Atmospheric parameters and abundances of sdB stars

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Abstract. We summarize recent results of quantitative spectral analyses using NLTE and metal line-blanketed LTE model atmospheres. Temperatures and gravities derived for hundreds of sdB stars are now available and allow us to investigate systematic uncertainties of $T_{\text{eff}}$, $\log g$ scales and to test the theory of stellar evolution and pulsations. Surface abundance patterns of about two dozen sdB stars are surprisingly homogenous. In particular the iron abundance is almost solar for most sdBs. We highlight one iron deficient and three super metal-rich sdBs, a challenge to diffusion theory. SdB stars are slowly rotating stars unless they are in close binary systems which is hard to understand if the sdB stars were formed in merger events. The only exception is the pulsator PG 1605+072 rotating at $v\sin i = 39 \text{ km/s}$. Signatures of stellar winds from sdB stars have possibly been found.

Keywords: stars: sdB, temperatures, gravities, abundances, rotation, mass loss

The theories for the evolution and pulsations of sdB stars, for diffusion processes in their envelopes, and for winds from their surfaces have made enormous progress during recent years. However, they need to be tested observationally and we need to know the sdB atmospheric parameters ($T_{\text{eff}}$, $\log g$), surface abundances, rotation velocities, and mass loss rates accurately. Quantitative spectral analyses using LTE and NLTE model atmospheres are required to achieve this goal.

The first quantitative analyses of sdB spectra (Sargent & Searle, 1966) already revealed that helium is strongly deficient (by a factor of 100) due to gravitational settling (Greenstein et al., 1967) Metal abundances were also found be peculiar (Baschek et al., 1972). In their pioneering papers, Newell (1973) and Greenstein & Sargent (1974) presented temperatures and gravities of large numbers of sdB stars and related objects and concluded that the sdB stars form an extension of the horizontal branch, with $T_{\text{eff}}^4 / g =$constant. UBV colours were used as $T_{\text{eff}}$ and Balmer line widths as $\log g$ indicators. With the advent of the IUE satellite the spectral energy distribution was used to determine $T_{\text{eff}}$ while gravity was derived from Balmer line profiles. High-resolution IUE UV spectra allowed the abundances of many metals to be measured (see Heber 1998 for a review). New generations of model atmospheres and high quality spectra have become available in the mean time which allow accurate quantitative analyses even of quite faint sdB stars.
Figure 1. Comparison of atmospheric parameters derived from LTE and NLTE model atmosphere analyses (Δ=LTE-NLTE).

MODEL ATMOSPHERES AND ATMOSPHERIC PARAMETERS

Saffer et al. (1994) introduced the method of Balmer and helium line profile matching which has now become the Standard analysis method in the field. Synthetic spectra calculated from LTE and NLTE model atmospheres, respectively, are matched to the observations by a $\chi^2$ method and $T_{\text{eff}}$, g, and He abundance are fitted simultaneously. Different model atmospheres have been used. Saffer et al. used metal-free LTE models, whereas Heber et al. (1999, 2000), Maxted et al. (2001), and Edelmann et al. (2003) used metal line blanketed LTE and metal-free NLTE model atmospheres to calculate synthetic spectra. It has been realized (e.g. Saffer et al. 1994) that results from different methods can be quite different. Also the use of different atmospheric models can result in systematic differences (Heber et al., 2000). For the sample of Edelmann et al. (2003) we compared the results from two different model atmosphere sets, i.e. metal-line blanketed LTE model atmospheres versus metal-free NLTE atmospheres (see Fig. 1). Effective
temperatures derived from NLTE models are higher by only a few hundred Kelvin up to $T_{\text{eff}}=35000$ K. NLTE gravities are lower by about 0.06 dex, which translates into a luminosity offset of about the same amount increasing somewhat with increasing luminosity. A comparison of results for individual stars is as yet possible only for a few stars common to the samples. We can, however, compare the samples in a global sense using their cumulative luminosity functions. In Fig. 2 we plot these functions for our sample and those of Saffer et al. (1994) and Maxted et al. (2001). The luminosity is expressed in units of the Eddington luminosity. Additionally the positions of the ZAEHB and the TAEHB are indicated. Since the metallicity of the stars is unknown, we have plotted models for various metallicities. As can be seen from Fig. 2, the overall shape of the cumulative luminosity function is similar for all three samples. However, there is an offset of about 0.2 dex in luminosity between the Saffer et al. (1994) sample and Edelmann et al. (2003), whereas the relation for the Maxted et al. and Edelmann et al. samples are in better agreement. Possible reasons for the discrepancy are different observations, the different synthetic spectra used in the analysis, or both.
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Figure 3. Plot of the helium abundance versus effective temperature. Additionally the results of Saffer et al. (1994, squares) and Maxted et al. (2001, triangles) are plotted. The dotted line indicates the regression line for the bulk of the sdB stars (open symbols) and the dashed-dotted line shows the regression line for the peculiar sdB stars (filled symbols). The dashed horizontal line denotes the solar helium abundance.

