerides for a particular data set. Of course, for eccentric orbit binaries, both primary and secondary minima are being computed separately.

For the input, there are the data points, the time intervals, the ephemerides, and also parameters of the method. These are the duration of eclipse (how large portion of the phase curve around

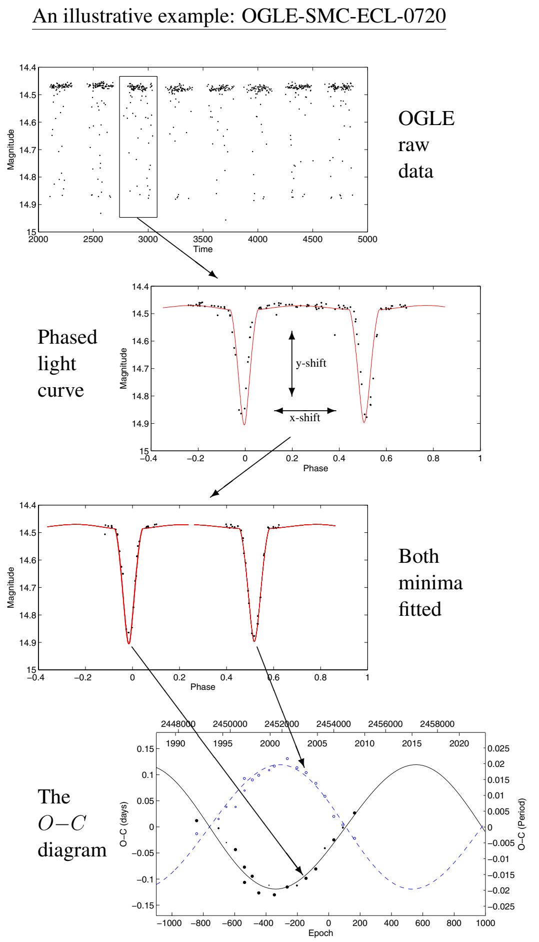

Fig. 1. How the AFP method works.

minima is being used for computing), minimum number of data points (if lower, the minimum is not computed), and the depth of minima. If 1/5 of the depth of minima is covered with data points, then this particular minimum is being computed.

Hence, by using this technique, we can usually obtain both primary and secondary minima for each data subset from an original photometry file. Moreover, this method can also be used in these cases, where the minimum is covered only very poorly, or only a descent to the minimum is covered. In these cases, the classical Kwee-van Woerden method would not work properly, so we can obtain more useful data points. On the other hand, we would like to emphasize that the method is suitable only for systems with low eccentricity, where the shape of the light curve is changing only slightly. Otherwise, we have to construct a separate light curve template for each of the data subset.

The whole method is graphically shown in Fig. 1, where an illustrative example of OGLE-SMC-ECL-0720 is being presented. All of the derived times of minima are stored in Table A.1. There are also given the errors of individual minima times, which are being computed also by AFP in the following way. The set of different solutions was computed for a particular minimum with different parameters of the code (length of interval around each minimum used for the analysis, number of data points according to their precision, etc.), yielding a set of times of minima, which is usually more than 10. From these minima data set, an average and its variance were computed. The variance is then taken as an approximate error estimation for the particular minimum.

5. Notes on individual systems

All of the eclipsing systems were analysed using a similar approach, hence we cannot focus on every star in detail. See Table 1 for information and cross-identification of these stars. The abbreviations of the star names were used for all of the systems for a better brevity. That is, OGLE-SMC-ECL-0720 was shortened as #0720, etc. Only the most important results are summarized below. The final light curve fits, and the O–C diagrams are presented in Figs. 2 and 3; the parameters are given in Tables 2 and 3. The whole set of eighteen analysed systems can be divided into a few subsets according to available spectral information.

The largest group in our sample of stars comprise these stars, which were never observed spectroscopically, hence no spectral classification or radial velocity study was published so far. These systems are #0781, #1001, #1298, #1407, #2225, #2251, #2524, and #5233. Most of them were discovered as eclipsing binaries by Udalski et al. (1998), Wyrzykowski et al. (2004), or Faccioli et al. (2007). Several of them were mentioned as eccentric ones with apsidal motion in some of the above mentioned papers. Owing to having no information about their spectra, we only roughly estimated the spectral types from the measurements in photometric filters, as seen in Table 1. These observations were usually taken from Massey (2002) and from the dereddened photometric indices the spectral types were estimated (Popper 1980; Ducati et al. 2001; or Cox 2000). For some of the systems, there resulted a non-negligible third light contribution (e.g. #2225, #2251).

For some of the systems, the spectral types were published, so we can use them for a better primary temperature estimation for a subsequent light curve analysis. These systems are #0720, #2534, #3677, #4955, #5422, and #5434 (to this group of stars, two systems #0888 and #3951 also belong, but these were given a special focus in the following subsections). These binaries were also discovered by Udalski et al. (1998) and Faccioli et al. (2007); for some of them, a short note about their apsidal motion was published. The spectral types for these systems given by Evans et al. (2004) and Bonanos et al. (2010) are in good agreement with our spectral types that are estimated from the dereddened photometric indices.

5.1. *OGLE-SMC-ECL-2186*

Two systems, #2186 and #3594, were even published with their light and radial velocity curves solutions. The first one (#2186) was analysed by Wyithe & Wilson (2001), who presented a preliminary light curve solution with an eccentric orbit with $e = 0.068$. Graczyk (2003) analysed the LC of #2186, yielding an eccentricity of 0.251, no third light, and the luminosity ratio of $L_2/L_1 = 0.843$. Wyrzykowski et al. (2004) presented a note about its apsidal motion but with no estimation of its period. Concerning the spectral type, Graczyk (2003) estimated the types of about O9V+O9V but dealt only with the photometry. Later, Hilditch et al. (2005) published its spectral type to be B0+B0-3 based on 15 spectra of the star. They also analysed

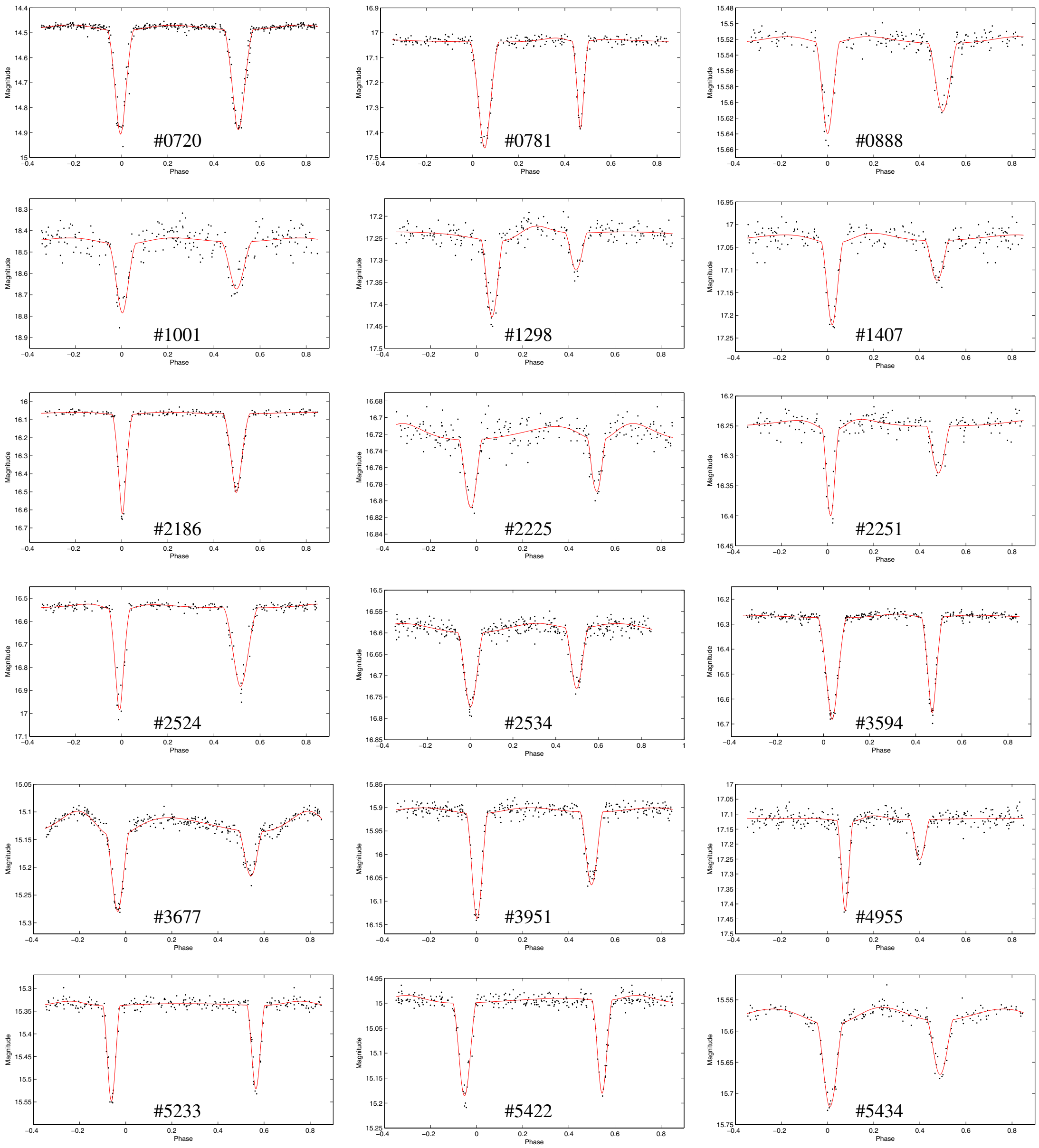

Fig. 2. Light curves of the analysed systems, the data taken from the OGLE III survey, and the *I* filter.

the light curve, yielding a value of the eccentricity of the orbit to be 0.063. However, their LC solution is not very convincing due to poor fit of the secondary minimum.

5.2. OGLE-SMC-ECL-3594

The second system (#3594) was also studied by Wyithe & Wilson (2001), who included this star into their sample of SMC eclipsing binaries with the light curve solution, which result in orbital inclination of 88.9° and an eccentricity of 0.144. Hilditch et al. (2005) analysed the system in more detail, resulting in an orbital eccentricity of 0.19 (based on photometry and spectroscopy together) and the spectral types of both components as B1+B1-3.

