CASPEC Observations of sdO Stars: Are Some sdOs Lazy Remnants from the AGB?

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The hot subdwarfs are ideal test objects for the theory of stellar evolution. Their core masses are pretty well known, as they originate ultimately from the horizontal branch, $M_c \approx 0.5\ M_\odot$, and their envelope masses lie in the narrow range $0 < M_{env} \lesssim 0.2\ M_\odot$. Moreover, their atmospheres are well understood through detailed NLTE model atmosphere analyses which appear especially suited to this class of hot high gravity objects. It appears from these analyses that the subdwarf B stars are extended horizontal-branch stars and thus have $M_{env} \lesssim 0.02\ M_\odot$. The same is true for the subdwarf OB stars, only that the latter have even smaller envelope masses ($\lesssim 10^{-3} M_\odot$). For both classes, further evolution proceeds directly towards the white dwarf domain. The subdwarf O stars, on the other hand, belong to the subgroup with envelope masses of the order of $0.1\ M_\odot$. They reached their present position in the HR diagram along a rather complicated track (Fig. 1, for a detailed discussion see Groth et al., 1985). After they had left the horizontal branch they moved towards the AGB; there was not enough fuel remaining in the envelope for them to throw off planetary nebulae and thus to become central stars. They then contracted towards hotter temperatures, which are typically T_{eff} = 40,000–60,000 K. Further evolution would again follow a direct track to white dwarf dimensions. So the small differences in the initial mass of the envelope decide whether a horizontal branch star evolves to either a subdwarf B (or OB) or to a subdwarf O star. Those with envelope masses exceeding $\approx 0.2\ M_\odot$, finally, would be progenitors of the central stars of planetary nebulae.

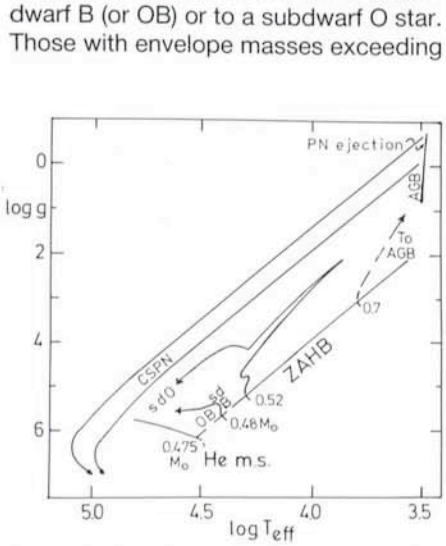

Figure 1: *Post-horizontal-branch evolution (schematic).*

This simple distinction, on account of the envelope mass is not actually quite correct; there are 8 newly discovered subdwarf O stars which seem to be of a particular nature and which seem to indicate that the above sketched picture may be too simple. But first let us report on the spectral analysis of these objects.

Data Reduction

The stars were observed with CASPEC in the blue spectral range (3900–4800 Å). In the beginning (1984), the 31.6 l/mm grating was employed while for the later observations the 52 l/mm was preferred because it yields wider separations of the orders. The spectra were reduced in two steps: first, the ESO-MIDAS software was used for both wavelength calibration and extraction of the Echelle orders. Then background correction and flat fielding were performed in Kiel using a computer programme written by G. Jonas. Data obtained with the 31.6 l/mm Echelle grating suffered from contamination of the background by scattered light from neighbouring orders, while no scattering was experienced with the 52 l/mm grating. The fraction of scattered light could be determined from the observations of standard stars (observed with both gratings). The last step of the data reduction procedure was the correction for the Echelle blaze. The Echelle blaze function ("Ripple function") was empirically determined for every order using the sdOB star Feige 110 plus the helium star BD-9°4395 as standard stars, since the spectra of the two stars are complementary: Feige 110 displays a line-poor spectrum, the only strong lines being the Balmer lines, whereas BD-9°4395 displays only very weak Balmer lines. The "Ripple function" was determined empirically from a least-square fit to the normalized continuum of BD-9°4395 for those orders containing Balmer lines, while for all other orders it was determined form the normalized continuum of Feige 110.