HELIUM ABUNDANCES AND THE $^3$He ISOTOPIC ANOMALY

A correlation between the photospheric helium content and $T_{\text{eff}}$ (Fig. 3) and log $g$ becomes apparent. The larger the effective temperature and/or gravity, the larger is the helium abundance. However, for sdB stars, $T_{\text{eff}}$ and gravity are strongly connected and a plot of helium abundance versus luminosity does not reveal any correlations. Additionally, a population of stars with very low helium abundances was identified. These stars clearly separate from the bulk (see Fig. 3) providing evidence that surface abundances of sdB stars are not a simple function of their position in the HR diagram. It rules out time-independent diffusion models and points to a dependence on the star’s history.

Because gravitational settling depends on atomic mass we expect the $^3$He/$^4$He ratio to increase slowly with time. Therefore the isotopic ratio can potentially be calibrated by diffusion models as an age indicator.

It can be measured best from the isotopic line shift of the He I 6678Å line (0.5Å). He I 5876Å provides an important check because its line shift is almost negligible (0.04Å). Because of its very low abundance, the $^3$He isotope can not be detected in normal B stars. The presence of $^3$He in the spectrum of an sdB star was first discovered in the case of SB 290 (Heber, 1991), for which the measured line shift is larger than for any other known $^3$He star, indicating that $^4$He is almost entirely replaced
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Figure 4. Observed line profiles of He I 5876 Å and 6678 Å in the $^3$He sdB stars Feige 36, BD+48°2721, and PG 0133+114 and the normal sdB HD 205805. The laboratory line positions for $^3$He (dotted) and $^4$He (dashed) are indicated. Note that the $^3$He line is stronger than the $^4$He component.

by $^3$He in SB 290. $^3$He was also discovered in Feige 36 (Edelmann et al., 1999). We have carried out a search for the $^3$He anomaly amongst the brightest sdB stars and discovered two more $^3$He sdBs: BD+48°2721 and PG 0133+114 and found the $^3$He anomaly to be rare, i.e. it occurs in less than 5% of our programme stars.

METAL ABUNDANCES

We have determined abundances of C, N, O, Mg, Al, Si, S, Ar, and Fe of pulsating (Heber et al. 1999, 2000) and non-pulsating stars (Napiwotzki et al. 2001; Edelmann et al., in prep.) covering a wide range of atmospheric parameters, i.e. $T_{\text{eff}} = 20000$ K ... 40000 K and $\log g = 4.8$ ... 6 in order to search for possible trends for the elemental abundances with atmospheric parameters. Fig. 5 displays the results for C II, Ar II and Fe III as an illustration. While carbon and oxygen display a large scatter, the abundances of other elements (most notably N) are quite homogenous and no trends with the $T_{\text{eff}}$, log $g$ or $L/L_\odot$ become apparent (see Fig. 5). While many elements have subsolar abundances (by 0.5 to 1.0 dex), iron is nearly solar in most cases. There are, however, three stars, for which no iron lines could be detected and upper limits for Fe were determined only. HE 1047-0436 is deficient in iron by 0.6 dex or more (Napiwotzki et al., 2001). This star has a white dwarf companion. Except for its low iron content the abundance...
Figure 5. LTE abundances for C II, Ar II and Fe III. Filled circles mark stars that are not known to be pulsating or radial velocity variable. Pulsating stars are plotted as open circles, radial velocity variables as filled triangles. Upper limits are marked by arrows pointing downwards. The dashed line denotes the solar abundance.

pattern is typical for sdB stars. Comparing radial velocity variable stars and non-variable ones we do not find any significant differences except for HE 1047-0436. The same holds for the comparison of pulsating and non-pulsating stars (see Fig. 5).