5.3. OGLE-SMC-ECL-0888

The object #0888 was first mentioned by Wyrzykowski et al. (2004), who also noted about its apsidal motion. Its spectral type

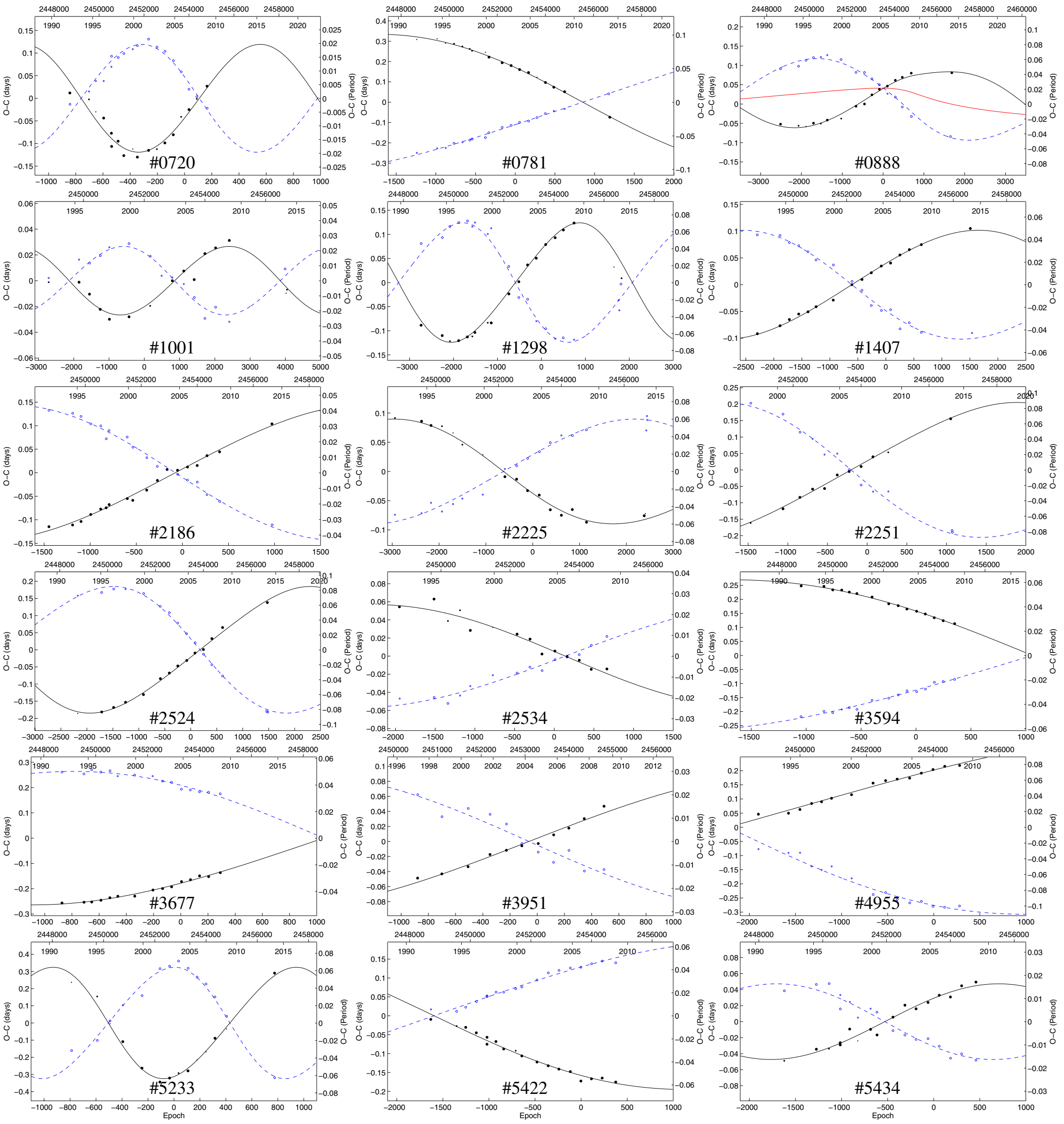

Fig. 3. O–C diagram for the times of minima for the analysed systems. The continuous and dashed curves represent predictions for the primary and secondary eclipses, respectively. The individual primary and secondary minima are denoted by dots and open circles, respectively. Larger symbols correspond to the measurements, which were given higher weights.

was derived to be about O9V by Evans et al. (2004). We found that the pure apsidal motion is not able to describe the O–C diagram in detail, hence another effect has also to be included. We also tried to fit the parabolic fit to the ephemerides, with the apsidal motion hypothesis (can be interpreted as a mass transfer between the components, despite improbable for detached binary). However, this fit was also not very satisfactory. Therefore, we used a different code that computes the apsidal motion parameters with the third-body orbit (a so-called "light travel time" effect), as seen in for example Irwin (1959) or Mayer (1990). Ten parameters were fitted (five from the apsidal motion, five from the third body hypothesis); thus, this approach led to an acceptable solution with the lowest sum of squares residuals. The final parameters of the fit are given in Tables 3 and 4; the complete O–C diagrams are shown in Figs. 3 and 4.

From the third-body parameters, we could also compute the mass function of the distant component, which resulted in $f(m_3) = 0.059 \pm 0.015\ M_\odot$. From this value, one can calculate a predicted minimal mass of the third body (i.e. assuming coplanar orbits $i_3 = 90°$), which resulted in $m_{3,\min} = 4.9\ M_\odot$. If we

Table 1. Relevant information for the analysed systems.

System	OGLE II*	MACHO	RA	Dec	I_{max}	$(B-V)$	$(U-B)$	$(B-V)_0$	Sp.type**	Ref.
#0720	SC3 139376	213.15620.12	$00^h44^m08^s.67$	$-73°14'18''.5$	$14^m.47$	–0.16	–0.91	–0.26	B0(IV)	1, 2
#0781	SC3 157218	212.15624.89	$00^h44^m39^s.73$	$-72°59'58''.5$	$17^m.03$	–0.10	–0.78	–0.23	*B2*	1
#0888	SC4 29231	212.15680.18	$00^h45^m30^s.72$	$-73°03'29''.7$	$15^m.52$	–0.09	–0.82	–0.25	O9V	1, 2
#1001		208.15744.1836	$00^h46^m11^s.29$	$-72°35'17''.3$	$18^m.44$	–0.31	–0.58	–0.12	*late B/early A*	3
#1298	SC4 163754	212.15848.1258	$00^h47^m52^s.73$	$-73°16'34''.0$	$17^m.22$	–0.04	–0.89	–0.29	*B0*	1
#1407		208.15861.734	$00^h48^m19^s.26$	$-72°21'40''.2$	$17^m.02$	–0.04	–0.67	–0.21	*B3*	1
#2186	SC5 311566	208.16083.86	$00^h51^m34^s.84$	$-72°45'46''.4$	$16^m.06$	–0.04	–0.79	–0.25	B0+B0-3	1, 4
#2225	SC6 72782	208.16084.117	$00^h51^m41^s.80$	$-72°41'06''.1$	$16^m.71$	–0.128		–0.22	*B3*	5, 6
#2251	SC6 61418		$00^h51^m46^s.64$	$-72°51'21''.7$	$16^m.23$	–0.14	–0.91	–0.27	*B1*	1
#2524	SC6 158178	208.16141.60	$00^h52^m42^s.32$	$-72°41'27''.9$	$16^m.53$	–0.176	–0.86	–0.24	*B2*	3
#2534		208.16147.22	$00^h52^m43^s.85$	$-72°18'08''.6$	$16^m.57$	–0.04	–0.81	–0.26	*B1*	1
#3594	SC7 255621	207.16428.1423	$00^h57^m26^s.41$	$-72°36'46''.2$	$16^m.26$	–0.21	–0.72	–0.19	B1+B1-3	1, 4
#3677	SC8 52815	207.16490.6	$00^h57^m49^s.25$	$-72°16'55''.7$	$15^m.11$	–0.16	–0.84	–0.24	*B2*	1, 7
#3951	SC8 160725		$00^h59^m14^s.98$	$-72°11'35''.3$	$15^m.90$	–0.18	–0.84	–0.24	B1V	8, 9
#4955	SC10 94636	206.16886.52	$01^h04^m59^s.18$	$-72°25'29''.3$	$17^m.11$	–0.16	–0.68	–0.19	*B3*	1
#5233		206.17061.14	$01^h07^m12^s.54$	$-72°11'42''.0$	$15^m.34$	–0.08	–0.91	–0.28	*B0*	1
#5422	SC11 111907	206.17170.8	$01^h08^m45^s.74$	$-72°31'22''.4$	$14^m.99$	–0.22	–0.93	–0.26	*B1*	1
#5434	SC11 118966	206.17173.10	$01^h08^m50^s.47$	$-72°17'26''.1$	$15^m.56$	–0.11	–0.86	–0.26	*B1*	1

Notes. (*) The full name from OGLE II survey should be OGLE SMC-SCn nnnnnn, (**) Spectral types given in italics were only estimated from the photometric indices for the first time in the present paper.

References. (1) Massey (2002); (2) Evans et al. (2004); (3) Zaritsky et al. (2002); (4) Hilditch et al. (2005); (5) Udalski et al. (1998); (6) Massey et al. (1995); (7) Bonanos et al. (2010); (8) Massey et al. (1989); (9) Massey et al. (2012).

Table 2. Light curve parameters for the analysed systems.

