ABUNDANCES IN HOT EVOLVED STARS

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1. INTRODUCTION

In the upper left corner of the HR-diagram various stars have been found that are clearly not members of the hydrogen main sequence. The majority of them lie to the left and below the main sequence, indicating that they are highly evolved stars close to the extinction of their thermonuclear power source and hence to rapid cooling towards the white dwarf domain. The implication is that a "short" time ago they were red giants and as such experienced phenomena like mixing, dredge-up and heavy mass loss. Therefore, one expects the hot evolved stars to display the consequences of the afore mentioned processes that are up to now not satisfactorily understood.

However, the hot evolved stars do not form a homogeneous group. The most prominent division is into Central Stars of Planetary Nebulae (CSPN) and those stars that are apparently not surrounded by nebulosity. Further obvious differences exist in spectral type and chemical composition (as deduced from medium and high resolution spectra). Consequently, a unique progenitor for all kinds of hot evolved stars appears to be very unlikely and accurate stellar parameters are needed to compare these stars to predictions of stellar evolution theory.

This paper summarizes the results of analyses of highly evolved stars with spectral type B or hotter, namely sdB, sdOB and sdO types, CSPN and extremely helium-rich stars. It does not consider white dwarfs since their chemical surface composition is apparently governed by diffusion processes and accretion of interstellar material (Wesemael, 1979; Vauclair et al., 1979; Wesemael and Truran, 1982) and is not linked to their past evolution. Section 2 deals with the positions of the hot evolved stars in the (log T_{eff}-log g) plane and their helium to hydrogen ratios. Metal abundances are considered in section 3 and comparisons of stellar evolution calculations with the available data are performed in section 4.

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2. THE (LOG T_{eff}-LOG G) DIAGRAM AND THE HE ABUNDANCE

The quantities determined directly by the spectroscopic analysis as performed for hot stars are effective temperature T_{eff}, surface gravity g and element abundances. Of course, this is not sufficient to place a star in the HR diagram. This is possible only with further knowledge of either luminosity, radius, mass or distance of the star. However, uncertainties in these quantities (which are usually much larger than the uncertainties in T_{eff} and g) directly translate into the HR diagram. On the other hand, theoretical evolutionary tracks can be easily expressed in terms of T_{eff} and g without loss of precision. It is therefore good practice to discuss the results of spectroscopic analyses directly in a (log T_{eff}-log g) diagram as we shall do in this paper.

A detailed description of the analysis method to obtain T_{eff}, log g and the He/H ratio has been given elsewhere (see the references in Groth et al. (1985), Méndez et al. (1985), Heber (1987)) and will not be repeated here. A few important points, however, should be indicated. In the case of the B type stars, effective temperatures are low enough to bring the peak of the stellar flux distribution within - or close to - the range of the IUE satellite. T_{eff} is, therefore, most accurately determined by fitting model atmosphere fluxes to low resolution IUE spectrograms and visual photometric data. The surface gravity is then determined using the widths of the hydrogen lines that are subject to the linear Stark broadening effect. Model calculations for B stars can usually be made under the assumption of LTE.

On the other hand, O stars are too hot for a deduction of T_{eff} from their continuum slope in any reliable way. Instead, one has to use model predictions concerning ionization equilibria and related line strengths (commonly the HeI/HeII ratio) whereas log g is again determined from the wings of the broad H and HeII lines. All calculations must account for non-LTE effects even for the relatively high densities in the atmospheres of sdO stars (Kudritzki, 1979). It should be pointed out that the construction of non-LTE model atmospheres is still somewhat unsatisfactory because no realistic opacities of elements heavier than helium can be included due to limitations imposed by the available algorithms and computers. The situation will hopefully change in the near future when approaches like the one of Werner (1986) are used. Nevertheless, existing non-LTE model atmospheres are able to produce H-He line profiles accurately even when compared with spectrograms with S/N ≈ 100 (see for example Heber et al., 1987a,b).

