NLTE ANALYSIS AND CHEMICAL COMPOSITION OF HOT LOW-MASS STARS

U. Heber, K. Hunger and K. Werner
Institut für Theoretische Physik und Sternwarte
Olshausenstr. 40
D-2300 Kiel 1
Federal Republic of Germany

ABSTRACT. Spectroscopic analyses of hot pre-white dwarfs, i.e. subluminous O and B stars, are presented. In the B-type stars, the resulting abundance patterns are indicative of atmospheric diffusion (gravitational settling). Amongst the O-type subdwarfs, a new group of comparatively luminous stars is identified. Their position in the HR-diagram suggests that, unlike the "classical" sdOs, they are in a post-AGB stage of evolution. Spectroscopic evidence is presented showing that the born-again post-AGB star scenario of Iben et al. (1983) can explain their origin.

1. INTRODUCTION

The hot low-mass stars in question are the various types of pre-white dwarfs. The central stars of planetary nebulae (CSPN) have long since been recognised as immediate progenitors of the white dwarfs. In addition, two other groups of stars, the sdB and sdO stars, must be considered as pre-white dwarfs. Recent surveys have shown that the sdOs and sdBs are not just rare "freaks", but, in fact, dominate the population of faint blue stars (Green et al., 1986).

In their pioneering work on faint blue stars, Greenstein and Sargent (1974) carried out spectroscopic analyses of various O- and B-type subdwarfs. The evolutionary status of both groups, however, remained quite unclear. They appeared closely related to the horizontal-branch stars and an evolutionary link between the two groups seemed likely. However, growing evidence has recently been reported (Heber et al., 1984; Groth et al., 1985; Heber, 1986) suggesting that no such direct evolutionary link exists and that these groups of stars form two distinct evolutionary channels towards the white-dwarf stage. From these recent spectroscopic analyses, the following picture of pre-white dwarf evolution has emerged.

The three distinct evolutionary channels (CSPN, sdO, sdB) all start at the horizontal branch (HB). According to available evolutionary calculations, the evolution of a post-HB star depends strongly on the core-mass to total-mass ratio q. If q is small (red part of the

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 389–394.
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https://doi.org/10.1017/S0074180900035336 Published online by Cambridge University Press

HB), a post-HB star will ascend the AGB, eject a nebula at its tip and evolve as a CSPN towards the white-dwarf domain. If q is very large ($q > 0.95$), we reach the extremely blue end of the HB, the so-called extended horizontal branch (EHB). An EHB star is left with only one energy source, the helium-burning core, since the hydrogen-rich envelope is inert. The internal structure of an EHB star bears great resemblance to a helium main-sequence star (of half a solar mass) with a thin hydrogen-rich shell on top of it. An EHB star will evolve (similar to a helium main-sequence star) directly to the blue and into a white dwarf. The subluminous B stars can be identified with these EHB models (Heber et al., 1984).

For slightly smaller values of q ($q < 0.95$), a post-HB star evolves towards the AGB but does not ascend it. Instead, the evolutionary track turns towards the blue and towards the white-dwarf domain. Sweigart et al. (1974) were the first to identify the sdO stars with such evolutionary tracks.

In this review we shall discuss mainly new spectroscopic results for the subluminous O and B stars but will come back to the CSPNs at the end of it.

2. ANALYSIS AND CHEMICAL COMPOSITION OF SDB STARS

Some thirty sdB stars were analysed by model atmosphere techniques (see Heber, 1987, for a more detailed review). Their effective temperatures range from 22000 K to 40000 K and their surface gravities from $\log g = 5$ to 6. All the stars were found to be helium deficient.

Metal abundances have been derived for 11 stars only. The analyses of these were aimed mainly at the nucleogenetically important elements, carbon and nitrogen, and at silicon.

It turned out that helium deficiency is accompanied by deficiencies of carbon and silicon in all except two stars, whereas N is almost normal in all objects studied so far. There seems to be a trend for the Si abundance to decrease with increasing T_{eff}: Si is extremely deficient (3 dex or more) in all stars hotter than 30000 K while it is only mildly deficient (if at all) at lower temperatures. The greatest carbon deficiency also occurs in the hottest sdBs. Greenstein and Sargent (1974) were the first to suggest that the helium deficiency in the sdBs can be naturally explained by gravitational settling (diffusion). If this is true, the metal abundances must also be affected by diffusion. Indeed, gravitational settling appears to be the only conceivable mechanism which could produce the large Si and C deficiencies observed.

Admittedly, most of what is known today about the abundances of metals in the atmospheres of sdBs is based on high-resolution UV spectra obtained with IUE. These spectra are quite noisy. High-S/N, high-resolution optical spectra of a dozen sdBs were obtained recently using the ESO-Cassegrain echelle spectrograph (CASPEC). Equivalent widths as low as 10 mÅ can be measured which will allow precise abundance patterns to be determined. Moreover, the high spectral resolution which can be achieved with CASPEC will also allow the isotopic ratio $^3He/^4He$ to be measured.