System	T_1 [K]	T_2 [K]	i [deg]	Ω_1	Ω_2	L_1 [%]	L_2 [%]	L_3 [%]
#0720	31 500 (fixed)	31 700 (400)	84.57 (0.30)	5.524 (0.061)	7.356 (0.085)	66.87 (0.83)	33.13 (0.68)	0
#0781	23 100 (fixed)	16 700 (300)	85.08 (0.18)	7.265 (0.086)	8.690 (0.120)	71.90 (1.25)	28.10 (0.98)	0
#0888	33 200 (fixed)	38 100 (1100)	77.77 (0.38)	6.119 (0.101)	6.128 (0.112)	22.01 (1.85)	26.94 (3.46)	51.05 (4.98)
#1001	11 000 (fixed)	9700 (500)	79.13 (0.92)	5.064 (0.204)	6.661 (0.397)	67.48 (1.37)	32.52 (1.02)	0
#1298	30 000 (fixed)	19 900 (700)	74.68 (0.45)	6.364 (0.138)	6.701 (0.174)	70.46 (1.32)	29.54 (0.77)	0
#1407	19 000 (fixed)	19 100 (700)	75.60 (0.50)	5.907 (0.147)	6.833 (0.177)	56.26 (1.06)	39.10 (1.00)	4.64 (1.87)
#2186	30 100 (fixed)	28 500 (300)	87.02 (0.22)	6.843 (0.058)	8.040 (0.097)	62.73 (3.14)	36.00 (1.25)	4.03 (2.59)
#2225	11 600 (fixed)	7100 (200)	80.33 (0.53)	5.678 (0.100)	11.334 (0.490)	60.98 (2.87)	4.58 (0.57)	34.45 (1.55)
#2251	26 200 (fixed)	30 600 (900)	79.62 (0.26)	6.149 (0.080)	10.184 (0.184)	48.35 (3.02)	17.91 (1.26)	33.73 (4.05)
#2524	23 100 (fixed)	24 600 (600)	83.32 (0.37)	6.128 (0.085)	7.165 (0.112)	56.63 (1.26)	41.53 (2.03)	1.85 (5.76)
#2534	26 200 (fixed)	18 300 (300)	76.23 (0.28)	5.690 (0.050)	6.150 (0.052)	61.67 (1.79)	28.64 (1.58)	9.69 (2.63)
#3594	25 500 (fixed)	22 000 (200)	83.60 (0.41)	7.095 (0.040)	6.668 (0.055)	50.50 (1.56)	48.00 (1.03)	1.49 (1.96)
#3677	23 100 (fixed)	25 100 (300)	73.60 (0.22)	5.029 (0.029)	7.833 (0.064)	74.51 (1.07)	25.49 (0.94)	0
#3951	26 200 (fixed)	24 400 (200)	78.50 (0.24)	6.699 (0.055)	6.789 (0.056)	53.76 (0.97)	46.24 (1.16)	0
#4955	19 000 (fixed)	17 400 (500)	80.01 (0.31)	7.868 (0.165)	8.591 (0.180)	58.97 (0.75)	41.03 (0.79)	0
#5233	30 000 (fixed)	29 400 (300)	80.52 (0.21)	8.762 (0.098)	7.843 (0.093)	44.09 (1.02)	55.91 (0.93)	0
#5422	26 200 (fixed)	20 400 (300)	79.18 (0.33)	7.076 (0.098)	7.070 (0.102)	54.69 (2.34)	36.51 (4.57)	8.80 (7.82)
#5434	26 200 (fixed)	24 200 (400)	71.72 (0.40)	5.400 (0.061)	5.516 (0.059)	53.49 (1.14)	43.86 (1.62)	2.65 (2.01)

propose such a body in the system, one can ask whether it is detectable somehow in the already obtained data. The period is long for continuous monitoring of the radial velocity changes, but detecting the third light in the light curve solution would be promising. Assuming a normal main sequence star, its luminosity would be of about only $L_{3,min} = 1-2\%$ of the total system luminosity. Such a weak third light would be hardly detectable in our poor-quality photometric data, but it is worth of try. Hence, we performed a new light curve solution with a special focus on the value of the third light for a LC solution. The value was really obtained, and its value is not negligible at all. As one can see from the parameters presented in Table 2, the third light represents about one half of the total light. This finding naturally explains why both the eclipses are so shallow. On the other hand, one can ask to which body the estimated spectral type of O9V belongs. If the third body is the dominant source, this is probably the O9V component, but the primary temperature of 33 200 K was assumed using the O9V primary, which now seems to be incorrect. However, having no other relevant information about the individual spectral types, one cannot easily assume a different primary temperature. Thus, we can conclude that the third body is probably present and orbits around the EB pair on orbit which is mildly inclined from the originally assumed 90°. It is hard to say anything more about such a body because of the high errors of the parameters (period, third light, etc.). More precise photometry or radial velocities would be very welcome for a final confirmation of our hypothesis.

5.4. OGLE-SMC-ECL-3951

The object #3951 is a part of the SMC open cluster NGC 346. Its eclipsing nature and orbital period was first presented by

Table 3. Parameters of the apsidal motion for the individual systems.

System	$T_0 - 2\,400\,000$ [HJD]	P_s [days]	e	$\dot{\omega}$ [deg/cycle]	ω_0 [deg]	U [yr]
#0720	53 803.390 (21)	6.052322 (48)	0.062 (16)	0.2070 (300)	67.6 (5.0)	28.8 (5.5)
#0781	52 745.417 (32)	3.299923 (48)	0.310 (75)	0.0301 (37)	244.4 (10.3)	108.1 (15.1)
#0888	53 470.954 (15)	1.918337 (11)	0.143 (34)	0.0474 (193)	89.3 (4.7)	39.9 (11.6)
#1001	53 090.7643 (35)	1.1621122 (18)	0.072 (14)	0.0601 (69)	94.5 (7.8)	19.0 (2.4)
#1298	53 501.194 (14)	1.7532121 (99)	0.219 (42)	0.0677 (93)	130.0 (4.2)	25.5 (4.1)
#1407	53 470.497 (13)	2.100755 (11)	0.151 (47)	0.0427 (120)	115.9 (3.9)	46.3 (18.0)
#2186	53 470.314 (15)	3.291316 (20)	0.227 (82)	0.0258 (42)	91.9 (2.6)	125.7 (24.5)
#2225	53 089.914 (10)	1.491721 (8)	0.187 (48)	0.0351 (121)	291.9 (8.8)	41.9 (21.8)
#2251	54 179.695 (25)	2.336038 (33)	0.271 (22)	0.0484 (132)	99.8 (5.6)	47.6 (17.8)
#2524	53 471.664 (24)	2.169236 (23)	0.263 (68)	0.0475 (92)	81.5 (6.5)	45.0 (10.8)
#2534	53 277.1246 (72)	2.2967384 (72)	0.078 (24)	0.0357 (57)	265.0 (3.4)	63.3 (11.9)
#3594	53 280.315 (41)	4.330333 (80)	0.194 (69)	0.0300 (63)	238.1 (9.9)	142.1 (38.9)
#3677	53 278.036 (52)	5.241539 (117)	0.153 (55)	0.0554 (133)	40.2 (4.6)	93.3 (33.6)
#3951	53 277.2672 (75)	3.104291 (17)	0.092 (20)	0.0476 (165)	92.9 (4.0)	64.3 (33.9)
#4955	54 022.771 (52)	2.772183 (53)	0.338 (48)	0.0239 (84)	143.3 (5.0)	114.4 (51.5)
#5233	52 746.459 (45)	5.068362 (103)	0.199 (57)	0.1915 (321)	7.0 (8.7)	26.1 (5.2)
#5422	53 656.966 (26)	3.040295 (31)	0.199 (56)	0.0301 (83)	318.1 (6.0)	99.4 (37.9)
#5434	53 478.7191 (72)	2.886936 (9)	0.051 (16)	0.0747 (214)	129.6 (3.4)	38.1 (15.2)

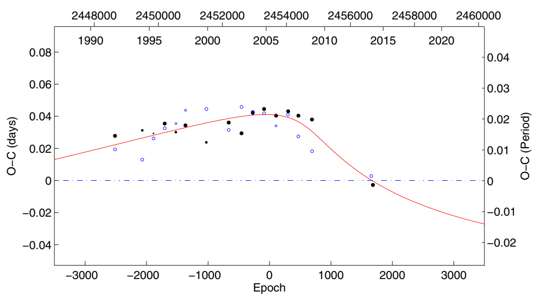

Fig. 4. O–C diagram of #0888 after subtraction of the apsidal motion term.

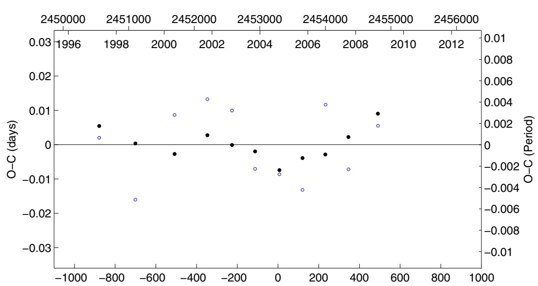

Fig. 5. O–C diagram of #3951 after subtraction of the apsidal motion term.

Udalski et al. (1998). Later, the star was classified as B1V by Massey et al. (2012). From the period analysis, a weak quasi-periodic signal also on the residuals after subtraction of the apsidal motion hypothesis (see Fig. 5) resulted. However, the variation is still too spurious for any final confirmation yet and we have not even try to fit the data with any additional variation, as in the previous case.

Table 4. Third body orbit parameters for #0888.

Parameter [Unit]	Value
p_3 [yr]	72.1 ± 28.0
A_3 [day]	0.030 ± 0.011
T_3 [HJD]	2 454 900 ± 8700
e_3	0.709 ± 0.247
ω_3 [deg]	154.0 ± 15.6

6. Discussion and conclusions

Our study provides the parameters of the apsidal motion for eighteen early-type binary systems located in the SMC. For most of the binaries, this is the first attempt to estimate the apsidal motion rates, and the light curve solution. In our own Galaxy there are a few hundreds of apsidal motion eclipsing binaries known; however, in other galaxies their number is still very limited. Hence this study still presents an important contribution to the topic. However, for only three systems from our sample (#1001, #1298, and #5233), the apsidal motion was derived from adequately large data set covering almost one apsidal period. The relativistic effects for the selected systems are weak, being up to 10% of the total apsidal motion rate. For the system #0888, the third body hypothesis was also presented and discussed.

