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SUBLUMINOUS O STARS

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Abstract. We report results of spectral analyses of sdO stars selected from the Supernova Ia Progenitor Survey, the Hamburg Quasar Survey and the Sloan Digital Sky Survey and based on state-of-the-art NLTE model atmospheres. By combining the sdO with the sdB samples we discuss trends of the atmospheric parameters in order to search for evidence for possible evolutionary linkage. The He-sdO stars are found to cluster near $T_{\rm eff} = 45\,000$ K, $\log g = 5.5$, whereas the number of sdO stars in this area is very small. The "cooler" sdO stars seem to form an extension to the sdB sequences. A couple of sdO stars are obviously evolved from the extended horizontal branch and reach temperatures as high as 80 000 K. We conjecture that the He-sdO stars and sdO/sdB stars have a different evolutionary origin. This is corroborated by the much lower binary frequency of the former. Strong enrichments of iron group elements are discovered for hydrogen-rich sdO stars as well as for sdB stars from high resolution UV spectra and have severe implications for the temperature scale. We finally highlight the discovery of a hyper-velocity He-sdO star with a radial velocity of 708 km s^{-1} unbound to the Galaxy.

Key words: stars: hot subdwarfs – stars: helium – stars: atmospheres

1. INTRODUCTION

Ever since the field has been introduced by Greenstein & Sargent (1974), the helium-rich sdO stars were believed to be linked to the evolution of the hydrogen-rich subluminous B stars. Any evolutionary link between subluminous B and O stars, however, is difficult to explain since the physical processes driving a transformation of a hydrogen-rich star into a helium-rich one remain obscure. The convective transformation has been explored by Wesemael et al. (1984) as well as by Groth, Kudritzki & Heber (1985). While the former found helium convection to occur even at subsolar helium abundances which mixes helium from deeper layers into the photosphere, the latter concluded that a helium driven convection zone develops only in helium-rich atmospheres. If the latter is true, convective transformation would not work.

Several evolutionary scenarios for subluminous O stars have been suggested: invoking either a delayed helium core flash or merging of white dwarfs. 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 are dredged-up to the surface (Sweigart 1997).

The merger scenario is favored by binary population synthesis models and has met with some success to explain the origin of subluminous B stars. Merging of two helium core white dwarfs will result in helium main sequence stars with masses between 0.3 $M_\odot$ and 0.9 $M_\odot$. It has been proposed that some of the subluminous O and B stars may form through this channel (Webbink 1984). Recently detailed population synthesis models have been calculated by Han et al. (2003) which demonstrate, that a significant fraction of sdB stars can indeed form either through mass exchange or through merging of two Helium white dwarfs The first mass exchange episode (on the RGB) results in sdB stars with a main sequence companion, while after the second mass exchange a white dwarf companion forms. After correcting for selection effects birthrates are predicted. The models predict rather high birth rates for mergers, which in some case even exceed the birthrate of sdB-white dwarf binaries.

Whether or not the merger scenario is applicable to subluminous O stars as well is yet unclear. The situation is more complicated than for the sdB stars since the sdO stars form a much less homogenous class than the sdB stars (cf. Heber 1992). They have to be divided into at least three subclasses. Most of the sdO stars are enriched in helium, from mild cases (helium abundance slightly above solar) to extreme cases (no hydrogen detectable which translates into enrichments of at least several hundred times solar). The helium richness is accompanied by peculiar C and N line spectra. In addition the sdO stars have to be subdivided according to their luminosity. The most luminous sdO stars are very similar to some central stars of planetary nebulae and can be explained by post-AGB evolution which strongly suggest an evolutionary linkage to the helium giants (extreme helium stars and R CrB stars). Amongst the less luminous sdO stars again two spectroscopic subclasses differing in chemical composition must be distinguished. The first one, which we shall name He-sdO, does not show any trace of hydrogen but strong nitrogen and/or carbon lines. The second subclass, which we shall term simply sdO from now on, has hydrogen in quite different amounts. The evolutionary link between these two subgroups on the one hand and the sdB stars on the other is not yet clear.

