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CHEMICAL ABUNDANCES OF HELIUM-RICH SUBDWARF B STARS

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Abstract. Helium-rich subdwarf B (He-sdB) stars represent a small fraction of the population of hot subdwarfs. We report recent results of our spectral analysis of He-sdB stars including surface chemical abundance measurements of a bright He-sdB star – JL 87 – measured from its high-resolution optical spectrum using line-blanketed LTE model atmospheres. These measurements provide further insight into the formation mechanism(s) of these rare faint blue stars.

Key words: stars: chemically peculiar – stars: early-type - subdwarfs – stars: fundamental parameters – stars: abundances

1. INTRODUCTION

A very small fraction ($\leq 5\%$) of the subdwarf population comprises the so called helium-rich subdwarf B (He-sdB) stars. These are "cooler" subdwarfs with strong neutral helium lines in their optical spectrum. They are found in the field of our Galaxy (Green et al. 1986) and also in some globular clusters (Moehler et al. 1997, 2002, 2004).

He-sdB stars were originally identified as sdOD in the Palomar Green survey (Green et al. 1986) as subdwarfs showing strong He I lines plus weak He II lines but with no detectable hydrogen Balmer lines. From this spectral definition one would expect all sdOD stars to be extremely helium-rich and cooler than sdO stars. However, this is not the case as our spectral analysis (Ahmad & Jeffery 2003) showed that He-sdB stars exhibit a wide range in helium abundance and temperatures similar to both sdB and sdO stars.

Since "helium-rich" can be interpreted differently by different authors, it is vital that the label "He-sdB" is used homogeneously. The new MK-type classification scheme being developed by Drilling et al. (2000) would address this issue. For now we would use the He-sdB label for all subdwarfs that have previously been identified as such by other authors.

Two evolutionary models have been proposed for the formation of these He-sdB stars. The first, by Iben & Tutukov (1986), involves the merger of two white dwarfs (WD) to form a He-sdB star. The second, by Lanz et al. (2004), involves convective flash mixing of the atmosphere of a star on the white dwarf cooling track which has previously undergone high mass-loss.