The apsidal motion in EEBs has been used for decades to test evolutionary stellar models. Thus, one can ask whether our results can be used for deriving the internal structure constants for these stars in SMC. However, dealing with no radial velocities for most of the systems and with rather poor data coverage during the apsidal motion period, the parameters are too uncertain and affected by large errors. For these systems where the apsidal period is well-covered, a detailed spectroscopic analysis is missing, and vice versa, for systems where the radial velocity study was performed, the apsidal period has yet to be only poorly covered with data. However, for any testing of the stellar structure models or for the general relativity tests, the quality of the input data has to be an order of magnitude better (which implies long-term collection of the observations and data that covers the whole apsidal period in the following decades). Some of the systems are bright enough for a spectral monitoring, hence we encourage the observers to obtain new, high-dispersion, and high-signal-to-noise spectroscopic observations. With such data, methods, like spectral disentangling, can help us construct the radial velocity curves of both components, confirm the apsidal motion hypothesis, test the stellar structure models, or detect the third bodies, as indicated from our analysis.

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Letter to the Editor

HS Hydrae about to turn off its eclipses

P. Zasche[1] and A. Paschke[2]

[1] Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, 18000 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz
[2] Weierstr 30, 8630 Rueti, Switzerland

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ABSTRACT

Aims. We aim to perform the first long-term analysis of the system HS Hya.

Methods. We performed an analysis of the long-term evolution of the light curves of the detached eclipsing system HS Hya. Collecting all available photometric data since its discovery, the light curves were analyzed with a special focus on the evolution of system's inclination.

Results. We find that the system undergoes a rapid change of inclination. Since its discovery until today the system's inclination changed by more than 15°. The shape of the light curve changes, and now the eclipses are almost undetectable. The third distant component of the system is causing the precession of the close orbit, and the nodal period is about 631 yr.

Conclusions. New precise observations are desperately needed, preferably this year, because the amplitude of variations is decreasing rapidly every year. We know only 10 such systems on the whole sky at present.

Key words. binaries: eclipsing – stars: individual: HS Hydrae – stars: fundamental parameters – stars: solar-type

1. Introduction

Eclipsing binaries are astronomical objects of high importance, especially owing to the possibility of deriving the basic physical properties of these stars with high precision. This is mostly because one can easily calculate the individual masses, semimajor axis, etc. if one knows the inclination of the system and the radial velocity curves. However, in some systems the plane of the orbit is moving slowly, and the radial velocity data have to be obtained at the same time as the data for the light curve solution. Otherwise, the method yields incorrect results.

At present, we know only a few systems where the orbital plane is moving and the eclipsing light curve had different shapes in different epochs. Six such systems were summarized by Mayer (2005). Moreover, three more systems show changes of minima depths, therefore they are also suspected to undergo a precession of the orbits, these are V685 Cen (Mayer et al. 2004), AH Cep (Drechsel et al. 1989), and V699 Cyg (Azimov & Zakirov 1991).

2. The system HS Hya

The eclipsing binary system HS Hya was discovered to be variable by Strohmeier et al. (1965), who also classified the system as an Algol-type, but the orbital period given is incorrect. Popper (1971) measured the radial velocities (hereafter RV) of the system, and analyzed the RV curves. The spectral type was derived to be F3-4, the correct orbital period is given to be about 1.568024 days, and the mass ratio is about 0.96. However, the RV data were obtained over a period of five years, from 1966 to 1970. Later, the complete light curve (hereafter LC) was obtained in the Strömgren *uvby* system by Gyldenkerne et al. (1975). These data were measured in 1972. The authors used the RV results from Popper (1971) and their inclination of about 85.3°, which yielded a reliable picture of the system.

However, Torres et al. (1997) published a new finding about HS Hya. The analysis was based on older data from photometry, RVs by Popper, but also Torres and coworker's own new RV data, revealing that one more distant component is orbiting around the eclipsing pair. The period of this body is about 190 days, and it is probably of the spectral type M0. Its light contribution is quite low (below 1%), but the RV residuals obtained by a cross-correlation clearly show periodic modulation.

3. The change of inclination

The star has also been observed by the Hipparcos satellite (Perryman et al. 1997). During its three-year mission both minima were observed, but the coverage is only poor. However, after transformation from H_p to V magnitude (Harmanec & Božić 2001), it is clear that the depths of both minima are much lower than in the LCs obtained 20 yr ago. We solved the Hipparcos LC with the same parameters as given in Torres et al. (1997). The Phoebe program (Prša & Zwitter 2005) was used, which is based on the Wilson-Devinney code, Wilson & Devinney (1971). All relevant parameters were fixed except for the inclination, see Table 1. The value of the third light was fixed at a value of 0.4% only, in agreement with the finding published by Torres et al. (1997).

The star was also included into the photometric survey ASAS (Pojmanski 2002). We divided the whole data set into three parts and separately solved the light curves in 2002, 2005, and 2008. The procedure of LC fitting was the same as for the Hipparcos data, and the results are given in Table 1. As one can see from Fig. 1, the depths of the minima are still decreasing.

Table 1. Inclination as obtained from various light curves.

Year	Inclination [deg]	Reference
1964	88.9 ± 1.1	Strohmeier et al. (1965)
1972	85.30 ± 0.41	Gyldenkerne et al. (1975)
1991	79.83 ± 0.21	Perryman et al. (1997)
2002	76.13 ± 0.15	ASAS
2005	75.19 ± 0.28	ASAS
2008	74.60 ± 0.50	ASAS

Unfortunately, it is not easy to find other reliable photometry to do a similar analysis in different time epochs. One of the limiting problems is the role of the filter, because the entire abovementioned photometry can easily be transformed into the standard V magnitudes. The photometry from the automatic survey called "Pi of the sky" (Burd et al. 2005) is another possibility, but this photometry is unfiltered, and therefore it is problematic to solve its light curve. Moreover, it has fairly high scatter and covers a similar time span as the ASAS data.

We also tried to use the data from the discovery paper (Strohmeier et al. 1965), but these are only the photographic data and were not obtained in any standard photometric filter. Another problem is that the original data are not available, only the phase plot, but this was constructed with incorrect ephemerides. As one can see from the LCs published in Gyldenkerne et al. (1975), the individual depths in different filters are quite similar to each other. Moreover, fixing the other relevant parameters during the fitting process, we were able to construct a plot of minima depth versus inclination. Using the eight dimmed data points from Strohmeier et al. (1965), we were able to roughly derive the inclination from these data obtained in 1964, see Table 1.

The data from Table 1 were used to construct the plot given in Fig. 2. Fitting these data points with a linear curve, one sees that the change of inclination is about 0.3° during one year. Therefore, the amplitude of photometric variations is decreasing rapidly every year.

4. The nodal period

The precession effect of the close pair's orbit due to the distant third body was described elsewhere, e.g. Söderhjelm (1975). The nodal period can be computed from the equation

$$P_{\rm nodal} = \frac{4}{3}\left(1 + \frac{M_1 + M_2}{M_3}\right)\frac{P_3^2}{P}(1 - e_3^2)^{3/2}\left(\frac{C}{G_2}\cos j\right)^{-1},$$

where subscripts 1 and 2 stand for the eclipsing binary components, while 3 stands for the third distant body. The term G_2 stands for the angular momentum of the wide orbit, and the C is the total angular momentum of the system. However, the problem of the unknown inclination of the wide orbit (which is included in the last term in brackets) led us to use a different approach. Drechsel et al. (1994) analyzed the system IU Aur, where a similar problem arose, hence one can also fit the term $\cos i$ with a sinusoidal fit, following the equation

$$\cos i = \cos I \cdot \cos i_1 - \sin I \cdot \sin i_1 \cdot \cos(2\pi(t - t_0)/P_{\rm nodal}),$$

where I is the inclination of the invariant plane against the observer's celestial plane, i is the inclination of the eclipsing binary, while i_1 is the inclination between the invariant plane and the orbital plane of the eclipsing binary.

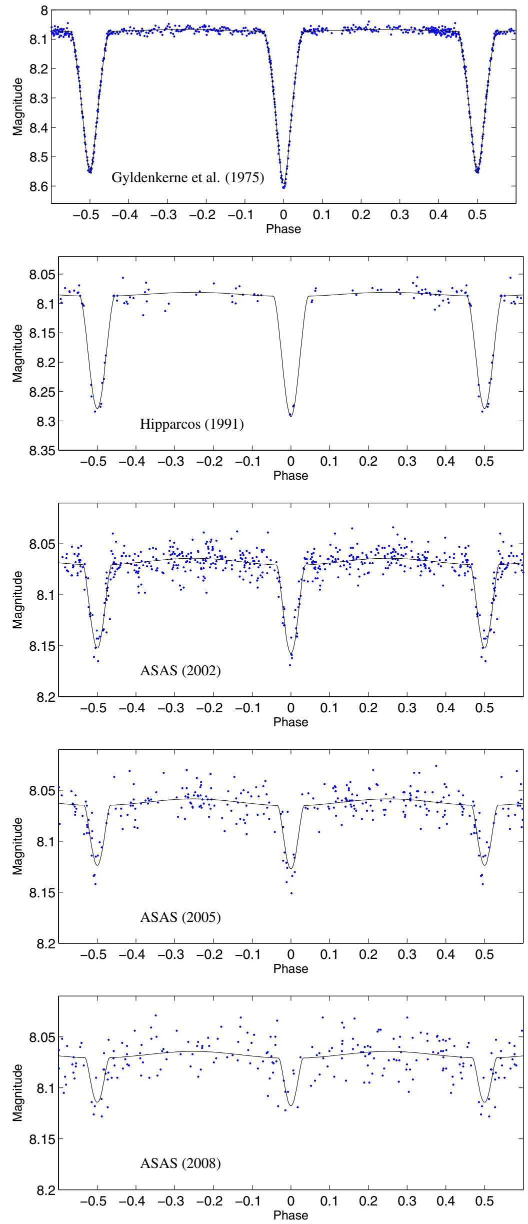

Fig. 1. Available light curves of HS Hya in the V filter. The changing depth of both minima is clearly visible. The three bottom figures were plotted with the same range in the y-axis.

A similar analysis was performed (see Fig. 3), but regrettably only a small part of the nodal period is covered with data points nowadays. Fitting a sinusoidal curve, the nodal period is about 631 yr, of which only about 1/14 is covered. The other two adjustable quantities were only poorly constrained. New precise observations are urgently needed.