Detailed quantitative spectral analyses are available for the subluminous B stars but only a few have been carried out for the sdO class because of the complexity of their spectra. In addition deviations from local thermodynamic equilibrium (NLTE) have to be taken into account, because of their high effective temperatures. However. only few quantitative spectral analyses have been published (Dreizler 1993; Dreizler et al. 1990; Thejll et al. 1994; Bauer & Husfeld 1995; Haas et al. 1996; Lanz et al. 1997), with some conflicting results becoming apparent. This is probably due to shortcomings in the early NLTE models used. Therefore we construct a new grid of atmospheric models and synthetic spectra using a state-of-the-art NLTE model atmosphere code.

2. MODEL ATMOSPHERES

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

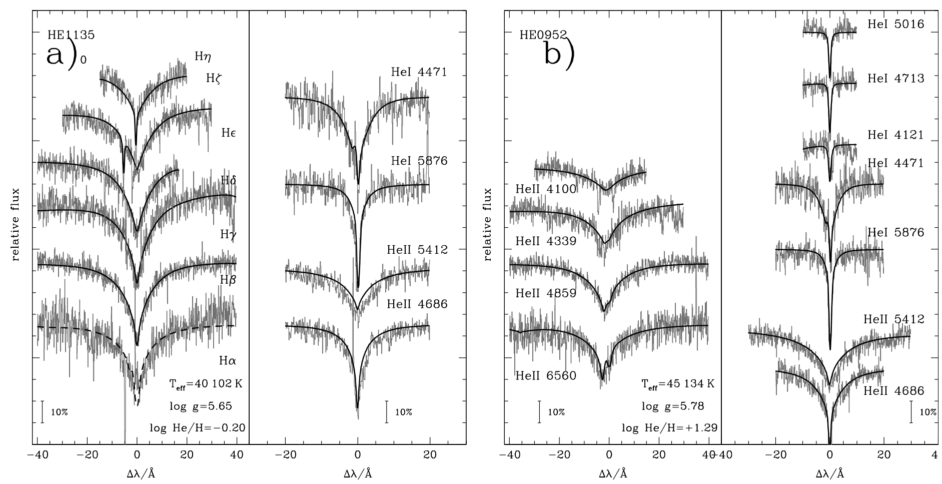

Fig. 1. Line profile fits for a H-sdO (left panel) and a He-sdO (right panel).

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, i.e., $\log(N_{\rm He}/N_{\rm H})$, in order to match the diversity of observed spectra (see Ströer et al. 2005).

We have used this model grid to analyze spectra of sdO stars from the ESO SPY-survey (Ströer et al. 2005), the Hamburg Quasar Survey (HQS, Ströer 2004) and the Sloan Digital Sky Survey (SDSS).

3. SDO STARS FROM THE SPY, HQS AND SDSS SURVEYS

SPY. The ESO Supernova Progenitor Survey (SPY) has identified 137 hot subluminous stars. 79 of them were classified as hydrogen rich subluminous B stars, 58 of them were classified as subluminous O stars. The spectra of the subluminous B/OB stars have been analyzed by Lisker et al. (2005).

High resolution spectra of sdO stars 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. Napiwotzki et al. (2004) searched for radial velocity variables amongst the SPY sdB and sdO stars and found a large fraction ($\sim 40\,\%$) amongst the sdB stars as well as amongst the sdO stars but only one He-sdO star turned out to be radial velocity variable. This star is unique amongst the SPY-subdwarfs as it turns out to be a double sdO (Lisker et al. 2004).