Figure 1 summarizes the results of all available fine analyses of hot evolved stars. It is important to note that most of these stars are not known to be members of binary systems. We find that all sdB and sdOB stars are drastically depleted in helium. A well-defined border line at T_{eff} = 42000K separates these stars from the classical or "compact" sdOs which cluster at T_{eff} ≈ 50000K, have surface gravities log g ≥ 5 and are systematically enriched in helium ($y := N_{He}/(N_H+N_{He})$ ≈ 0.5). Some members of the class of extremely helium-rich sdOs (no traces of hydrogen in the spectrum) are located in the same area of the (log T_{eff}-log g) plane as the sdOB and classical sdO stars, falling on either side of the border-line between them.

Recently, another subtype of sdO stars has been found at significantly lower gravities and higher temperatures thus placing these stars among the CSPN (Husfeld, 1986; Husfeld et al., 1986; Heber et al., 1987a). As they have higher luminosities than the classical sdOs, we call this subtype the "luminous" sdOs. For this subtype helium abundances range from roughly normal to extremely high (y > 0.9).

The bulk of the analyzed CSPN is hotter than 60000K, covering a wide range in gravity. They are clearly separated from the classical sdOs and the sdB/sdOB stars. Most of them have normal helium abundances. However, some cases of intermediate and extreme enrichments as well as depletion of helium have been found too. (Note that the helium-poor CSPN are almost at a DA white dwarf stage).

3. METAL ABUNDANCES

Up to now, the sdB/sdOB stars, the classical sdOs and the extremely helium-rich luminous sdOs have been analyzed for the most important (and accessible) metal abundances. The analyses usually require extensive non-LTE line formation calculations to solve the statistical equilibrium in detailed model atoms simultaneously with the radiative transfer equations for all relevant frequencies. With the advent of computer codes based on modern powerful solution algorithms (Auer and Heasley, 1976; Werner and Husfeld, 1985) it has now become possible to test (and eventually remove) approximations necessary in older computations. This and the availability of improved atomic data make the non-LTE predictions more reliable, and obstacles in obtaining accurate abundance determinations come now mainly from the observational side where high-quality spectra are needed to identify and to measure weak

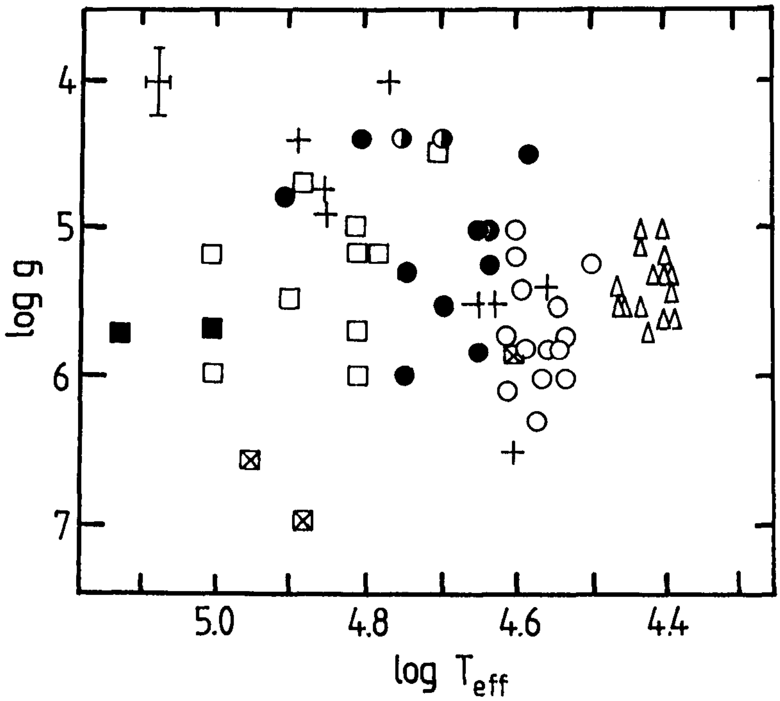

Figure 1: Positions of spectroscopically analyzed hot evolved stars in the (log T_{eff}-log g) plane. Symbols denote type and He abundance. Δ: sdB (y<<0.09); O: sdOB (y<<0.09); ◑: sdO (y≈0.09); ●: sdO (y≈0.5); +: sdO (y≈1.0); □: CSPN (y≈0.09); ■: CSPN (y≳0.5); ⊠: CSPN (y≈0.01). The cross in the upper left corner indicates typical ranges of uncertainty in log T_{eff} and log g.