Table 2. Known eclipsing binaries with changing minima depths.

System	Mag V [mag]	Sp. type	Eclipsing period [day]	Long period [day]	Nodal period [yr]	Reference
IU Aur	8.39	B3Vnne	1.8115	293.3	330	Özdemir et al. (2003)
V685 Cen	8.85	A0	1.1910	?	?	Mayer et al. (2004)
AH Cep	6.88	B0.5V	1.7747	?	?	Drechsel et al. (1989)
V699 Cyg	11.6	B2	1.5515	?	?	Azimov & Zakirov (1991)
SV Gem	10.57	B3	4.0061	?	?	Guilbault et al. (2001)
HS Hya	8.07	F5V	1.5680	190	631	This study
SS Lac	10.12	B9V	14.4162	679	600	Torres (2001)
AY Mus	10.35	B9	3.2055	?	?	Söderhjelm (1975)
RW Per	9.68	A5Ve	13.1989	?	?	Olson et al. (1992)
V907 Sco	8.61	B9V	3.7763	99.3	68	Lacy et al. (1999)

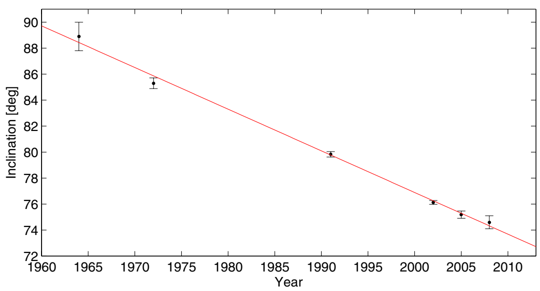

Fig. 2. Inclination of the eclipsing binary with respect to the time.

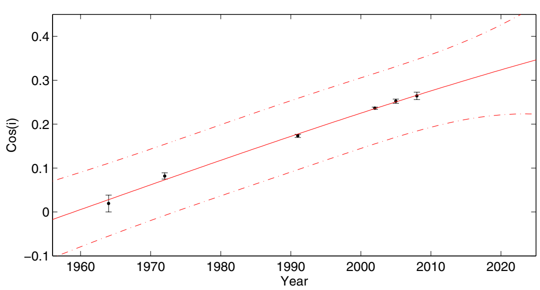

Fig. 3. Fitting the cos(i) with the sinus term on available data, the confidence level of 95% is shown with the dash-dotted line.

5. Observational consequences

HS Hya belongs to a group of unique systems, and therefore more observations are needed to confirm our hypothesis with higher confidence and to study its other physical properties. The amplitude of eclipses is lower than 0.015 mag in V filter at present, and is still decreasing. However, the ellipsoidal variations outside the eclipse will remain even when the photometric eclipses disappear. According to our model the photometric eclipses will stop in about 2022. Nevertheless, detecting these shallow eclipses is problematic, especially from the northern hemisphere, owing to the low declination of the star.

Concerning the third body period, one can ask why the 190-day orbit was not discovered earlier via analyzing the minima times via period variations. There exists a huge database of minima observations (more than 100), but no variation was detected. This is because of the short period of the third body and its low mass. This amplitude (see Irwin 1959) resulted in about 1 min only, which is comparable with the precision of individual times of minima observations.

Table 3. Masses as derived from different data sets/methods.

	RV 1968	RV 1992	Torres et al. (1997)
$M_1/M_\odot =$	1.319	1.307	1.255
$M_2/M_\odot =$	1.291	1.267	1.219

6. Discussion and conclusions

Assembling all available systems with changing minima depths (see Table 2), one can see how unique these systems are. We know only 10 such systems today and the nodal period was derived in only four of them. Moreover, it seems that this effect was preferably observed in early type systems (B and A spectral types), and HS Hya is the first exception.

Our hypothesis of changing inclination would also slightly shift the physical parameters of components as presented in Torres et al. (1997). These authors assumed constant inclination and used light curve and radial velocity data from different epochs. However, the time gap of more than 20 years between photometry and spectroscopy yields a difference in inclination of about 7.8°. This difference is able to shift the true stellar masses as computed from the term $m \cdot \sin^3(i)$. The inclination in 1968 (when the RV data were obtained by Popper 1971) was about 87.15°, while in 1992 (roughly the middle of the time interval of radial velocities used in Torres et al. 1997) was about 79.3°. Using these values, the masses resulted in the values presented in Table 3.

These values agree much better with the predicted stellar masses of F4+F5 spectral types (i.e. with the temperatures) for normal metallicity. Hence, the errors of masses as presented by Torres et al. (1997) of about 0.007 $M_\odot$ are too optimistic, because they neglect the systematic effect described above. Torres et al. (1997) presented a perfect fit of the derived values of $\log M$, $\log T$, and $\log g$ on the model isochrones. Likely an adjustment of metallicity or age will be required to accommodate the new mass determinations.

The plot presented in Fig. 3 needs to be spread in the next years. However, deriving the inclination of HS Hya when it stops having eclipses will be hard, because the ellipsoidal variations have only low amplitude. On the other hand, the interferometry of the close pair would solve this problem. Detecting the two eclipsing components via interferometry is difficult, but worth trying. The system itself is relatively bright and the two eclipsing components have a similar luminosity (i.e. magnitude difference close to zero). The computed angular separation of the two eclipsing components is about 0.4 mas.

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Astronomy & Astrophysics

The first analysis of extragalactic binary-orbit precession★ *(Research Note)*

P. Zasche and M. Wolf

Astronomical Institute, Charles University in Prague, Faculty of Mathematics and Physics, 180 00 Praha 8, V Holešovičkách 2, Czech Republic
e-mail: zasche@sirrah.troja.mff.cuni.cz

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ABSTRACT

Aims. The main aim of the present paper is the very first analysis of the binary-orbit precession out of our Galaxy.
Methods. The light curves of an eclipsing binary MACHO 82.8043.171 in the Large Magellanic cloud (LMC) were studied in order to analyse the long-term evolution of its orbit.
Results. It is a detached system that is undergoing rapid orbit precession. The inclination of the orbit towards the observer has been changing, which has caused the eclipse depth to become lower over the past decade, and this is ongoing. The period of this effect was derived as only about 77 years, so it is the second fastest nodal motion known amongst such systems nowadays. This is the first analysis of an extragalactic binary with nodal precession. This effect is probably caused by a distant third body orbiting the pair, which could potentially be detected via spectroscopy.
Conclusions. Some preliminary estimates of this body are presented. However, even such a result can tell us something about the multiplicity fraction in other galaxies.

Key words. binaries: eclipsing – stars: fundamental parameters – stars: individual: MACHO 82.8043.171

1. Introduction

After more than a century of intensive study of eclipsing binaries (EBs), they still represent the best method for deriving the masses, radii, and luminosities of stars. Thanks to modern (ground- and space-based) telescopes, we are able to also study these objects in other galaxies and to apply the same methods as used in our solar neighbourhood. Nevertheless, there is still a difference in the precision of EB parameters as derived for Galactic (~2–3%) and extragalactic (~10%) eclipsing binaries (see e.g. Clausen 2004; Ribas 2004).

The extragalactic EBs can serve as an independent tool for deriving Galactic properties and also help us answer such important questions as "Is the chemical composition of our Galaxy the same as the neighbouring ones?" or "What is the binary and multiplicity fraction in other galaxies?". Studying other galaxies via detailed analysis of individual stars can provide some useful hints for answering these questions.

EBs are quite common, even in some nearby galaxies (Vilardell et al. 2006). However, one special group of EBs is still rather rare – those undergoing an orbit precession. If the orientation of the EB orbit is moving in space, then the depths of eclipse also change, and we can detect this orbit precession. Observing the binary at different time epochs can help us to derive the inclination towards the observer as a function of time. This effect is usually caused by the third component orbiting the close pair (Söderhjelm 1975). However, we still know of only a few such systems, and detailed analysis has only been carried out for those located in our Galaxy at present. This is the first time such an effect has been studied in an extragalactic source.

★ Based on data collected with the Danish 1.54 m telescope at the ESO La Silla Observatory.

2. The system MACHO 82.8043.171

The Large Magellanic Cloud (LMC) is a close galaxy, which has been observed quite frequently during the past decades. There have been two major photometric surveys of LMC stars, MACHO (Faccioli et al. 2007) and OGLE (Graczyk et al. 2011), while discovering a huge number of variable stars including the EBs. The MACHO survey lasted from 1993 to 1998 and the OGLE from 2002 to 2008. Quite surprisingly, thanks to these two surveys we know more eclipsing binaries in the LMC than in our Galaxy (Graczyk et al. 2011). However, owing to the low declination of LMC stars, there are still many interesting systems that lack detailed analysis.

The object called MACHO 82.8043.171 (=OGLE-LMC-ECL-17359, $V = 16.98$ mag) was observed by both photometric surveys, so we can harvest the databases for a complete light curve analysis. The system is a detached eclipsing binary with its short orbital period of about 1.26 day (Graczyk et al. 2011). According to its photometric indices (see below), it is probably a B2V-type system. Our new observations were obtained during a four-month period in the 2012/2013 season, using the 1.54-m Danish telescope located at the La Silla observatory in Chile (hereafter DK154), but operated remotely from the Czech Republic. The standard Cousins filter I was used for our new observations, in agreement with the OGLE survey. Therefore, we can make the first analysis of this interesting system ranging over two decades to detect some long-term changes.

For a complete light curve analysis, we need up-to-date ephemerides of the binary. Using the MACHO and OGLE photometry and deriving the precise times of minima, the following ephemerides were used for the light curve analysis:

$$\text{Prim.Min.} = \text{HJD}\ 2\,453\,901.4155 + 1\overset{\text{d}}{.}25652350 \cdot E.$$

These ephemerides are also suitable for planning future observations. From the observations we determine that the orbit is circular (i.e. no deviation of secondary minima appears).

3. Analysis

The light curve fitting of available photometric data was performed using the program PHOEBE, ver. 0.31a (Prša & Zwitter 2005), which is based on the Wilson-Devinney algorithm (Wilson & Devinney 1971) and its later modifications.