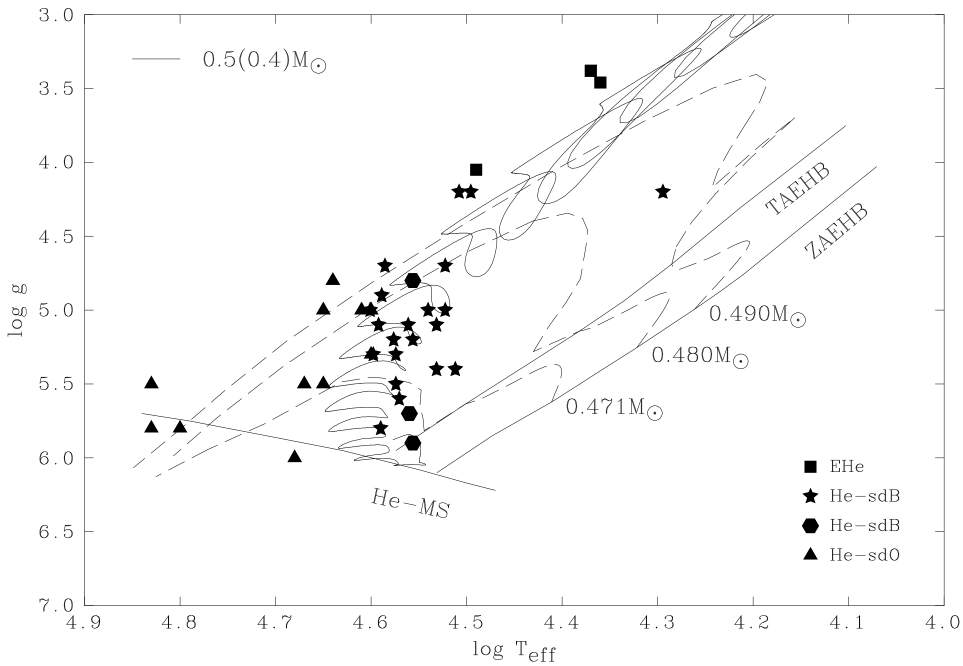

Fig. 1. Helium-rich stars on the $T_{\rm eff}$ vs. $\log g$ diagram plotted with evolutionary tracks. He-sdB stars from this study are plotted using the filled star symbol. He-sdB stars found in globular clusters (Moehler et al. 1997, 2002, 2004) are plotted with filled hexagonal symbol. Single star evolutionary tracks (dashed lines) are taken from Dorman et al. (1993) and merged He+He WD tracks (solid lines) are taken from Saio & Jeffery (2000). Adapted from Ahmad (2004).

Our aim is to establish whether either or both these models fit the observed properties of He-sdB stars. In this paper, we present physical parameters of additional He-sdB stars, new observations of the double-lined spectroscopic binary PG 1544+488, discuss preliminary abundance measurements of a He-sdB star JL 87, and discuss their possible evolution.

2. PHYSICAL PARAMETERS

In order to understand the evolution of He-sdB stars our first study involved determining the position of these stars on the $T_{\rm eff}$ vs. $\log g$ diagram. We measured atmospheric physical parameters of 22 He-sdB stars using LTE model atmospheres and the χ^2 fitting program SFIT2 (cf. Ahmad & Jeffery 2003) and plotted them on the $T_{\rm eff}$ vs. $\log g$ plane (Figure 1). In general, the effective temperatures ($T_{\rm eff}$) of He-sdB stars lie in the range 30 000–40 000 K, surface gravities ($\log g$) in the range 4.5–6.0 and helium abundance (by number, $n_{\rm He}$) in the range 0.10–0.99. Ten additional He-sdB stars appear to be hotter than 40 000 K. Since NLTE effects become increasingly important at such high temperature, these stars were not analyzed.

We have also divided our sample of He-sdB stars into carbon-rich and carbon-poor. Carbon-rich He-sdB stars show strong C II/III lines in their optical spectra and C III/IV lines in their ultraviolet (UV) spectra. It is likely that these two groups are produced by different evolutionary channels. To get some estimate of the carbon abundance in carbon-rich He-sdB stars we calculated a number of models with different carbon abundances and tried to match the strength of the carbon lines in the UV spectra. Preliminary results suggest that $n_{\rm C} \leq 0.01$ in carbon-rich He-sdB stars.

3. ABUNDANCES

The surface chemical abundances of a star provides further clues about its prior evolution. In our next study we carried out high-resolution spectroscopy of He-sdB stars to measure these abundances. Two bright ($V \sim 12$) He-sdB stars – PG 1544+488 and JL 87 – were selected for this study.

3.1. PG 1544+488

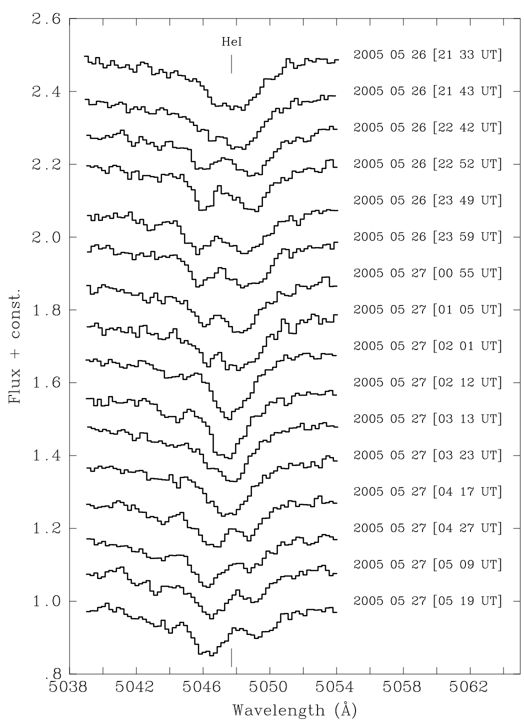

Fig. 2. One night's data from the 2005 WHT run of PG 1544+488 showing line profile variations in the He I 5047 Å absorption line.