Effective temperatures ($T_{\rm eff}$), surface gravities ($\log g$), and helium abundances ($N_{\rm He}/N_{\rm H}$) 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 36 000 K to 78 000 K, gravities from $\log g = 4.9$ to 6.4 and helium abundances from $\log(N_{\rm He}/N_{\rm H}) = -3$ to +3. Four stars have temperatures in excess of 60 000 K and are probably post-AGB stars and will not be discussed further. Figure 1 gives two examples, one for each spectral subclass.

HQS. During our follow-up observations of blue stars from the Hamburg

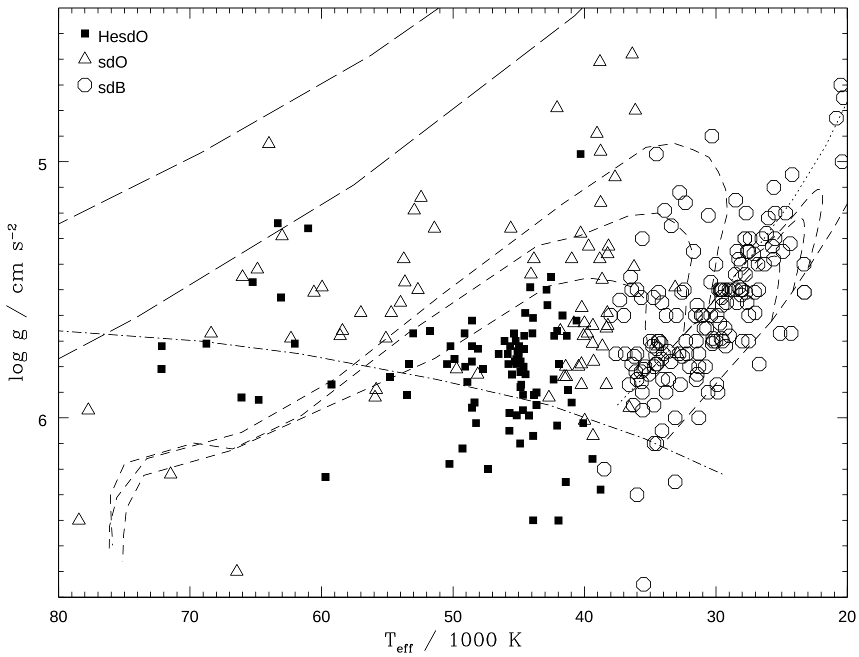

Fig. 2. Distribution of sdB, sdO and He-sdO stars (combined sample) in the $T_{\rm eff}$ vs. $\log g$ plane. Also shown are evolutionary tracks for post-EHB and post-AGB evolution.

Quasar Survey we have discovered many hot subdwarf stars. The analysis based on medium to low resolution spectra of the more than 100 HQS sdB stars has been presented by Edelmann et al. (2003).

In addition several sdO stars have been found. Due to insufficient S/N some of the spectra could not be analyzed. We also had to exclude the lowest resolution spectra because the results had errors too large to be useful. This left us with 14 hydrogen-rich sdO stars and 23 He-sdOs analyzed from spectra of 3.5 Å resolution.

SDSS. The ongoing Sloan Digital Sky Survey is a rich source of hot subluminous O stars. Candidates were found photometrically by selecting all stars with $u-g < 0.2$, $g-r < 0.1$. Inspection of their spectra yielded 40 sdO and 43 He-sdO stars, which were analyzed as described above.

Combined SPY, HQS & SDSS sample. In Figures 2 and 3 we combine the results of the spectral analyses of all three samples including the sdB stars. Figure 2 displays the distribution in the $T_{\rm eff}$ vs. $\log g$ plane. A strong concentration of the He-sdO stars near $T_{\rm eff} = 45\,000$ K, $\log g = 5.5$ is obvious. Some of the sdO stars lie in between the sdB star domain and the He-sdO stars, while others are of lower gravity than the sdB stars. It is worthwhile to note that a gap in the sdO sequence becomes apparent. There are very few sdO stars in the $T_{\rm eff}$ range from 40 000 to 50 000 K, where most of the He-sdOs are found.

