Referee report of the PhD thesis of MSc. David Bahena-Bustos "Physics of Hot Luminous Stars. Structure, Evolution and Nucleosynthesis of the First Stars"

The PhD thesis of MSc. David Bahena-Bustos is devoted to a very actual topic of the study of the evolution of first stars that existed in the Universe. The correct knowledge of properties of first stars and their evolution is very important for our understanding of structure formation in our Universe.

The PhD thesis itself has a very impressive extent (nearly 500 pages). The broad theoretical background of first star studies is discussed in the first three chapters of the thesis. The observations that play a key role in our current view of the properties of the Universe and its evolution are summarised in the second chapter. The observations of massive stars and extremely metal-poor stars are also discussed in this chapter. The next chapter is devoted to the discussion of cosmological models, again with emphasis on our current view of properties of the Universe, its evolution and structure formation from primordial density fluctuations.

The next chapter summaries available studies devoted to the first stars. The formation of first stars from primordial density fluctuation is discussed on the basis of ΛCDM theory. The individual steps that lead to the formation of first stars (i.e. the protostellar collapse, the fragmentation, the accretion process) are reviewed. The theoretical reasons that lead to the common view that the first stars were very massive (with masses of order $100\,M_{\odot}$) are thoroughly discussed. Finally, the cosmological implications of first stars like their contribution to the reionization and reheating of the Universe and enrichment of the intergalactic medium with metals are given.

The basic equations that are used for the modelling of stellar structure and evolution are summarised in the following chapter (No. 5). Also the method of solution of these equations is described there. The detailed description of basic physical processes that are incorporated in models of stellar evolution (i.e. the equation of state, convection, mass-loss and opacity) is given in the next chapter. Finally, the part of PhD thesis devoted to the physical description of stellar modelling is closed by the chapter that describes the thermonuclear reactions with emphasis on those reactions that are important for hydrogen and helium burning phases of the stellar evolution.

The basic results of PhD thesis are described in the final five chapters of the thesis. First, zero age main sequence models for stars with masses $0.8 - 10^4\,M_{\odot}$ with different initial metallicities are presented. Next, the evolutionary models of massive very low metallicity stars with and without mass loss are provided. Finally, the nucleosynthesis in these stars is discusses and the yields from studied stars are calculated. In these last chapters (that constitute a major part of the thesis) the original and valuable scientific results obtained by the author of PhD thesis are provided. These results may be used by other astronomers working in the field of first stars and those studying the processes in the early Universe.

Nevertheless, there are some minor mistakes, omissions and weak points in the PhD thesis. Some of them occur in the introductory chapters that describe our current view on the evolution of the Universe, the formation of the structure within the preferred ΛCDM theory and the role of massive stars in our Universe. Generally, there is an impressive number of citations included in the thesis. The author provides remarkably broad view on the subject of study. However, in many cases the concluding remarks are missing and the reader may feel finally a little bit confused. In some cases the matter does not seem to be very well ordered. Another general weak point of the PhD thesis is that some papers that can be considered as outdated now are discussed in detail.

As an example of the weak points in the first introductory chapter of PhD thesis I include those remarks:

- page 4: The galactic Pop III stars are defined as stars with $Z = 10^{-6}$ and similarly pregalactic Pop III stars are defined. But it is unclear to me how the selected values of metallicities were obtained. The term "galactic/pregalactic" Pop III stars is also unclear (especially in the view of hierarchical structure formation) and does not play, to my knowledge, in the present studies of first stars any important role.

- page 4 and the following ones: Papers, that are (in my view) only of a historical importance are thoroughly discussed. For example, the twenty year old papers on massive star evolution are outdated now, since our understanding of many physical ingredients of these models (e.g. opacity, mass-loss) as well as the overall physical description (inclusion of rotation and magnetic fields) significantly changed. The discussion of recent work of e.g. Geneva modelling group would be more valuable.

- page 6: The stellar black holes can not solve the dark matter problem, because the dark matter was already present in the epoch of the reionization.

- page 30: It is not correct that the baryon-photon ratio η is now obtained by comparison of predictions of big bang nucleosynthesis with measured abundances (that are expected to be of a primordial origin). The current cosmological observations (WMAP) are able to obtain η more precisely and the predictions of big bang nucleosynthesis are used as an additional test of cosmological theories.