The following procedure was used for the analysis. First, the ephemerides and temperature of the primary component were fixed for the entire computational process. The temperature of the primary component was estimated from its photometric index. Owing to many different sources and a rather wide range of magnitude values for the red and infrared filters, this approach was found to be problematic. For example, the $(V-R)$ photometric index ranges from −0.60 mag (Zacharias et al. 2004) to 0.065 mag (Derekas et al. 2007), which yields a range of spectral types from O to A. On the other hand, Larsen et al. (2000) published the Strömgren *uvby* photometry, which can be transformed (Harmanec & Božić 2001) into the Johnson *UBV* system. After these transformations, the unreddened values of the photometric indices $(B-V)_0 = -0.23$ mag resulted, as did $(U-B)_0 = -0.87$ mag, which clearly show the star to be about a B2V spectral type (Golay 1974). Although the star is not single, the two components are rather similar (see below), so we accepted this estimation. The resulting value of $E(B-V) = 0.42$ mag was quite surprising, because it is a bit larger than commonly used for LMC binaries, but it is still acceptable (Larsen et al. 2000). Another source of Johnson magnitudes is, for example, the one by Zaritsky et al. (2004), who published the *UBVI* photometry. Regrettably, this photometry is also unusable due to larger errors and unacceptable $(U-B)_0$ values. To conclude, after assuming the B2V spectral type, we fixed the temperature at $T_1 = 21\,000$ K (Worthey & Lee 2011) for the computing process.

Owing to rather different quality of the individual light curves, the first OGLE data set (2002.5) was used as the initial one. With this light curve we analysed the system, resulting in a set of parameters for both components, see Table 1. These parameters are the best we were able to derive from the available light curves. The values for temperature, the secondary component, Kopal's modified potential, luminosities, etc. were used for the subsequent light curve analysis of data obtained at different epochs. However, the lack of other relevant information (e.g. from spectroscopy) meant that some of the parameters have to be fixed for the whole analysis. We assumed a circular orbit (i.e. $e = 0$) and a mass ratio $q = 1$. The albedo coefficient remained fixed at value 1.0, gravity darkening coefficients at $g = 1.0$, and the synchronicity parameters at $F = 1$. The limb darkening coefficients were interpolated from the van Hamme's tables (van Hamme 1993). No third light was detected for any of the light curves.

This analysis is based on the assumption that the two components are rather similar to each other. This presumption was derived from the resulting parameters from Table 1 (similar temperatures and luminosities), as well as from the $(B-R)$ photometric index at various orbital phases as derived from the MACHO data. On the other hand, the use of photometry by Larsen et al. (2000) was obtained during many nights of observations, which did not take the current orbital phase of the binary into account, which means that some of the photometric data points could have been obtained during the eclipses. However, no other better photometry is available, and owing to the duration of eclipses (both about 1/10 of the orbital period), only about 20% of the data points are likely to be influenced by the eclipses. However, we still believe that this does not play a significant role because of the similarity of the two eclipsing components. The best way would be to obtain the individual times of observations for the photometry of Larsen et al. (2000), but after communicating with the author, this information is no longer available.

Table 1. Parameters of the light curve.

Parameter	Value	Error
T_1 [K]	21 000 (fixed)	
T_2 [K]	20 040	260
Ω_1	5.426	0.048
Ω_2	4.548	0.031
L_1 [%]	41.0	2.4
L_2 [%]	59.0	2.6
r_1/a	0.267	0.005
r_2/a	0.284	0.006
$q = M_2/M_1$	1.00 (fixed)	
e	0.00 (fixed)	
$F_1 = F_2$	1.00 (fixed)	
$A_1 = A_2$	1.00 (fixed)	
$g_1 = g_2$	1.00 (fixed)	

During the fitting process, the mass ratio can also be fitted. As a result, we made this attempt, but it did not result in any significant improvement of the fit. The mass ratio is only poorly constrained here, which agrees with a previous finding that detached eclipsing binaries with only partial eclipses are not suitable for deriving the mass ratio only from the light curves, see e.g. Terrell & Wilson (2005). We can therefore only roughly estimate the uncertainty of the mass ratio to be about 0.1.

A sample of fitted light curve plots at different time epochs is given in Fig. 1. As one can see, the depths of both primary and secondary minima are changing over the two decades. From these fits, the individual inclination angles as derived from the Wilson-Devinney algorithm are given in Table 2 and plotted in Fig. 2. The inclination is seen to change quite fast (more than 2° every year), and the amplitude of photometric variation is rather shallow at present.

One can also ask how we dealt with the different light curves in different filters for the complete analysis. Our new observations were obtained in the same filter (I) as the OGLE survey. The second OGLE filter (V) was not used because of a limited dataset. On the other hand, both the B and R filters from the MACHO survey were used for the analysis. The light curves in different filters and different epochs were analysed separately, resulting in different inclination angles. These two values of inclination angles (but obtained during the same epoch) were averaged into the value presented in Table 2. We could afford to combine different filters and instruments for the analysis, because the different luminosity levels for different passbands were also computed.

4. Results

The system undergoes a nodal precession of its orbit, which is probably caused by an orbiting third body. This effect of binary orbit precession is nothing new; however, it has been observed and analysed for the first time for an extragalactic source.

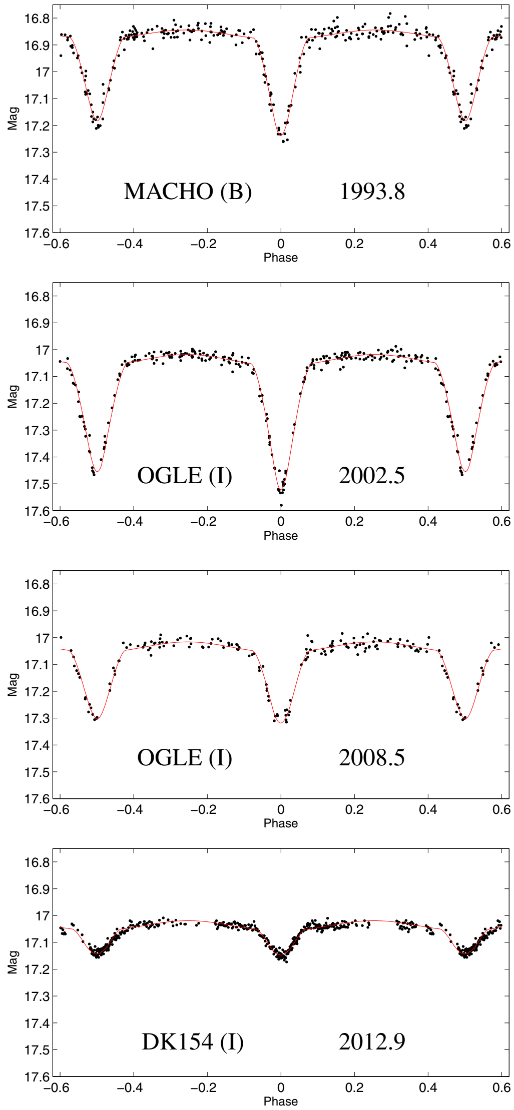

Fig. 1. Sample of plots of the light curves at different epochs. Since the range for the y-axis is the same for all plots, the change in amplitude is clearly visible.

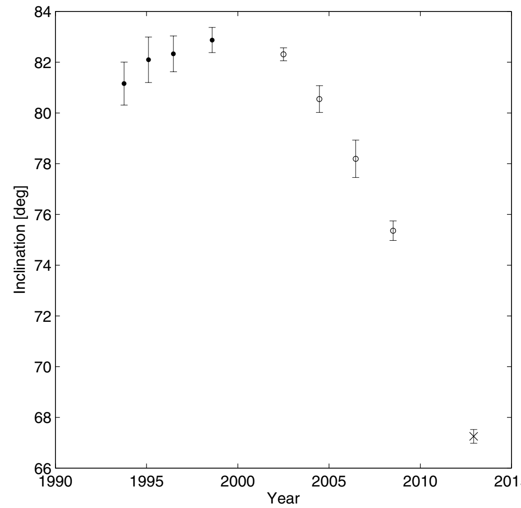

Fig. 2. Changing inclination as a function of time. For the explanation of the symbols see Table 2.

Table 2. Inclination angles as derived from different light curves.

Year	Source	Inclination [deg] value	error	Fig. 2 symbol
1993.770	MACHO	81.16	0.85	•
1995.104	MACHO	82.09	0.90	•
1996.473	MACHO	82.33	0.70	•
1998.594	MACHO	82.87	0.50	•
2002.504	OGLE	82.31	0.26	○
2004.474	OGLE	80.55	0.53	○
2006.459	OGLE	78.19	0.74	○
2008.510	OGLE	75.36	0.38	○
2012.925	DK154	67.25	0.27	×

Notes. Mean epochs for each data set are given.

One can compute the nodal period from the equation given in Söderhjelm (1975):

$$P_{\text{nodal}} = \frac{4}{3}\left(1+\frac{M_1+M_2}{M_3}\right)\frac{P_3^2}{P}(1-e_3^2)^{3/2}\left(\frac{C}{G_2}\cos j\right)^{-1},$$

where subscripts 1 and 2 stand for the components of the eclipsing binary, while 3 stands for the third body. The term C is the total angular momentum of the system, while G_2 stands for the angular momentum of the wide orbit.

Unfortunately, we are not able to derive the nodal period using this equation owing to unknown individual orbital parameters and masses of the components. We therefore used a simplified approach to fitting the term "$\cos i$", as given, say, in Drechsel et al. (1994):

$$\cos i = \cos I \;\cos i_1 - \sin I \;\sin i_1 \;\cos(2\pi(t-t_0)/P_{\text{nodal}}),$$

where I is the inclination of the invariant plane against the observer's celestial plane, i is the inclination of the eclipsing binary, and i_1 is the inclination between the invariant plane and the orbital plane of the eclipsing binary.