We obtained optical blue spectra of the prototype PG 1544+488 with the William Herschel Telescope (WHT) in 2003 April. In total, seven spectra were obtained over two consecutive nights. While carrying out the spectral analysis we noticed that some of the neutral helium line profiles had an unusual shape seen here in Figure 2. On closer examination it became evident that this was due to line-doubling. It was suspected to be due to binarity. However to confirm this hypothesis, more data were required.

Coincidentally, PG 1544+488 had been observed twice with the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite (PI: T.M. Brown) in 2002. At first, it was observed in 2002 March but since one of the detectors on FUSE failed during the observations it was re-observed in 2002 July. The FUSE observations were made in the time-tag (TTAG) mode. In this mode, both the position and time of each photon event on the detector is recorded and therefore it was possible to re-extract the archival data and split them into short time-resolved spectra (∼900 s).

We then measured radial velocities from the WHT and FUSE spectra (for details, see Ahmad et al. 2004). The FUSE data showed similar velocity variations as the optical WHT data. We then combined the radial velocities from the FUSE spectra with those obtained from the WHT spectra and solved for the orbit. From the orbital solution we were able to demonstrate that PG 1544+488 is a short period binary with a period of ∼0.48 day, comprising two helium-rich hot subdwarfs and likely to be a product of close-binary evolution (cf. Ahmad et al. 2004). Some recent observations of PG 1544+88 from the 2005 WHT run are shown in Fig. 2.

No abundances could be measured for PG 1544+488 as line-doubling makes it impossible to measure the equivalent widths of the spectral lines. However in future, with better data it might be possible to deconvolve the spectra of the two components of the binary and measure their individual chemical abundances.

3.2. JL 87

A high-resolution optical spectrum of JL 87 was obtained at the Anglo-Australian Telescope (AAT) with the University College London Echelle Spectrograph (UCLES) in 1996. The spectrum was reduced using standard IRAF routines. Physical parameters of the star were measured from the optical spectrum using SFIT2 as described in section 2, and indicates that $T_{\rm eff} = 24\,000$ K and $\log g = 4.5$. Lanz et al. (2004) have measured $T_{\rm eff} = 29\,000$ K and $\log g = 5.5$ for JL 87 using far-ultraviolet spectrum of the star obtained with FUSE and NLTE model atmospheres. There is significant disagreement between the atmospheric parameters derived from the optical and far-ultraviolet spectra which cannot just be accounted for by NLTE effects.

Using our derived physical parameters, we measured the atmospheric chemical abundance listed in Table 1. There is some agreement between our preliminary measurement of hydrogen, helium and nitrogen abundances with those of Lanz et al. (2004).

There is a significant amount of hydrogen in the atmosphere of JL 87 ($n_{\rm H} \sim 0.80$). This is also evident from the strong hydrogen Balmer lines in the optical spectrum (Figure 3). Such a high hydrogen abundance is not typical for most He-sdB stars ($n_{\rm H} \leq 0.10$). Nitrogen is enriched while oxygen is depleted in JL 87 suggesting CNO processing. However carbon, which is destroyed in CNO cycle, is also enriched. The metal lines in the optical spectrum are quite sharp and can be reproduced with $v \sin i \leq 5\,{\rm km\,s^{-1}}$.

Table 1. Chemical abundances in JL 87 in mass fraction compared to Lanz el al. (2004) – L04 and solar values.

