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Subluminous O Stars from the ESO Supernova Progenitor Survey - Observation versus Theory

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Abstract. The ESO Supernova Progenitor Survey (SPY) has identified 58 (mostly helium-rich) subluminous O stars. We use the Balmer line strength to distinguish sdO from He-sdO (no Balmer lines) and present the results of the analyses of high resolution optical VLT-UVES spectra using an extensive grid of NLTE atmosphere models covering a large range in T_{eff}, $\log g$ and helium abundances. The stellar atmospheric parameters are derived from line profile fits using a χ^2 technique. The resulting distribution in the (T_{eff}, $\log g$) diagram as well as the luminosity function are discussed in the context of stellar evolution scenarios. By combining our results with those for the sdB stars from SPY (Lisker et al. 2004) we discuss the implications for binary population synthesis models of Han et al. (2003). Models with a low CEE efficiency and a constant mass ratio distribution provide a reasonable explanation of the observed properties of the SPY sample of sdB and sdO stars indicating that the sdO stars form the hot and luminous extension of the sdB sequence. However, for the He-sdO stars none of the considered evolution scenarios are in agreement with the measured parameters of our programme stars. We conclude that He-sdO stars are formed by a different process than the sdB and sdO stars.

1. Introduction

The ESO Supernova Progenitor Survey (SPY; Napiwotzki et al. 2003) has identified 137 hot subluminous stars. 79 of them were classified as hydrogen rich sdB stars, 58 of them were classified as subluminous O stars. The sdB spectra have been studied by Lisker et al. (2004, see also these proceedings). They tested several evolutionary scenarios by comparing the results of their spectroscopic analyses to model predictions. In particular, the binary population synthesis models of Han et al. (2003, hereafter HPMM) were discussed. However, two diagnostic tools used yielded conflicting results. Moreover, the HPMM models predict that some EHB stars should be even hotter than those found in the sdB star sample of Lisker et al. (2004). This led the authors to the conclusion that the subdwarf sample may not be sufficiently complete to describe the whole parameter range covered by the simulations. By including the subluminous O stars we attempt here to correct for this observational bias in the study of Lisker et al. (2004).

2. Spectral Classification and Analysis

High resolution spectra covering the spectral range from 3300 Å to 6650 Å at a resolution of 0.36 Å have been obtained with the UVES spectrograph at the ESO-VLT. In the course of spectral classification we distinguished He-sdO (30) from sdO stars (28) by the absence of Balmer line absorption in the former.

An extensive grid of NLTE atmosphere models was calculated using the latest version of the PRO2 code (Werner & Dreizler 1999) that employs a new temperature correction technique (Dreizler 2003). A new detailed model atom for helium appropriate for the sdO temperature regime was constructed. 2700 partially line blanketed NLTE model atmospheres consisting of hydrogen and helium were calculated resulting in a grid of unprecedented coverage and resolution, extending from 30 000 K to 100 000 K in $T_{\rm eff}$, from 4.0 to 6.4 in $\log g$ and from -4 to 3 in helium abundance $\log N_{He}/N_H$ in order to match the diversity of observed spectra. The step sizes are 2 000 K from 30 000 K to 52 000 K and 5 000 K from 55 000 K to 100 000 K; 0.2 and ~0.5 dex, respectively.

Effective Temperatures ($T_{\rm eff}$), surface gravities ($\log g$), and helium abundances (N_{He}/N_H) for 49 stars were determined by fitting simultaneously hydrogen and helium lines to our synthetic model spectra, using a χ^2 procedure (Napiwotzki 1999). Resulting temperatures range from 36000 K to 78000 K, gravities from $\log g$=4.9 to 6.4, and helium abundances from $\log N_{He}/N_H$=-3 to +3. Four stars have temperatures in excess of 60000 K and are probably post-AGB stars and will not be discussed further.

3. Evolutionary Status

In Fig. 1 we compare the derived atmospheric parameter for the combined sample of subluminous O and B stars to the EHB band, the helium main sequence and canonical tracks for EHB and post-EHB evolution. We shall focus here, however, on the binary population synthesis models of HPMM and discuss other possibilities briefly in Sect. 3.2.