Edelmann et al. (2003) noticed a trend of increasing helium abundances with increasing $T_{\rm eff}$ for sdB stars. They also pointed out that two distinct sequences exist. The "cooler" sdO stars nicely match the sdB sequences (see Figure 3) and extend the trend to higher $T_{\rm eff}$ ($\approx 40\,000$ K).

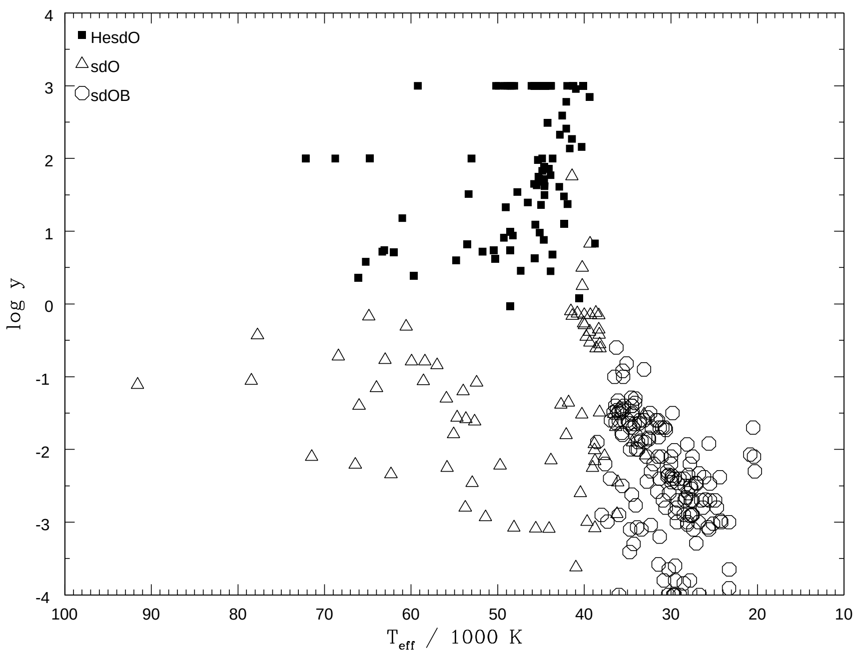

Fig. 3. Distribution of sdB, sdO and He-sdO stars (combined sample) in the $T_{\rm eff}$ vs. $\log y$plane ($y = N_{\rm He}/N_{\rm H}$). For stars with $\log y > +3$ lower limits are given.

4. METAL ABUNDANCES

While metal abundances of several dozens of sdB stars have been derived using LTE techniques from optical spectra (see Edelmann et al. 2006) very few detailed abundance analyses are available for sdO stars. A self-consistent spectral analysis is available for BD+75 325 only (Lanz et al. 1997). Abundances of Fe and Ni have been determined in a few sdO and He-sdO stars. Haas (1997) finds strong enrichments of Fe (10 times solar) and Ni (70 times solar) in the hot hydrogen-rich sdO stars Feige 34, Feige 67 and LS II+18 9. These high abundances cause strong backwarming and the temperatures derived from the Fe/Ni ionization equilibria (60 000 K) is much lower than the one (75 000 K) obtained from optical Balmer and He II lines using metal free NLTE model atmospheres.

Recently, O'Toole & Heber (2005) analyzed high resolution ultraviolet spectra of five sdB stars from HST/STIS. Many heavy elements (up to lead) become accessible to a detailed quantitative analysis. Abundance of 23 metals were derived. While the cooler sdB stars ($T_{\rm eff}$ <30 000 K) show abundances of the iron group elements similar to the sun. The hotter ones ($T_{\rm eff}$ ≈35 000 K) have near solar iron abundances as well, but strong enrichments (100 times) of other elements are found. The high Ni abundances are very similar to those found by Haas (1997) for the hydrogen-rich sdO stars.