Line Identification

Strong lines of ionized helium are present in all eight stars, whereas He I is very weak (W_λ (4471) $\leq$ 100 mÅ) or even absent. This clearly indicates very high effective temperatures (> 55,000 K) which are hotter than in any "classical" sdO star studied previously (Hunger et al., 1981).

The high spectral resolution (0.25 Å) also allows metal lines to be searched for and these have indeed been found in 6 objects. They are lines of highly ionized elements (e. g. CIV and NV). LSE 153, LSE 259 and KS 292 are remarkable in that they show a strong carbon spectrum. Surprisingly, some lines occur in emission (see Fig. 2) rather than in absorption. (Note that all emission lines are allowed transitions. No forbidden lines which are typical for nebula spectra are found.) The most extreme case in this respect is LSS 1362, the spectrum of which shows all metal lines in emission. In two objects, ROB 162 and LS IV-12°001, no trace of a metallic line can be found, in spite of the high spectral resolution. The discovery of faint metal lines, especially those in emission, is particularly valuable as it will supply the clue as to the nature of our programme stars.

NLTE Analyses

NLTE analyses of the hydrogen and helium line spectrum were carried out with the Kiel programme (Kudritzki and Simon, 1978; Simon, 1980; Husfeld, 1986). For illustration, we have displayed the line-profile fits for the helium lines in ROB 162 (Fig. 3). The resulting atmospheric parameters, i. e. effective temperature, surface gravity and helium abundance, are summarized in Table I. Three programme stars have normal helium abundances, whereas the others are enriched with helium. In LSE 153, LSE 259 and LSE 263, no hydrogen is detectable and only upper limits to the hydrogen abundance can be derived. The position of our stars in the (g, T_{eff})-diagram is plotted in Figure 4, together with the position of previously analysed "classical" sdOs. Stars with normal helium abundance are shown as open circles, intermediate helium-rich stars as filled circles and extremely helium-rich stars (no hydrogen detectable) as crosses. The programme stars are indicated by error bars. Also shown are evolutionary tracks descending from the asymptotic giant branch for masses between

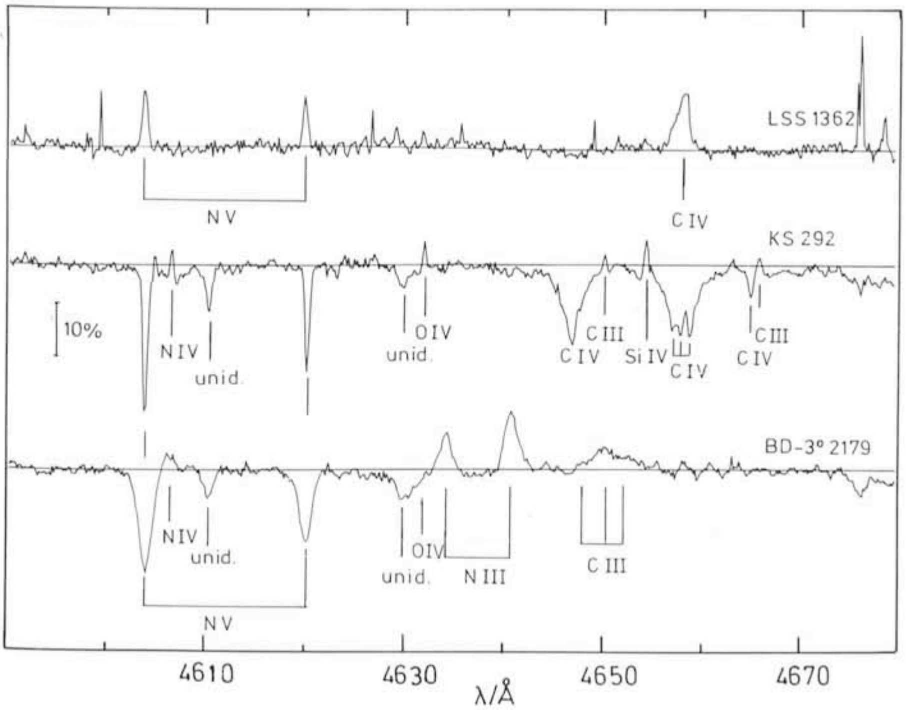

Figure 2: *Caspec spectra of LSS 1362 (top), KS 292 (middle) and BD-3°2179 (bottom). Note the metallic emission lines. 10% continuum height is indicated by a vertical bar.*

0.546 $M_\odot$ and 0.76 $M_\odot$ (Schönberner, 1979, 1983; Faulkner and Wood, 1984).