3.1. Binary Population Synthesis

HPMM calculated close binary population synthesis models and showed that core helium burning EHB stars can form via (a) stable Roche lobe overflow (RLOF), (b) common envelope ejection (CEE) and (c) by the merging of two He white dwarfs (see Lisker et al. 2004 for details). Since we do not know a priori whether the sdO and the He-sdO stars belong to the same population or not we studied two hypotheses. In hypothesis I, sdO and He-sdO stars were treated as separate populations. Thus only sdO and sdB stars were considered to belong to the EHB (see Fig. 2). Hypothesis II treats sdO and He-sdO stars as being of the same origin, thus also He-sdO stars were considered to belong to the EHB.

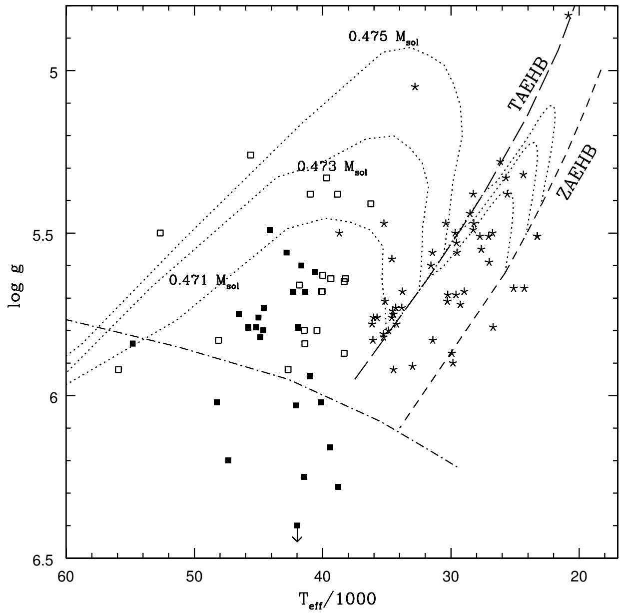

Figure 1. Distribution of parameters of our analyses of sdO and He-sdO stars, compared to all sdB stars analyzed in Lisker et al. (2004). Filled squares show He-sdO stars, open squares sdO stars and asterisks represent sdB stars. The location of the EHB band, the helium main sequence and tracks for post-EHB evolution (dotted; Dorman et al. 1993) are also shown.

We compared our results to all 12 simulation sets of HPMM in the ($T_{\rm eff}$, $\log g$)-diagram as well as by making use of the cumulative luminosity function.

Hypothesis I: sdB and sdO stars combined. Fig. 2 compares the sdB + sdO sample in the ($T_{\rm eff}$, $\log g$)-plane to six of the HPMM simulation sets and Fig. 3 its luminosity function to three simulation sets. Details of the models are given in the caption of Fig. 2. Some of the HPMM models match the observed density distribution in the ($T_{\rm eff}$, $\log g$) plane reasonably well (e.g. set 1). The location of the four hottest sdO stars in the sample, however, cannot be matched by any of the HPMM simulation sets. Another four sdO stars and one sdB have gravities too low to be explained by any of HPPM's simulation sets. These stars may have evolved beyond core helium burning (post-EHB, see also Fig. 1). Based on evolutionary time scale estimates we would expect about 10% of our sample of 72 stars to be post-EHB stars, roughly consistent with the number of stars (9) outside the predicted area in the ($T_{\rm eff}$, $\log g$) diagram. The cumulative luminosity function tends to be shifted to higher luminosities than predicted (see Fig. 3a), which again may be due to the contamination by post-EHB stars, as demonstrated in Fig. 3b) where the eight potential post-EHB stars were excluded. In addition a bump is obvious at L/L_{edd} = -2.65, which separates sdO from sdB stars. Hence the sdO stars can be regarded as the hot and luminous extension of the sdB sequence.