As has been noted by Heber, Reid & Werner (2000) in their quantitative spectral analysis of pulsating sdB stars, there is a discrepancy between temperatures derived from Balmer line fitting and helium ionization equilibrium. For PG 1219+534, the difference in $T_{\rm eff}$ was found be as large as 2000 K.

After the initial discovery of strongly super-solar abundances of heavy metals in three sdB stars (Feige 66, CD $-24°731$ and PG 1219+534), we investigated how this affects the determination of the atmospheric parameters. Using LTE atmospheres with metals scaled by a factor of 10 ([M/H] = 1.0), we have recalculated both our abundances and stellar parameters ($T_{\rm eff}, \log g$). There are currently no opacity distribution functions with higher metallicities.

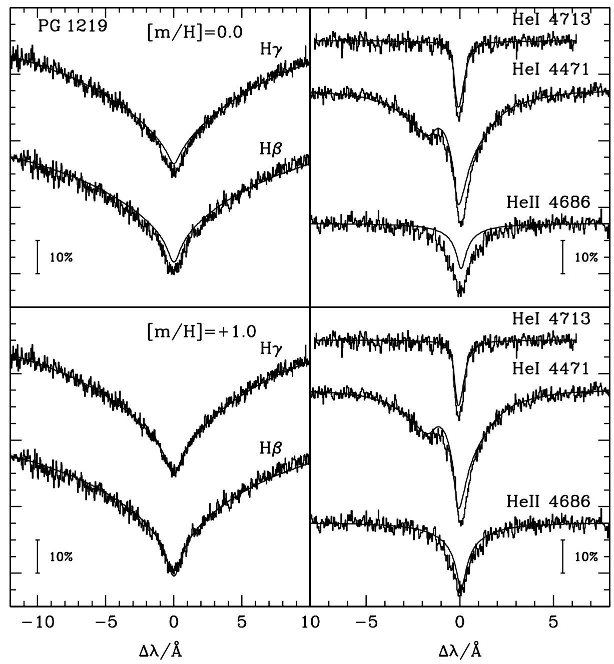

Fig. 4. Line profile fit for PG 1219+534 using solar metallicity models (top panel) and metal-rich models (10 times solar, bottom panels). The Balmer lines and He II at 4686 Å match simultaneously when using the metal-rich models.

In Figure 4 we show a fit with these models to the optical spectrum of the pulsating sdB star PG 1219+534. The Balmer lines and the He II can now be matched simultaneously. The parameters we derive with our metal-enhanced models is closest to those found by fitting the Balmer lines only with a solar-metallicity model. Hence the discrepancy between Balmer and He-ionization can be traced back to an metallicity effect. Unfortunately, however, the heavy metal abundances can be derived from UV spectra, only. Opacity sampling techniques (see Behara & Jeffery 2006) are required to account for the different enrichment of individual heavy elements.

5. A HYPER-VELOCITY SDO STAR

While all the hot subluminous stars studied by us have low radial velocities (system velocities in case of close binary stars), one object sticks out. In the sample of sdO stars selected from the SDDS we found the faint He-sdO US 708 ($g = 18.75$) to have a radial velocity of more than 700 km s^{-1}. To improve this measurement and to check for radial velocity variations, we observed the star with the Low Resolution Imaging Spectrometer LRIS at the KECK I telescope and obtained spectra of 5 Å and 4.4 Å resolution in the blue and red channels, respectively, with much better S/N than the SDSS spectrum (see Figure 5). The heliocentric radial velocity of 708±20 km s^{-1} is consistent with that from the SDSS spectrum, and we conclude that the high radial velocity is due to a very large space motion. Its radial velocity corresponds to a minimum Galactic rest frame velocity of 750 km s^{-1} exceeding the Galactic escape velocity at the position of the star. Hence the US 708 is unbound to the Galaxy. A spectral analysis of the LRIS spectrum is performed and the preliminary result is $T_{\rm eff} = 45\,500$ K, $\log g = 5.2$ and He/H = 10, typical for He-sdO stars. Assuming a mass of 0.5 $M_\odot$ this places US 708 at a distance of almost 20 kpc.