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3. NLTE ANALYSIS OF VERY HOT SDO STARS

The ESO-CASPEC was also used recently to observe about 20 relatively bright sdO stars ($10 < V < 13$) at high spectral resolution (0.25 Å) and high S/N (30 to 100). Most of the objects were selected from the (low galactic latitude) survey by Drilling (1983).

IUE observations have indicated that these objects are hotter ($T_{eff} \gtrsim 60000$ K) than any of the sdO stars analysed previously (e.g. Hunger et al., 1980). The high-resolution optical spectra confirm the very high T_{eff} in many cases, since He I is often absent, the limiting equivalent width being ~30 mÅ.

A subsample of 9 stars seemed to be especially interesting because their spectra displayed emission lines of highly ionised metals and/or relatively narrow Balmer lines (see Heber and Hunger, 1987). The latter is regarded as evidence for a comparatively low surface gravity. We analysed the spectra of these nine objects using improved NLTE model atmospheres computed with the "accelerated-lambda-iteration" method described by Heber et al. (these proceedings). As an example of the quality achieved in the analysis, we display in Fig. 1 the line profile fit for the hottest programme star LSS 1362 (V = 12.5).

The results are summarized in Fig. 2, where the programme stars are designated by error bars. Other sdOs, analyzed previously from low resolution spectra are also plotted (without error bars). Three programme stars have normal helium abundances, whereas the others are enriched in helium. Four of the latter even do not show any hydrogen.

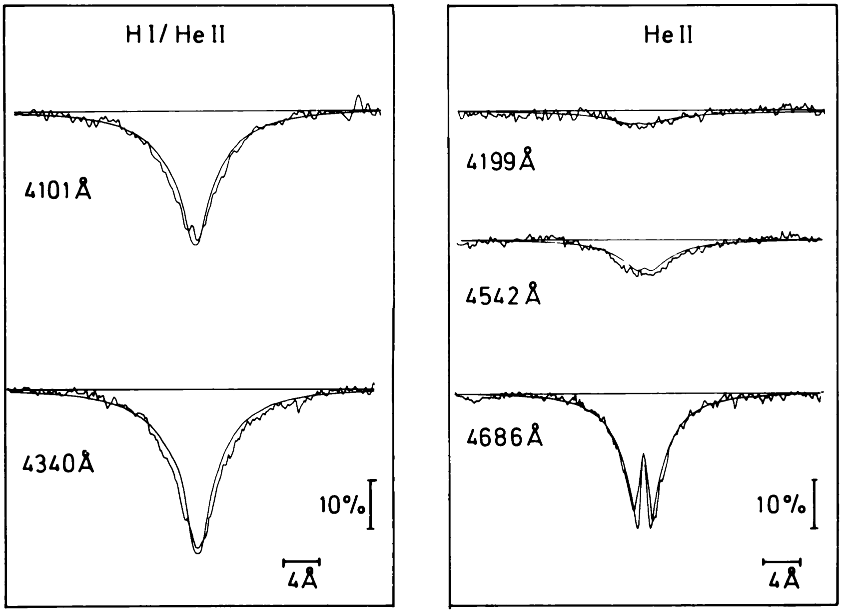

Figure 1: H- and He II- line profile fits for LSS 1362. The model parameters are: T_{eff} = 100000 K, log g = 5.3, n_{He}/n_H = 0.1.

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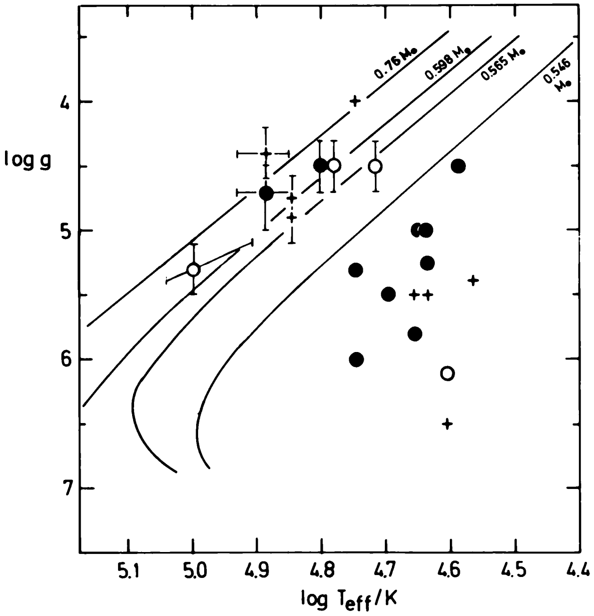

Figure 2: Position of the programme stars in the (g, T_{eff})-plane and comparison with evolutionary tracks (see text). Stars with normal helium abundance are shown as open circles, intermediate helium-rich ones as filled circles and extremely helium-rich stars as crosses.