Element	this work	L04	Sun
H	0.5636	0.56 – 0.77	0.7054
He	0.4198	0.43 – 0.28	0.2758
C	0.0056	0.0140	0.0031
N	0.0031	0.0040	0.0011
O	0.0023	–	0.0096
Si	0.0003	0.0007	0.0007
S	0.0001	–	0.0004
Fe	0.0024	0.0013	0.0012

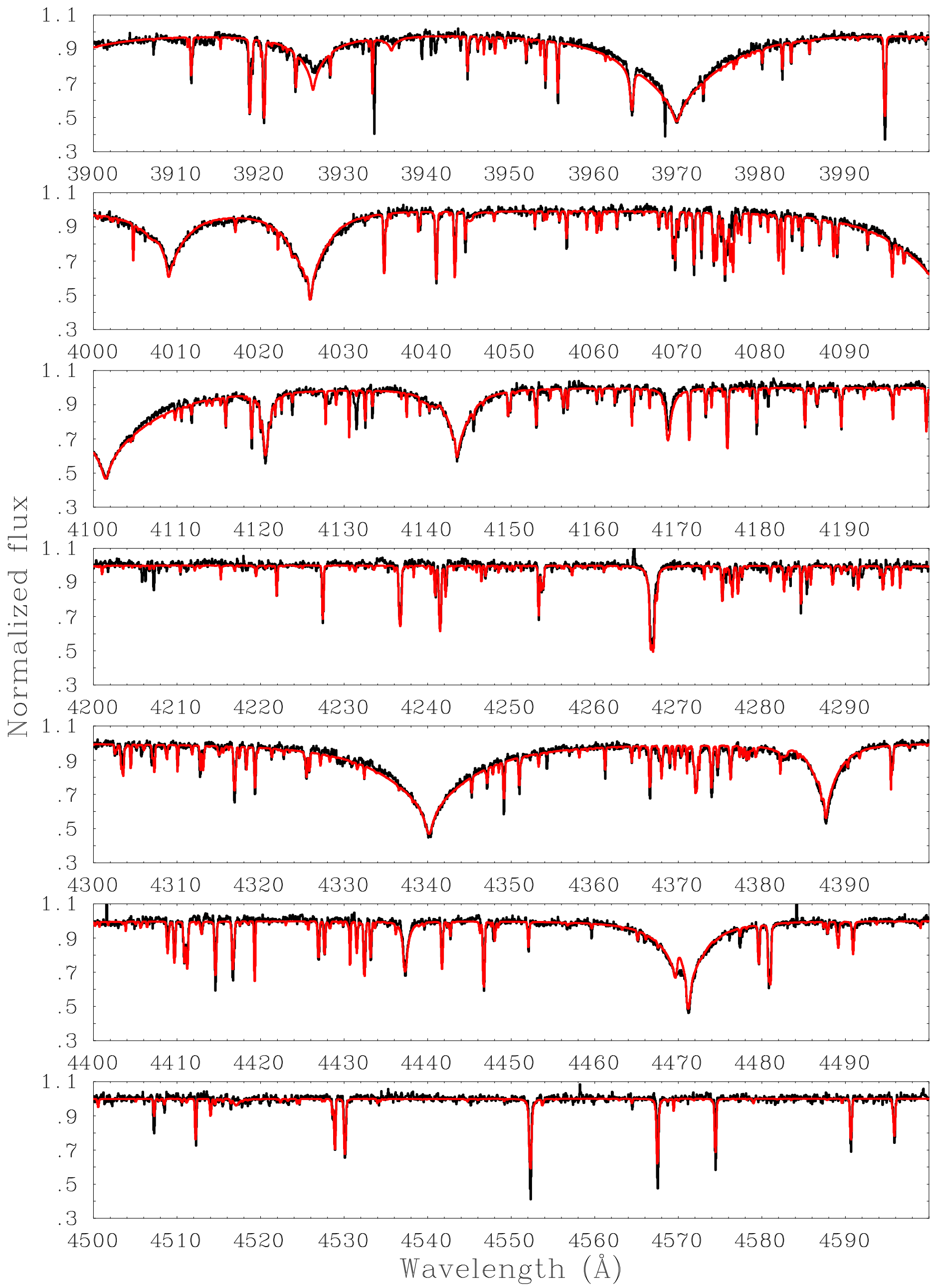

Fig. 3. A section (3900–4600 Å) of the high-resolution optical spectrum (3900–5000 Å) of JL 87 (dark line) along with best fit model.