Three stars in our sample (not included in Fig. 5) have very peculiar abundances, one example is shown in Fig. 6. Their optical spectra show lots of lines mostly from Ca III, Ti III/IV and V III/IV but no iron lines. These spectral lines have not be seen in any other sdB star before. These elements are strongly enriched with respect to the sun (1000 times for V and 10 000 times for Ti).

**Rotation and stellar winds from sdB stars**

Projected rotation velocities derived from optical spectra provide important information about the angular momentum evolution of the stars. A large fraction of sdB stars may have been formed by mergers of two He white dwarfs (Han et al., 2003) during which angular momentum is transferred. Hence we expect such sdB stars to be born
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Figure 6. LTE abundances for PG 0909+276 relative to solar composition (dashed line). Abundances derived from neutral elements are shown as open circles, from doubly ionized ones as filled triangles, and from triply ionized ones as filled squares. The numbers at each error bar indicated the number of lines used.

with a high surface rotation. However, the spectra of most sdB stars are very sharp lined indicating that they are slow rotators (vsin i < 5 km/s). However, rapidly rotating stars such as HS0705+6700 (Drechsel et al. 2001) are found amongst close binary systems, their rotation being caused by tidal locking to the binary orbit. The enigmatic pulsator PG 1605+072 is the only sdB star known today that is rotating (vsin i = 39 km/s) but not in a close binary system. Is it a merger?

The masses of sdB stars formed by mergers tend to be higher than the canonical mass (Han et al. 2003). Hence an independent measurement of its mass would be tale telling. This can possibly be achieved by asteroseismology (see O’Toole et al. this meeting).

Stellar winds have frequently been suggested as an explanation for the helium abundances. The first realistic calculations have been carried out by Fontaine & Chayer (1997) and Unglaub & Bues (2001). The observed He abundances can indeed be explained if a mass loss rate of $10^{-12}$ to $10^{-14}$ M$_\odot$/yr is adopted. Yet it is not clear whether diffusion models incorporating mass loss can explain the metal abundance anomalies, at the same time as the He abundance.

Mass loss has been detected in some “low gravity” sdO stars but not in any sdB star. Since sdBs are less luminous we expect the mass loss rates to be lower than in sdO stars and therefore harder to detect. Indeed, up to now there is no observational proof for mass loss and, therefore, the mass loss rate is still a free parameter in diffusion models.

First hints about stellar winds came from the quantitative analysis of Hα line profiles of 40 sdB stars (Heber et al. 2003) A comparison
of synthetic NLTE Hα line profiles to the observations revealed perfect matches for all stars except for the four most luminous sdBs. Heber et al. (2003) speculate that the peculiar Hα lines are a signature of a stellar wind. Because the mass loss rate is expected to increase with increasing luminosity, the most luminous sdBs are most likely to show wind signatures. Sophisticated wind models such as presented by Vink at this meeting and UV observations are required to prove or disprove this conjecture and to determine mass-loss rates.

CONCLUSION

The field of research into EHB stars is rapidly developing. Quantitative spectral analyses are progressing very well, both in quantity (number of stars) as in quality (fine abundance analyses). New subjects have been addressed recently, such as stellar winds from sdB stars. The next step has already been undertaken: a homogenous set of high quality, high resolution spectra for a large sample of sdB stars drawn from the ESO SPY survey are analysed (preliminary results are presented by Lisker et al. at this conference). A thorough investigation of the temperature and gravity scale, however, has still to be done. Finally, the role of magnetic fields in sdB stars is unexplored up to now but can now be tackled with modern telescopes and instruments (e.g. ESO VLT + FORS).

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