Two so-called hyper-velocity stars have recently been discovered with radial velocities of 853 $\rm km\,s^{-1}$ (Brown et al. 2005) and 723 $\rm km\,s^{-1}$ (Edelmann el al. 2005). The corresponding minimum Galactic rest frame velocities are 709 $\rm km\,s^{-1}$ and 563 $\rm km\,s^{-1}$, respectively. Proper motions are unavailable but their measurement probably has to await future space missions, such as *Gaia* as they are probably very small given the large distances of the stars. Unlike US 708, the two hyper-velocity stars are young massive B stars at distances of 60 kpc. It is generally believed that interaction with the massive black hole in the Galactic center can accelerate stars to such high velocities. Hills (1988) investigated the tidal break-up of binary stars by a massive black hole and found ejection velocities, indeed, to be as high as 4000 $\rm km\,s^{-1}$. Some kinematical experiments are presently being carried out to check whether a Galactic center origin is feasible for US 708.

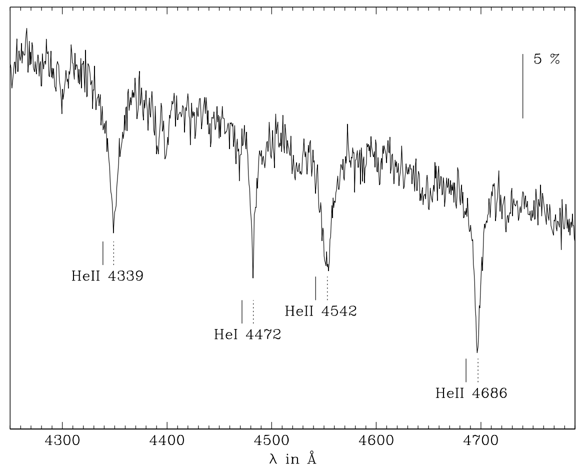

Fig. 5. Keck/LRIS spectrum of the He-sdO US 708 in the blue channel showing the typical He I and He II lines shifted by 708 $\rm km\,s^{-1}$.

6. CONCLUSION

Recent spectral analyses of sdO stars have paved the way to discuss the evolutionary status of these stars as well as their linkage to sdB stars. The Supernova Ia Progenitor Survey has provided a set of high resolution spectra of sdO stars. The most important result is a separation of the subluminous O stars into at least two groups, the He-sdOs and the sdOs. The sdO stars form an extension of the sdB stars to higher temperatures and higher helium abundances. A couple of sdO stars are obviously evolved from the extended horizontal branch and reach temperatures as high as 80 000 K. The He-sdO stars, however, cluster near $T_{\rm eff} = 45\,000$ K, $\log g = 5.5$. The second important result from SPY is that the binary fraction of sdO stars is similar to that of the sdB stars, while it is very low for He-sdO stars. Therefore we conclude that the two types of subluminous stars have different evolutionary origin. Recently, many sdO stars have been analyzed from low-resolution spectra from the HQS follow-up project and the SDSS spectral database. The results strength the conclusions drawn from the SPY set substantially and suggest the presence of a gap in the distribution of sdO stars at the position of He-sdO cluster in the $T_{\rm eff}$ vs. $\log g$ plane.

From high resolution UV spectra strong enrichments of iron group elements are discovered for hydrogen-rich sdO stars as well as for sdB stars and have severe implications for the temperature scale.

We finally highlighted the discovery of a hyper-velocity (HVS) He-sdO star with a radial velocity of 708 km s^{-1} unbound to the galaxy. While the two known HVS stars are main-sequence stars, this is the first highly-evolved HVS. The star is probably ejected by the supermassive black hole in the Galactic center.

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