It seems unlikely that JL 87 is the product of a white dwarf merger in which any remaining hydrogen is converted to helium resulting in an extremely helium-rich surface. It has been suggested that JL 87 is a product of shallow mixing (Lanz et al. 2004) as it can satisfactorily explain the surface abundances. However, our surface gravity measurement indicates that the star is too luminous to have been flash mixed. The atmospheric parameters and helium abundance of JL 87 are similar to those of chemically peculiar massive helium-rich stars known as intermediate helium stars (e.g., Zboril & North 1999). However, carbon is underabundant in these stars.

4. EVOLUTION

4.1. Late flash mixing model

It has been proposed by Lanz et al. (2004) that stars evolving with high mass-loss on the red giant branch undergo a late helium core flash on the white dwarf cooling track, leading to convective "flash mixing" of the envelope which then forms a helium and carbon rich hot subdwarf. All hot subdwarfs produced by this channel show carbon enrichment. Their recent analysis of the FUSE spectra of two He-sdB stars provide support for this evolutionary scenario.

4.2. Binary merger model

Iben & Tutukov (1986) on the other hand have suggested that the merger of two white dwarfs (WD) can produce a hot subdwarf with a depleted hydrogen atmosphere. More recently this has been modeled by Saio & Jeffery (2000) to explain the origin of extreme helium (EHe) stars. Some of these EHe stars are thought to evolve into He-sdB stars. The binary merger model can explain both carbon-rich and carbon-poor He-sdB stars. A merger of two helium WDs can produce a carbon-poor He-sdB star. A low-mass CO+He WD merger might produce a star which resembles a carbon-rich He-sdB during its evolution to the WD track. The analysis presented in section 2 (Ahmad & Jeffery 2003) and Fig. 1 lends general support to the white dwarf merger model for the formation of He-sdB stars.

4.3. Binary evolution

Both the existing evolutionary models for He-sdB stars assume a "single" star. The discovery that the prototype PG 1544+488 is a binary containing *two* He-sdB stars poses a challenge for both models. It is therefore likely that a close-binary evolution channel might be responsible for the formation of some He-sdB stars (see discussion in Ahmad et al. 2004).

4.4. Wind and magnetic field

None of the models discussed above satisfactorily accounts for all the observed parameters of JL 87. However, the observed properties of JL 87 are very similar to those of intermediate helium stars. These are massive young stars with stellar winds and magnetic fields. In normal B-type star atmospheres (assuming no wind), diffusion cannot lead to helium enrichment. However, it was shown by Vauclair (1975) that in the presence of stellar winds, diffusion can lead to helium overabundance. The intermediate helium stars normally show typical CNO abundances. However, peculiar CNO abundances patterns can also be produced depending on several parameters like magnetic field configuration and effective temperature. It is therefore possible that luminous He-sdB stars showing some helium enrichment like JL 87 are in fact intermediate helium stars.

5. SUMMARY

Spectral analysis of He-sdB stars shows that they are a very inhomogeneous group of hot subdwarfs. A fraction of these stars are misclassified (or cool) He-sdO stars. Their evolution is still under much debate. We have discovered that the prototype, PG 1544+488, is a short-period binary containing two low-mass hot helium subdwarfs which demonstrates that close binary evolution also plays an important role in their formation. The observed atmospheric parameters and abundances in JL 87 are similar to those of intermediate helium stars which are chemically peculiar massive young stars.

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