- page 31: Apparently the scaled Hubble constant h is used without proper definition (at the same page h_{100} is introduced that have likely the same meaning). Its value in Tab. 2.1 is incorrect.

- page 32: I am completely missing any more detailed discussion of the stellar rotation, its influence on the stellar rotation and the problem of $\Omega\Gamma$ limit (e.g. work of Geneva modelling group, Maeder & Meynet, 2005, A&A, 440, 1041; Maeder & Meynet, 2000, A&A, 361, 159).

- page 34: Current hot star wind theory does not generally predict that modest (even relatively fast) stellar rotation can create wind equatorial density enhancement (Owocki et al. 1996, ApJL, 472, 115).

- page 46: It is not true that the age of the Universe must be less than H_0^{-1}.

- page 51: Ω_r is missing in the equation for Ω_{tot}.

- page 74: The redshift of the collapse in the work of Haiman, Thoul & Loeb (1996) is $z = 10$, not $z = 0$.

- page 127: Castor, Abbott & Klein (1975) did not predicted that the mass-loss rate depends on the stellar luminosity linearly (viz. Eq. (6.78) of the thesis).

- page 144: $\dot{M}$ is sometimes defined as a positive quantity, sometimes as a negative one, citations to new results (e.g. Vink et al., 2001, A&A, 369, 574) are missing.

- Final conclusions are missing.

Despite of the criticism mentioned above, I think that valuable scientific results were obtained in the refereed PhD thesis. The derived models can be used by the astrophysical community for the study of first stars and their influence on the evolution of matter in the early Universe. The PhD thesis shows that the author is able to independently obtain valuable scientific results.

Generally, the discussion of the dependence of mass-loss rate on metallicity is confusing. There are observational results that show the dependence of $\dot{M}$ on metallicity. The work of Brunish & Turan (1982b) and the following discussion of increase of mass-loss rate with decreasing metallicity (page 148) in evolutionary models is incorrect in that sense, because Brunish & Turan (1982b) did not accounted the explicit dependence of $\dot{M}$ on metallicity.

Finally, the introductory part can be written in a more concise form (some parts are repeated over and over again, I have found that lists on pages 18 and 102 are nearly identical, also some parts of 3rd paragraph on page 100 are nearly identical with 3rd on page 94).

The comments to the introductory part of PhD thesis do not influence the results obtained in the second part of the thesis that describe the author's own work. Except some formal comments that are related to this second part of the thesis (for example: most of the extensive tables and graphs can be included in the possible Appendix part of the thesis or on a CD; terms like $\log T_{\rm eff}$, $\log R$ used in the thesis are incorrect (although these terms are frequently used in the astrophysical literature); incorrect equations of CNO cycle on page 473) there are some more important comments:

- page 151: Which form of the opacity description was used in the models? Really that given in Eq. (6.100)? Tables from the Opacity Project or OPAL were not used?

- page 153: Are the nuclear reactions given in Fowler et al. (1975) and Harris et al. (1983) are the most accurate ones that are currently available? Were some improvements of these reactions included into the code?

- page 260: How can the size of the convective core (this parameters is – as I understand – constant for a given stellar model) depend on the radius r within the star?

- page 320: The sentence "When the transition to helium burning is explosive, stars contract..." is not clear to me.

- page 335: An important reason for the inclusion of mass-loss (even in a very rough form) is missing: the star may spin up at the stellar surface during its evolution and the equatorial rotational velocity may be close to the critical rotational velocity (more generally: the discussion of $\Omega\Gamma$ limit (e.g. Maeder & Meynet, 2000, A&A, 361, 159) is not included here).

There are also some general remarks:

- The properties of stellar models are given in a great detail, but the physical explanation of behaviour of both stellar parameters and the differences in stellar structure between individual models is often missing.

- Since the results presented in the thesis may have a broader impact, I would advocate for a more detailed comparison between results obtained by the author and those available in the literature (not just to summarise the different numbers obtained) and possibly to compare stellar models with solar metallicity with observations.

- From the presented thesis I understood that more models were calculated (this is discussed e.g. on page 338). What are the parameters of these models?