As can be seen from Figure 4, our stars (as well as BD+37°442, Giddings, 1980) 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 $10^{3.8}$ $L_\odot$. These masses and luminosities are typical for central stars of planetary nebulae (CSPN) and, indeed, the spectra of our programme stars reveal a further similarity to CSPN, i.e. the presence of the metallic emission lines, for similar emission lines can be observed in some CSPNs (Méndez et al., 1981). Hence, spectroscopically, the programme stars may also be termed as CSPNs except that they lack the nebulae (or perhaps it wasn't noticed?). A careful inspection of the ESO sky survey plates did in fact reveal the existence of a very extended faint nebulosity around LSS 1362. All other stars, however, do not show nebulosities. Why is this the case?

According to the theory of evolution the age of our CSPN candidates, after they had left the AGB, should not have exceeded a few thousand years; if they had ejected nebulae at the tip of the AGB, they should still be visible. The question arising from these facts is whether there are further parameters which distinguish our stars from CSPNs. There are three conceivable reasons why no nebula 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 and carbon.

(ii) After ejection of a nebula, our stars evolved much more slowly than the other CSPNs and, therefore, the nebulae had already been dispersed before the stars became hot enough to ionize it. Calculations (Schönberner, 1979; Iben, 1982) show that there may be a discriminating factor: the metallicity. The rate of evolution, namely, is slow for post-AGB stars when the metallicity is low and vice versa. The effect, however, is small. It might explain the cases of ROB 162 and LSIV-12°001, as ROB 162 belongs to the metal-poor cluster NGC 6397 ([Fe/H] = −1.83) and LS IV-12°001 has a metal-poor line spectrum (see above). The latter has an unusually large radial velocity (−178 km/s) and, therefore, is probably also a population II star. For the other 6 candidates, this hypothesis does not apply.

(iii) The third and most interesting explanation is the concept of "born again"