Simulation sets with a low CEE efficiency (such as set 1) are reasonably consistent with the observed distribution in the ($T_{\rm eff}$, $\log g$) diagram as well

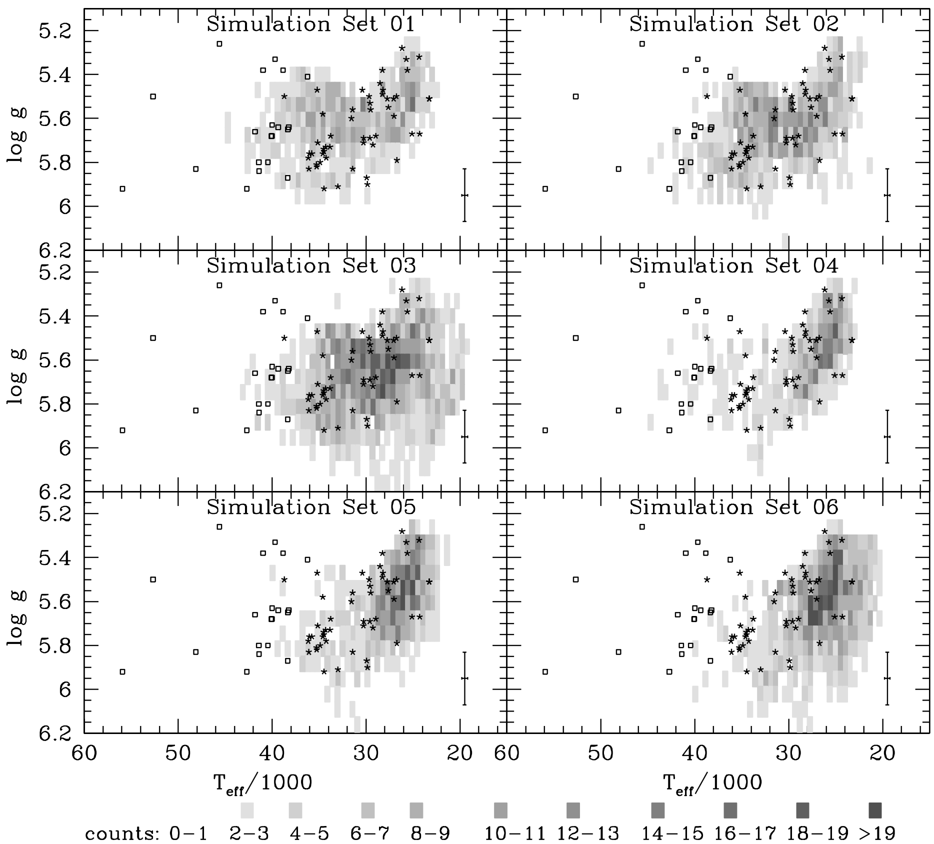

Figure 2. Comparison of atmospheric parameters for sdO and sdB stars with six of the HPMM simulation sets. The theoretical predictions are shown as shaded boxes, where a higher density per box corresponds to darker shadings. In all sets solar metalicity and a critical mass ratio q for the first stable RLOF of q=1.5 are used. In sets 1…3 a constant mass-ratio distribution was adopted whereas in sets 4…6 the component masses are uncorrelated. The CEE efficiency is 50% in sets 1&4, 75% in sets 2&5 and 100% in sets 3&6.

as with the cumulative luminosity function if one accounts for some probably evolved stars. Those sets, however, adopting the highest CEE efficiency (100%) as well as those assuming uncorrelated component masses are at variance with the observations and therefore can be excluded.

Hypothesis II: sdB, sdO and He-sdO stars combined. The combination of He-sdO and sdO stars causes several problems when compared to the HPMM models. None of the simulation sets predicts stars as hot as most of the He-sdO stars are. Inclusion of the He-sdO stars also results in a shift of the cumulative