Figure 3 shows the result of our fitting. The resulting nodal period is only about 76.9 ± 10.1 years. However, because of the poor coverage of this period with only two decades of data, this result is still rather preliminary. New and more precise observations (both photometry and spectroscopy) are needed in upcoming years. The resulting period of nodal precession is the second shortest among known systems to date, the fastest motion being that of the well-known system V907 Sco (Lacy et al. 1999) with its nodal period about 68 years. For MACHO 82.8043.171, we do expect that the photometric eclipses will stop as late as about 2017. Until that time only very shallow ellipsoidal variations of the order of 0.03 mag (I filter) remain.

As a by-product we also derived the inclination angles I and i_1 from the equation for $\cos i$. These two quantities resulted in

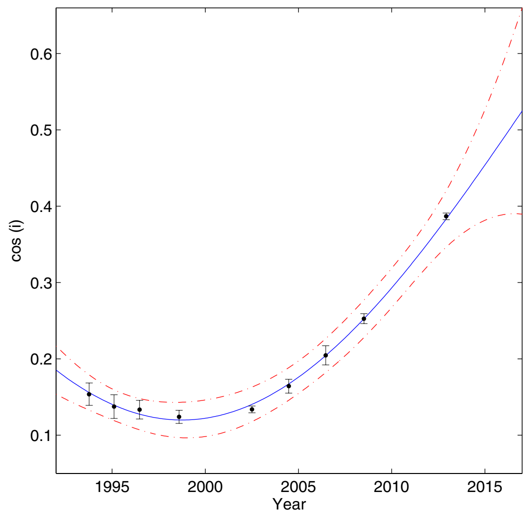

Fig. 3. "cos i" term and its final fit (see the text). A confidence level of 95% is shown with the dash-dotted lines.

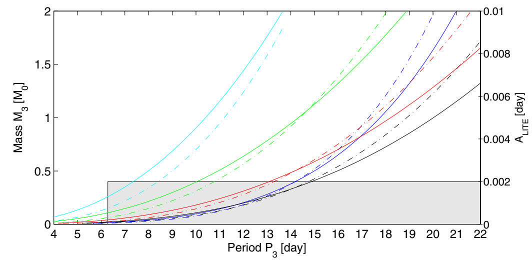

Fig. 4. Predicted parameters of the third body resulting from the nodal period. Its period (the x-axis) versus its mass (y-axis, solid curves) is computed from the nodal period, and the corresponding amplitude of the light-time effect was computed (y-axis on the right, dash-dotted curves). The shadowed area represents the possible parameters. Different colours represent different orientations of the orbit in space. See the text for details.

$I = 41.1° \pm 11.8°$ and $i_1 = 42.0° \pm 13.2°$. The values define the orientation of the system in space and towards the observer (see Fig. 2 in Söderhjelm 1975). Both these angles could potentially be used for future dynamical studies, should the third-body orbit be discovered via spectroscopy.

5. Discussion

Discovering the nodal precession of MACHO 82.8043.171, one can ask whether the third body causing this effect is detectable with current data or facilities. The easiest method is the light curve analysis and detection of the third light. However, no such additional light was discovered, so that it gives some constraints on this body. Assuming a detection limit of about 1% of the total light, then the undiscovered third component has to be spectral type A2 or later, assuming it lies on the main sequence. We can only speculate about its period and semimajor axis, so that the amplitudes of radial velocity variations are also questionable. The absence of any third light makes it similar to the recently discovered system HS Hya (Zasche & Paschke 2012), where the third body causing the nodal precession of the eclipsing pair also cannot be detected in the light curve solution, but was discovered via spectroscopy.

Moreover, the configuration of the system has to be hierarchical because of its stability (Harrington 1992). Another limiting factor is the fact that any variation in the times of minima is detectable in the O–C diagram of MACHO 82.8043.171 (also analogous to HS Hya). As a result, a detection limit of about 0.002 days also yields some constraints on the third-body orbit, mainly the period, see e.g. Mayer (1990). Using the equation introduced in Söderhjelm (1975), and applying many ad hoc assumptions (e.g. orientation of the orbit in space, fixing the eccentricity to zero), we can roughly estimate, for example, the orbital period of the third component. See Fig. 4 for some results, where the predicted masses (solid curves) and amplitudes of the light-time effect (dash-dotted curves) are plotted with respect to the orbital period P_3. The individual colours stand for different inclinations of the orbits: 90° (blue), 70° (black), 50° (red), 30° (cyan), and 10° (green), respectively. Moreover, the dynamical stability criterion also exists, and it gives the lower limit of the third-body period: $P/P_3 > 5$, see e.g. Tokovinin (2008), resulting in a minimum period of about 6.28 days. Considering all these criteria, the shadowed area in Fig. 4 shows the most probable solutions. The expected period P_3 should probably be from 6 to 15 days. Moreover, as we can see from Fig. 4, the limit of no detectable period variation of the order of 0.002 day gives a better constraint on the mass of the third body (about 0.4 $M_\odot$) than the absence of the third light, which yields an upper limit of mass of about 2 $M_\odot$. Such a companion is therefore probably an M-dwarf star.

Besides MACHO 82.8043.171, we currently know of only four other systems with derived nodal periods. However, this unique system is the first analysed eclipsing binary with changing inclination outside our own Galaxy. The authors are aware of the most important deficiency of the present analysis, which is the lack of radial velocity measurements, or the detailed spectroscopic study discovering the third component. On the other hand, as we can see, for example, in the system of HS Hya, the third body could have a period of hundreds of days, so to discover it one needs spectroscopic monitoring over several months. Moreover, other EBs within the LMC are much brighter and also have longer periods. There is still no radial velocity study of an LMC eclipsing binary with such a short orbital period. Precise spectroscopic observations for such a faint target would only be possible using 4 m class telescopes or even larger. This first analysis of MACHO 82.8043.171 could serve as a starting point for other astronomers to initiate observing campaigns or to submit observing proposals for this target on large telescopes.

6. Conclusion

More detailed study of such systems would potentially be very important for several reasons. First, EBs are still the best method for deriving precise masses and radii of stars, and also for calibrating the cosmic distance ladder. Secondly, the chemical compositions of such systems should be studied in order to compare the LMC and our Galaxy. There are some traces of different composition between LMC, SMC, and our Galaxy stars, which were derived using EBs (Ribas 2004). Additionally, the EBs serve as independent distance indicators to the LMC (up to 2%, Pietrzyński et al. 2013). And finally, the changing inclination indicates that there is a hidden component orbiting this EB pair, which could tell us something about the stellar multiplicity of the LMC in general. Observing the suspicious EBs would help us discover these third bodies, which is otherwise rather complicated for such distant objects. (Spectroscopy is time-consuming and magnitude-limited, and interferometry cannot be used for Magellanic clouds.)

Additionally, multiple systems with moving orbital planes are ideal astrophysical laboratories for dynamical studies. The observable quantities can be directly compared with theoretical models. Therefore, each new system is very promising. In our Galaxy we know of 11 such systems nowadays (Zasche & Paschke 2012). Graczyk et al. (2011) noted 17 systems in the LMC, and from the *Kepler* data there were seven more of these binaries (Rappaport et al. 2013).

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Ole Rømer's method still on the stage: the study of two bound eclipsing binaries in quintuple system V994 Her

P. Zasche[1]⋆ and R. Uhlař[2]

[1]*Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague, V Holešovičkách 2, CZ-180 00 Praha 8, Czech Republic*
[2]*Private Observatory, Pohoří 71, CZ-254 01 Jílové u Prahy, Czech Republic*

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ABSTRACT

More than three hundred years ago, Ole Rømer measured the speed of light purely by observing the periodic shift of the observed eclipse arrival times of Jupiter's moons arising from the varying Earth–Jupiter distance. The same method of measuring the periodic modulation of delays is still used in astrophysics. The ideal laboratories for this effect are eclipsing binaries. The unique system V994 Her consists of two eclipsing binaries orbiting each other. However, until now it was not certain whether these were gravitationally bound and what their orbital period was. We show that the system is in fact quintuple and the two eclipsing binaries are orbiting each other with a period of about 6.3 yr. This analysis was performed only through studying the periodic modulation of the two periods: during the periastron passage one binary has an apparently shorter period, while the other one is longer, exactly as required by theory. Additionally, it was found that both inner eclipsing pairs orbit with slightly eccentric orbits, undergoing slow apsidal motion with a period of the order of centuries.

Key words: binaries: eclipsing – binaries: visual – stars: fundamental parameters – stars: individual: V994 Her.

1 INTRODUCTION

Eclipsing binaries are ideal astrophysical laboratories, and even after more than a century of intensive photometric and spectroscopic monitoring, they still represent the best method by which to determine the masses, radii and luminosities of stars. Thanks to modern ground- (and space-) based telescopes we are able to discover these objects in other galaxies and to apply the same methods as used in our Solar neighbourhood. One very specific method is the analysis of their orbital periods. Using the precise times of minima (centres of eclipses of the components), we can determine whether a system's period is constant, accelerating, decelerating or periodically alternating. If we detect a periodic shifting of the times of minima, we determine that there is an additional component in the system, which is orbiting around the barycentre with the eclipsing pair. If the system is moderately inclined to the observer, the light from the eclipsing binary needs alternately more and less time to reach us as it moves away from and closer to the observer as it orbits the unseen component. This method is in fact the same as was used in the 17th century by Ole Rømer when measuring the finite speed of light using the eclipse times of Jupiter's moons (see e.g. Cohen 1940).

⋆ E-mail: zasche@sirrah.troja.mff.cuni.cz

2 THE SYSTEM V994 HER

When dealing with eclipsing binaries, we have a few advantages. First of all, there are currently thousands of eclipsing binaries known. Moreover, the time baseline of observations for some eclipsing binaries is more than a century long. Importantly, the observations are very easy to obtain, even with small telescopes.

This is the case for one very interesting eclipsing system, V994 Her (HD 170314, ADS 11373 AB; $V = 7.00$ mag). In 2008 it was discovered (Lee et al. 2008) that V994 Her was the first (at that time) system consisting of two eclipsing binaries. From one point on the sky we can see two different sets of eclipses, one with a period of $P_{\mathrm{A}} = 2.08$ d while the other has a period of $P_{\mathrm{B}} = 1.42$ d. The star was also observed with the *Hipparcos* satellite (Perryman et al. 1997), however the strange eclipsing behaviour was missed for about 15 years. A complete study of this interesting system was made (Lee et al. 2008), also on the basis of new spectroscopic observations, yielding a set of physical parameters of all four eclipsing components. This study showed that the system consists of two pairs: A (B8V + A0V) and B (A2V + A4V). All components are well-detached and still located on the main sequence. Both orbits are slightly eccentric.