Table 1: Logarithms of mass fractions for abundant elements in four classical sdO stars and in the sun. Col. 6 gives theoretical predictions from hydrogen fusion in the CNO cycle at T = $2*10^7$K (Caughlan, 1964). Solar values are from Holweger (1979).

	HD 49798	BD+75°325	HD 127493	HD 128220B	sun	CNO cycle
H	-0.70	-0.85	-0.85	-0.36	-0.152	-0.85
He	-0.10	-0.07	-0.07	-0.25	-0.55	-0.07
C	-3.7	-3.7	-4.1	-2.7	-2.40	-4.1
N	-1.6	-1.9	-2.1	-2.2	-3.01	-1.9
Si	-3.0	-3.1	-3.0		-3.16	

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lines (W_λ = 20-30 mA) of subordinate transitions and/or less abundant ions. An abundance derived from several multiplets is usually accurate to 0.2-0.3 dex.

The abundances derived for some classical sdO stars - given as logarithm of the mass fractions - are compared with solar values in Table 1. Besides the notorious increase in the He/H ratio a consistent depletion of carbon and an enrichment of nitrogen is evident whereas silicon is essentially unaltered. From this pattern it might be suspected that these stars display the products of hydrogen burning in the CNO cycle. That this hypothesis is also in quantitative agreement with the observations can be seen from the last column in Table 1 where theoretical predictions at a plasma temperature of $2*10^7$K (Caughlan, 1964) are given.

Similarly, Table 2 presents the abundances in some sdB/sdOB stars. Remarkable here is the strong depletion of He and Si that can only be understood qualitatively as the result of gravitational settling. Carbon is also strongly underabundant with respect to the sun whereas nitrogen is roughly solar. The latter abundance could be explained in the framework of gravitational settling if a previous nitrogen enrichment due to the CNO cycle is assumed.

Table 3 summarizes the results of an analysis of four extremely helium-rich luminous sdOs (Husfeld, 1986; Husfeld et al., in preparation). Here, only upper limits for the hydrogen abundances can be given as no traces of this element can be found in the spectra. Consequently, helium appears as the most abundant element. Significantly overabundant are also carbon (with one exception: LSE 263) and nitrogen. Silicon is effectively unaltered. This abundance pattern compares well with the abundances found in the extreme helium stars of spectral type B (given in col. 6 of Table 3). However, it should be stressed that the carbon depletion in LSE 263 makes this star a peculiar object in its class.

Finally, we mention the central star of NGC 246. This star is known to display CIV as the strongest absorptions in the blue spectrum and broad shallow lines of HeII; hydrogen can not be detected (Heap, 1975; Husfeld, 1986). Analysis by Husfeld (1986) revealed that this CSPN is extremely hydrogen-deficient (n_H/n_{He} < 0.1) and strongly overabundant in carbon (30% by number). Nitrogen is not present, neither in the blue nor in the UV spectrum, but a solar abundance of this element cannot be excluded.