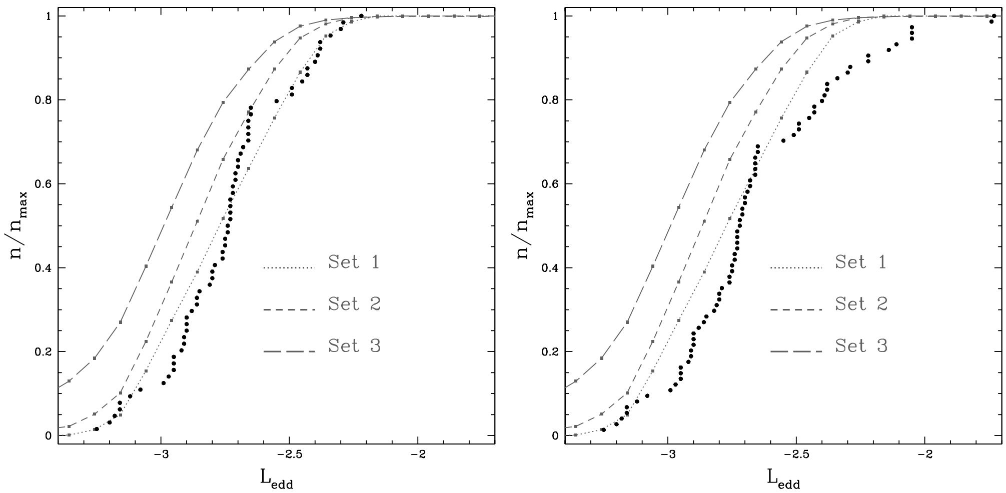

Figure 3. Cumulative luminosity functions for the combined sdB plus sdO sample (hypothesis I) for three of the HPMM simulation sets. The luminosity is given in units of the Eddington luminosity. For the model parameters see Fig. 2. **Left** hand side: **a)** all sdO stars included; **right** hand side: **b)** potential post EHB stars excluded.

luminosity function to even higher luminosities. None of the HPMM models predicts such luminosity functions. As none of the simulation sets is able to reproduce the observations for hypothesis II, we have to dismiss this assumption. Accordingly He-sdO stars do not belong to the same population as the sdO stars.

3.2. Evolutionary Status of He-sdO stars

Since He-sdO stars can not be explained by HPMM models, other possibilities for the origin of He-sdO stars have to be considered. Another close binary evolution model (the post-RGB scenario) as well as non-canonical evolution of single stars (the late hot flasher scenario) shall be discussed.

In a close binary mass transfer may occur when one of the stars fills its Roche lobe on the first giant branch (RGB) removing its envelope mostly. The remnant will evolve into a helium core white dwarf (see e.g. Heber et al. 2003). We find the distribution of the He-sdO stars (not shown) to agree reasonably well with the theoretical predictions (Driebe et al. 1998). However, in this scenario most of the He-sdO stars should be radial velocity (RV) variable. But only one out of 28 He-sdO stars shows such a RV-variability (Napiwotzki et al. 2004). Thus this scenario has to be regarded as unrealistic.

In the *late hot flasher scenario* the core helium flash occurs when the star has already left the RGB and is approaching the white dwarf cooling sequence (delayed He core flash). During the flash, He and C is dredged-up to the surface (Sweigart, 1997). We find that this scenario also can not explain the observed distribution. Therefore we discard this scenario.

Hence none of these scenarios matches the observations of He-sdO stars.

4. Conclusion

We conclude that those binary population synthesis models of HPMM with a low CEE efficiency and a constant mass ratio distribution can explain the observed properties of the SPY sample of sdB and sdO stars. Possible explanations for the evolution of He-sdO stars are more difficult to find. None of the considered evolution scenarios showed good agreement with the measured parameters of our programme stars. The lack of radial velocity variability of He-sdO stars (Napiwotzki et al. 2004) may support the merger hypothesis. However, the measured temperatures are too high. The same holds for the gravities of some of the He-sdO stars. It should be noted that in the HPMM models assumptions about the remaining hydrogen-rich envelope had to be made. The position of a model star in the ($T_{\rm eff}$, $\log g$) plane, however, depends on the envelope mass. By reducing the adopted envelope masses in the HPMM models it may be possible to match the observed positions of the He-sdO stars. The spectra of the He-sdO stars display lots of metal lines. Metal line blanketing, however, has been neglected in the model atmosphere calculations, which may have led to an overestimate of the effective temperatures. A metal line blanketed NLTE model grid needs to be calculated to derive more accurate parameters of He-sdO stars.

A larger sample of subdwarfs is needed to discriminate between the various scenarios and hypotheses outlined above. The Sloan Digital Sky survey (SDSS) will provide a promising source in the near future. Kleinman et al. (2004) already classified 240 subdwarfs from the first data release. At the end of the SDSS project spectra of more than 1000 hot subdwarfs will become available for spectral analyses.

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