On the other hand, one important question arises: whether the two eclipsing components comprise one gravitationally bounded system or whether the system is only an optical binary. The mutual orbital period of the two pairs can be very long and long-time monitoring is rather time-consuming. The system V994 Her also

Table 1. List of currently known double eclipsing systems.

System Name	Other designation	RA J2000.0	Dec. J2000.0	*V* (mag)	Period A (d)	Period B (d)	Type
OGLE LMC-ECL-16549	OGLE LMC-SC3 179761	05 28 09.41	−69 45 28.60	18.216	164.789 640	0.818 033	EA + EW
CzeV343	GSC 02405-01886	05 48 24.01	+30 57 03.60	13.679	1.209 373	0.806 931	EA + EA
TYC 3807-759-1	GSC 03807-00759	09 30 10.75	+53 38 59.80	9.538	1.305 545	0.227 715	EA + EW
BV Dra	HIP 74370	15 11 50.36	+61 51 25.25	8.040	0.350 067		EW +
BW Dra	HIP 74368	15 11 50.09	+61 51 41.16	8.834		0.292 165	+ EW
V994 Her	GSC 02110-01170	18 27 45.89	+24 41 50.66	7.001	2.083 269	1.420 038	EA + EA
KIC 4247791	TYC 3124-1500-1	19 08 39.57	+39 22 36.96	11.645	4.100 871	4.049 732	EA + EA

contains one more distant component observed interferometrically (Mason et al. 2001), the period of which was estimated at about a few thousand years. Therefore, the authors (Lee et al. 2008) speculated that the two eclipsing pairs could be identified with these two visual components. For a brief review of quadruple systems with two eclipsing binaries, see Cagaš & Pejcha (2012). Currently we know only six such systems: BV + BW Dra, V994 Her, CzeV343 (Cagaš & Pejcha 2012), KIC 4247791 (Lehmann et al. 2012), TYC 3807-759-1 (Lohr et al. 2013) and OGLE LMC-ECL-16549 (Graczyk et al. 2011); see Table 1 for details.

3 ANALYSIS

Here we introduce an original approach of delay-time variations of both eclipsing pairs, showing that the system is in fact quintuple and the two inner pairs are orbiting around each other with a much shorter period. We obtained many new observations of both pairs, as well as re-analysing *Hipparcos* and All-Sky Automated Survey (ASAS: Pojmanski 2002) photometry. The individual times of minima are presented in the Appendix (Table A1). These data were analysed simultaneously in a combined approach consisting of fitting both orbits together using a well-known method usually called the 'light-time effect' or 'light-travel-time effect' (hereafter LTTE), described elsewhere (e.g. Irwin 1959; Mayer 1990).

This method has been used for dozens of binaries in the past; however, V994 Her is the first eclipsing binary system in which the method can be applied to both binaries. The main advantage of this approach is that both eclipsing pairs serve as strictly periodic 'stellar lighthouses', the apparent period changes of which can be studied.

We used our new code for computing this combined approach of deriving both inner orbits (their periods and apsidal motion), together with the long orbit of mutual motion of the two pairs. Altogether 15 parameters were fitted, using all available times-of-minima observations (for A and B pairs: (25+36) published minima together with (18+17) new unpublished data points).

In Fig. 1 we plot the observed minus calculated (O−C) diagrams for A and B pairs, showing their period changes (the *y*-axis) with respect to time (the *x*-axis). In these plots, positive *y* values indicate that the detected signal occurs later while negative values indicate earlier detection than predicted from strictly periodic linear behaviour. As one can see, rapid period changes near periastron passage are clearly visible for both pairs. Most of the parameters for the LTTE fits for A and B are mainly the same. The exceptions are the omega angles (the argument of periastron, $\omega_A = \omega_B + 180^\circ$) and the $(O - C)$ amplitudes (A_A and A_B, see below). The long-term modulation arises from the apsidal motion of the inner orbits, because both are slightly eccentric. For the final parameters of the fit see Table 2.

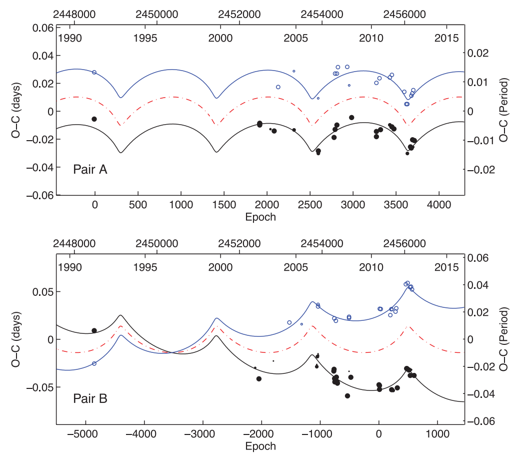

Figure 1. Plot of the O−C diagrams of both pairs. The dots stand for primary, the open circles for the secondary minima; the bigger the symbol, the higher the weight. The dash–dotted lines (red in the online article) indicate the LTTE fit, while the lower and upper curves (black and blue in the online article, respectively) represent the final fit (LTTE plus apsidal motion).

Table 2. V994 Her: final parameters of the fits for A and B pairs.

Parameter	Unit	Pair A Value	Pair A Error	Pair B Value	Pair B Error
JD_0	HJD	2448501.1302	0.0110	2455375.4555	0.0062
P	Day	2.0832691	0.0000038	1.4200381	0.0000051
e		0.0311	0.0074	0.1258	0.0032
ω	Deg	16.0	4.2	313.8	2.8
$d\omega/dt$	Deg/Cycle	0.0032	0.0013	0.0124	0.0010
p_3	Year	6.33	0.56	6.33	0.56
T_0	HJD	2456067	199	2456067	199
A	Day	0.0102	0.0042	0.0139	0.0057
ω_3	Deg	256.2	24.1	76.2	24.1
e_3		0.747	0.182	0.747	0.182

4 RESULTS

The main result of our analysis is the discovery that the two eclipsing pairs orbit around each other and also show detectable period modulation, together with slow apsidal motion. The period of motion of the apsides for pair A resulted in about (627 ± 439) yr, while for pair B the period is about (113 ± 10) yr.

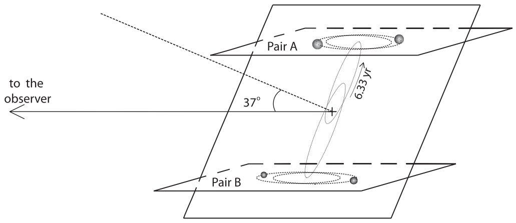

Figure 2. Schematic sketch of the V994 Her system (not to scale). The orbital planes of both A and B pairs are almost perpendicular to the celestial plane (i.e. edge-on to the observer: 84° and 86°, respectively).

From the parameters of LTTE we determine the semi-major axis of the LTTE orbit and, using the distance from the *Hipparcos* satellite (Perryman et al. 1997) of $\pi = (3.90 \pm 0.74)$ mas, we also derive the angular separation of the two eclipsing binaries on the sky. This resulted in an angular separation of $\Delta\alpha_{12} = (27.6 \pm 6.8)$ mas, which is well within the limits for modern stellar interferometers; hence its discovery is expected soon. Moreover, this indicates that the previously mentioned star at ∼1 arcsec away is another star and not the eclipsing one as suggested by Lee et al. (2008). Membership of this distant component to the eclipsing pairs was suggested via similar proper motions: see e.g. the Washington Double Star (WDS) catalogue[1] (Mason et al. 2001). Thus we have a quintuple star system. We currently know only 20 quintuples (Eggleton & Tokovinin 2008).

From the parameters of LTTE one can also calculate the mass function of the distant body:

$$f(m_3) = \frac{(m_3 \sin i)^3}{(m_1 + m_2 + m_3)^2} = \frac{1}{p_3^2}\left[\frac{173.15\,A}{\sqrt{1 - e_3^2 \cos^2\omega}}\right]^3,$$

see e.g. Mayer (1990). Using the masses of both pairs as determined by Lee et al. (2008), we can also calculate the inclination between the eclipsing binary and the LTTE orbit. If we label the inclination between the orbit of pair A and the LTTE orbit as '$i_{\rm A}$' and vice versa for B, then one can derive

$$\frac{m_{\rm A}\,A_{\rm A}}{\sin i_{\rm A}} = \frac{m_{\rm B}\,A_{\rm B}}{\sin i_{\rm B}}.$$

From this equation and the mass function found from the LTTE, we can directly determine the inclination between the orbits. This results in $i_{\rm A} = 37.1^\circ \pm 7.3^\circ$, while $i_{\rm B} = 36.8^\circ \pm 6.8^\circ$. Evidently the inclinations derived from both A and B pairs are comparable and hence we know the absolute orientation of the orbit in space (see Fig. 2). This is the first time that the mutual inclination between the orbits of the eclipsing pairs has been measured. Only about twenty other systems with unambiguous mutual inclinations between the eclipsing and outer orbits are known; see e.g. O'Brien et al. (2011).

5 DISCUSSION AND CONCLUSIONS

V994 Her is an interesting target for a future study. However, there still remain some open questions. These include, for example, detection of the distant component in the spectra and determination of its orbital period. Additionally, some of the orbital elements of the 6.3-yr orbit are still unknown, for instance the longitude of the ascending node Ω. The long-term evolution of outer and inner orbits should be studied over longer time-scales. However, detecting the mutual motion of the two eclipsing pairs is a unique discovery and we still hope to find similar configurations in other multiple systems also.

Surprisingly, for this analysis there was no need of spectroscopic observations of the radial velocities of the long-period system, which would be rather complicated given the current observing-time allocations on larger telescopes needed for such studies. It is noteworthy that all of our new observations were carried out with telescopes of 20-cm aperture or smaller by an amateur astronomer. As clearly demonstrated by this study, scientifically valuable results can be secured with small telescopes by amateur observers.

[1] http://ad.usno.navy.mil/wds/

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