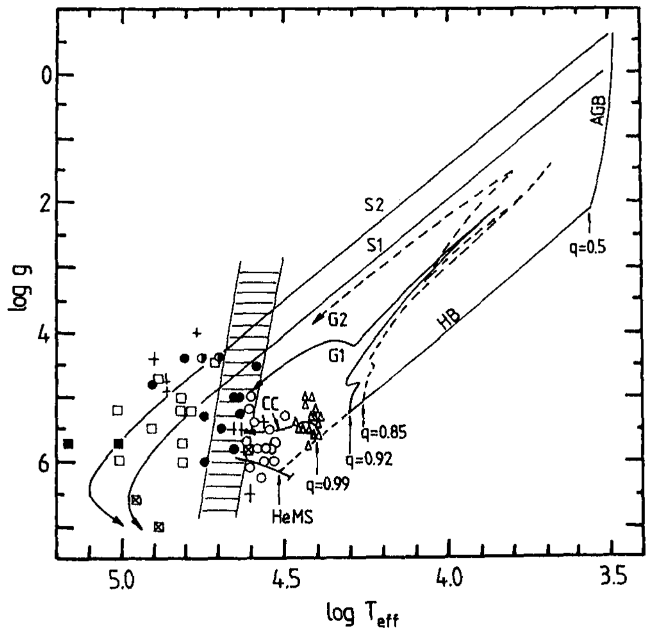

Figure 2: Comparison between observations and evolutionary tracks applicable for sdB, sdOB and classical sdO stars. HB is the horizontal branch with core mass M_{core} = 0.475 $M_{\odot}$, on which some values of $q = M_{core}/M_{total}$ are indicated. CC denotes the track of Caloi and Castellani (1985), the tracks G1 and G2 are from Gingold (1976). Post-AGB tracks applicable for CSPN are from Schönberner (1983; S1: M = 0.546 $M_{\odot}$, S2: M = 0.565 $M_{\odot}$). The hatched strip marks the area in which Groth et al. (1985) have found photospheric convection. Stellar symbols are the same as in Fig. 1.

Table 2: Logarithms of mass fractions for abundant elements in four sdB/sdOB stars.

	Feige 110	HD 149382	Feige 66	LB 2459	sun
H	-0.05	-0.07	-0.03	-0.005	-0.152
He	-0.96	-0.85	-1.12	-1.93	-0.55
C	<-7.9	-4.4	-4.5	-4.4	-2.40
N	-3.1	-2.9	-2.7		-3.01
Si	<-6.8	<-7.7	<-7.8	-4.2	-3.16

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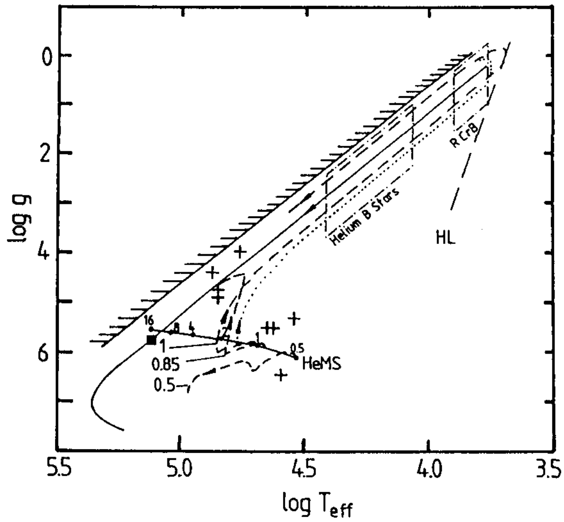

Figure 3: Comparison between observations and evolutionary tracks applicable for extremely helium-rich stars. The helium main sequence (HeMS) is labelled with stellar masses, HL is the Hayashi limit. The hatched line indicates the Eddington limit for pure helium composition. Evolutionary tracks are from Paczynski (1971; dashed lines labelled with $M/M_{\odot}$), Schönberner (1977, $M = 0.7\ M_{\odot}$, full drawn line) and Law (1982; $M = 1\ M_{\odot}$, dotted line). Stellar symbols are the same as in Fig. 1.

Table 3: Logarithm of mass fractions of abundant elements in four extremely helium-rich luminous sdOs, in the sun and in the Helium B stars (mean value derived from Heber, 1983).

	LSE 153	LSE 259	LSE 263	BD+37°442	sun	Helium B stars
H	<-1.7	<-2.0	<-1.7	<-1.7	-0.15	<-3.5
He	-0.05	-0.05	-0.05	-0.05	-0.55	-0.05
C	-1.3	-1.2	-3.6	-1.6	-2.40	-1.7
N	-2.1	-1.5	-1.8	-2.5	-3.01	-2.5
Mg	-2.5	<-1.8	<-2.8		-3.23	-3.0
Si	-2.9			-2.9	-3.16	-3.1

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4. EVOLUTIONARY STATUS

The discussion in this chapter will be restricted to those classes of hot stars for which metal abundances are available and described in section 3. Too little is known at present about the extremely helium-rich compact sdOs and the moderately helium-rich and helium-normal luminous sdOs to allow a meaningful consideration. CSPN, on the other hand, are clearly identified as post-AGB objects and do not need re-discussion.