Three of the extremely helium-rich sdOs (LSE 153, LSE 259, LSE 263) have also been analyzed for the abundances of carbon, nitrogen and magnesium (Husfeld, 1987). N is enriched in all three objects (0.9 to 1.8 dex.) as is C in LSE 153 and LSE 259 (by about 1 dex.). LSE 263, however, is C-deficient by 1 dex. (A magnesium overabundance might still be uncertain since it is based on the detection of only one line, Mg II, λ 4481Å.)

Also shown in Fig. 2 are evolutionary tracks descending from the asymptotic giant branch for masses between 0.546 $M_\odot$ and 0.76 $M_\odot$ (Schönberner, 1979, 1983; Wood and Faulkner, 1986). As can be seen from Fig.2 our stars do not lie in the region where the classical sdO stars are to be found. Instead, they can be identified with post-AGB tracks of about 0.6 $M_\odot$ and with a mean luminosity of about $10^{3.8}$ $L_\odot$. Effective temperatures and gravities of the programme stars (as well as their masses and luminosities) are typical for central stars of planetary nebulae (CSPN). Hence, spectroscopically, they may also be termed as CSPN except they lack the nebulae. Or perhaps the nebulae have not been noticed ? A careful inspection of the ESO sky survey plates did in fact reveal a very extended faint nebulosity around LSS 1362 (see Heber et al., 1987). All others do not show nebulosities on the sky survey plates. Why is this the case ?

There are three conceivable reasons why no nebulae can be detected:

i) The stars simply left the AGB without ejecting a nebula. This is not a satisfactory answer (at least for helium rich stars) since it cannot explain the enrichment of helium, carbon and nitrogen.

ii) After ejection of a nebula, our stars evolved much more slowly than the other CSPNs and, therefore, the nebulae had already been

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dispersed before the stars became hot enough to ionize them. As pointed out by Heber and Hunger (1987) this scenario is unlikely to be correct for the programme stars.

iii) The third and most interesting explanation is the concept of "born again" post-AGB stars. After ejection of a nebula, such a star crosses the HR diagram in the usual way, i.e. as a true CSPN, and finally reaches the hot end of the cooling sequence of white dwarfs. According to Iben et al. (1983), a last thermal pulse may occur in this phase. Such a pulse brings the star back to red giant temperatures and dimensions. During the pulse, most of the hydrogen left to the star at the onset of the pulse is mixed into the helium-burning convective shell and thus is completely burned. The star is now almost devoid of hydrogen and proceeds to burn helium in a shell. The evolutionary track in the (g,T_{eff}) diagram is approximately the same as that for hydrogen-burning post-AGB stars (CSPNs). However, no new nebula is expelled and the old one has long since disappeared. This scenario can also solve the riddle of the helium, carbon and nitrogen enrichment. A final hydrogen burning episode is predicted during the peak of the final thermal pulse and a mixing episode during the giant phase (see Iben et al., 1983). Both mechanisms can mix processed material (He and N from the CNO-cycle; C from the 3α-process) to the surface.

Hence we conclude that two different (evolutionary) subclasses of sdOs exist. A sdO might either evolve along a "Sweigart" track (see 1.) or as a "born-again post-AGB" star. As a consequence, sdO stars cover a wide range in absolute magnitude $(-1 \lesssim M_V \lesssim 7)$.

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Table I: Atmospheric parameters of the programme stars plotted in Fig.2

star	T_{eff}/K	log g	$n_{He}/(n_H+n_{He})$
ROB 162[a]	51000	4.5	0.1
BD+37°442[b]	55000	4.0	1.0
LS IV-12°1	60000	4.5	0.1
BD-3°2179	62000[c]	4.5[c]	0.2[c]
LSE 153[d]	70000	4.75	>0.9
LSE 263[d]	70000	4.9	>0.9
LSE 259[d]	75000	4.4	>0.95
KS 292	75000	4.7	0.25
LSS 1362	100000	5.3	0.1

[a] Heber and Kudritzki (1986, Astron. Astrophys. **169**, 244)
[b] based on photographic spectra, Giddings, 1980 Ph.D. thesis UCL
[c] preliminary values, analysis is not completed
[d] see Husfeld (1987)

DISCUSSION

JORISSEN Is it possible to have information about abundances for elements heavier than iron in these stars from UV spectrum ? It could provide some support to the "last thermal pulse" proposed scenario, if heavy elements appeared to be overabundant !

HEBER The high resolution IUE spectra display a crowding of lines in the 1200 Å to 1800 Å region. Many of these lines were identified as Fe V, Fe VI or Fe VII. However, more than half of the lines remained unidentified. It might well be that some of them arise from elements heavier than iron. Laboratory spectral analysis is quite incomplete for such highly ionized species.

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