Groth et al. (1985) have addressed the question as to why the sdB/sdOB stars on the one hand and the classical sdOs on the other display such remarkably different abundance patterns despite their close neighbourhood in the (log T_{eff}-log g) diagram. In their discussion they identified the sdB/sdOB stars with objects on the extended horizontal branch (EHB), i.e. with $q := M_{core}/M_{total} \geq 0.95$. Because of the small envelope mass such stars populate the blue end of the horizontal branch (HB) close to the helium main sequence where surface gravities are high and gravitational settling reduces the surface abundances of all elements heavier than hydrogen. The remaining hydrogen mass, however, is too small to re-ignite and the sdB stars evolve directly into the sdOB domain and then quickly towards the blue, leaving little chance to observe them at temperatures $T_{eff} \geq 45000$K. An evolutionary sequence with q = 0.99 from Caloi and Castellani (1985) is plotted in Figure 2.

Greenstein and Sargent (1974) proposed that a helium-poor sdOB star would turn into a helium-rich sdO once it reaches a sufficiently high temperature to doubly ionize helium. The resultant convection zone should then reverse (or perhaps overcompensate) the preceding effect of gravitational settling. However, as Groth et al. (1985) have shown, no convection zone develops at photospheric depths when helium is already depleted. Therefore, an evolutionary link between sdOB and sdO stars can be ruled out. Instead, the conclusion is that the precursors of sdO stars must have had larger envelope masses ($q < 0.95$) on the HB to be located there at lower gravities. According to evolutionary calculations by Gingold (1976) such stars make a redward excursion after leaving the HB but do not ascend the AGB. It is presently still an open question of how CNO-processed material is brought to the surface (mass loss? convective mixing? helium shell flashes?) and at what time this happens. In any case, when these stars with high helium abundance evolve towards the blue and reach $T_{eff} \approx 42000$K photospheric

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convection sets in and impedes gravitational settling (see Fig. 2). Therefore, the sdO stars remain helium-rich even at higher gravities.

Presently, no definite conclusions about the evolutionary status of the extremely helium-rich stars and the way in which they have lost their hydrogen envelope can be drawn although several scenarios have been proposed. In the white dwarfs (WD) merger scenarios of Webbink (1984) and Iben and Tutukov (1985) it is assumed that a close binary system - consisting of a CO- and a He-WD - contracts due to gravitational radiation and that finally both white dwarfs merge into a helium star that evolves up the AGB. Alternatively, one might - continuing somewhat the discussion of Groth et al. (1985) concerning the origin of the classical sdOs - imagine that the precursors of helium stars are slightly more massive than the classical sdO precursors and therefore evolve further up the AGB. The stronger mass loss would then lead to an even more pronounced depletion of hydrogen. However, our understanding of the mass loss phenomena in the red giant phase is too poor to decide whether it is really possible to remove nearly all of the hydrogen without triggering the (still unknown) PN ejection mechanism. A third possibility has been studied by Iben et al. (1983) in which a post-AGB star already in or close to the white dwarf stage suffers a final shell flash consuming most or all of the remaining hydrogen. For a very short time it becomes a cool supergiant again, before it finally evolves - this time as a helium star - through the CSPN domain until helium burning ceases and the star ultimately ends as a (DB-?) WD. In this case many of the luminous sdOs should be surrounded by a very diluted PN ejected when the central star left the AGB for the first time. The evolution of stars with a C/O core and a helium envelope from the AGB through the domains of RCrB, helium B and luminous sdO stars has been studied by Schönberner (1977) (see Fig. 3). It would nicely explain the agreement of abundances and luminosities in most of the extremely helium-rich luminous sdO and B stars. However, post-AGB evolution cannot explain the extreme helium stars in the compact sdO/sdOB domain. Instead, it is tempting to identify these as stars on or close to the helium main sequence (HeMS). Even the luminous helium sdOs could be produced by direct evolution from the HeMS without redward excursion if masses of the order of 0.85 $M_{\odot}$ are assumed (Paczynski, 1971). However, it is not clear how the HeMS can be populated. Nevertheless, the diversity of possible evolutionary histories offers an explanation of the inhomogenity of the luminous sdO star class (i.e. varying He/H ratios and carbon abundances).

In future work, more information about inhomogenities in the class of luminous sdOs should be collected. Similarly, more data (particularly metal abundances) are needed for the extremely helium-rich sdOs at high gravities. Finally, we urgently need quantitative predictions from the above-mentioned evolutionary scenarios to be able to discriminate between them.

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