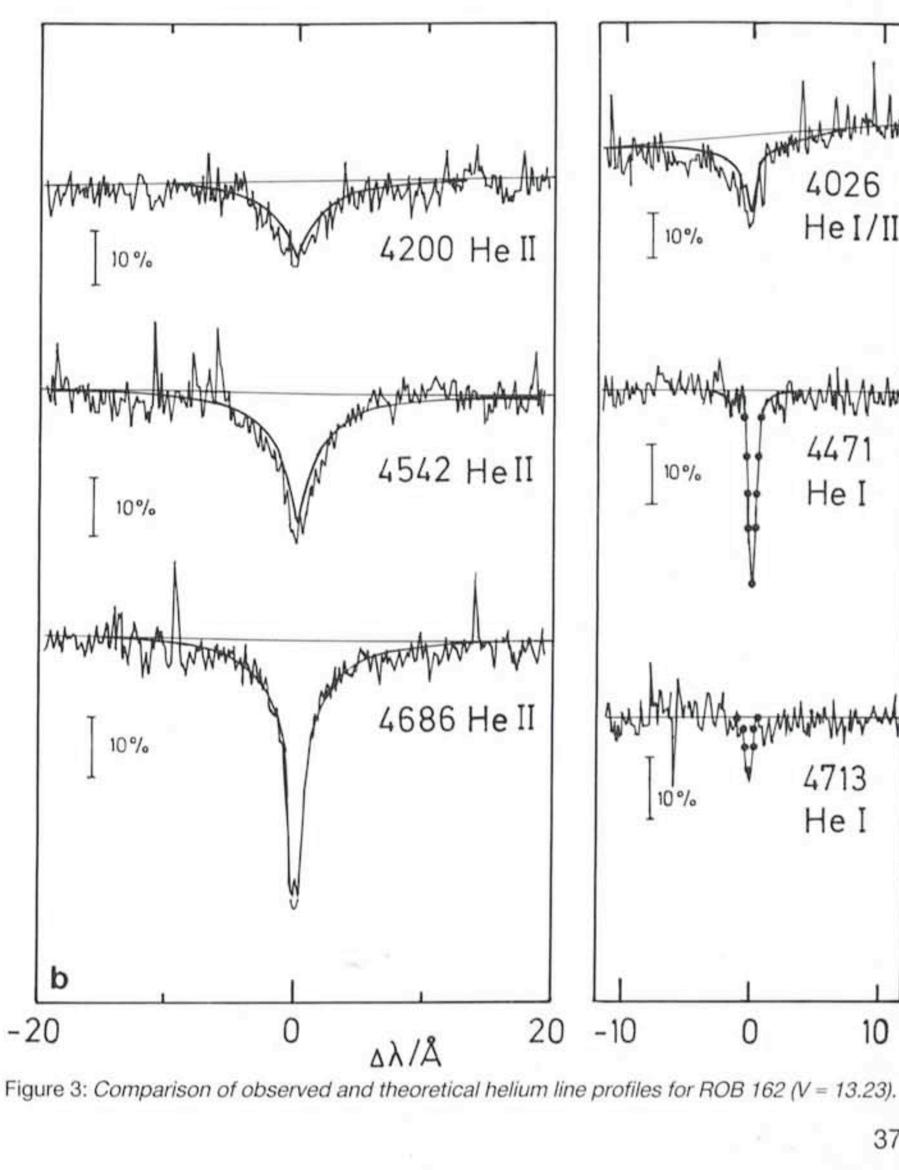

Figure 3: *Comparison of observed and theoretical helium line profiles for ROB 162 (V = 13.23).*

Table 1: *NLTE analyses of sdO stars*

Star	T_{eff}/K	log g	$n_{He}/(n_H+n_{He})$	Carbon line spectrum	Reference
BD+37°442[a]	55000	4.0	1.0	+	Giddings (1980)
LSE 153	70000	4.75	≥0.9	+	Husfeld, Heber, Drilling (1986)
LSE 259	75000	4.4	≥0.95	+	
LSE 263	70000	4.9	≥0.9	–	
BD–3°2179	62000[b]	4.5[b]	0.25[b]	–	
LS IV–12°1	60000	4.5	0.1	–	
KS 292	75000	4.7	0.33	+	
LSS 1362	100000	5.0	0.1	–	
ROB 162	51000	4.5	0.1	–	Heber, Kudritzki (1986)

[a] based on photographic spectra [b] preliminary values, analysis is not completed
+: carbon strong lined –: carbon weak lined

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 stars. According to Schönberner (1979) and 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 (CPNs). However, no new nebula is expelled and the old one has long since disappeared.

This scenario can also solve the riddle of the helium and carbon enrichment (the latter is found only in a few cases, see Table I). The theory of evolution does not predict any helium enrichment for "normal" CSPN since the hydrogen rich envelope is too massive ($\approx 10^{-4} M_\odot$) to allow any helium to be seen at the surface. Indeed most of the CSPNs studied so far, have a normal helium abundance. However, the situation is different for post-AGB stars that experience a final thermal pulse when they already have reached the cooling sequence. Theoretical calculations (see Iben et al., 1983), namely, predict a final hydrogen burning episode during the peak of the final thermal pulse and a mixing episode during the giant phase. Both mechanisms can mix processed material (He and N from the CNO-cycle; C from the 3 α-process) to the surface.

Conclusion

The NLTE analyses have revealed the existence of a new group of sdO stars that were once CSPNs but were born again just before they reached their final destiny, the white dwarf cemetery; a last thermal pulse brought them back to life as a post-AGB star. While the true CSPN lives on H-burning, the reborn post-AGB star lives on He-burning, which prolongs the active lifespan by some 10,000 years, a good fortune that only a small fraction of the central stars will experience.

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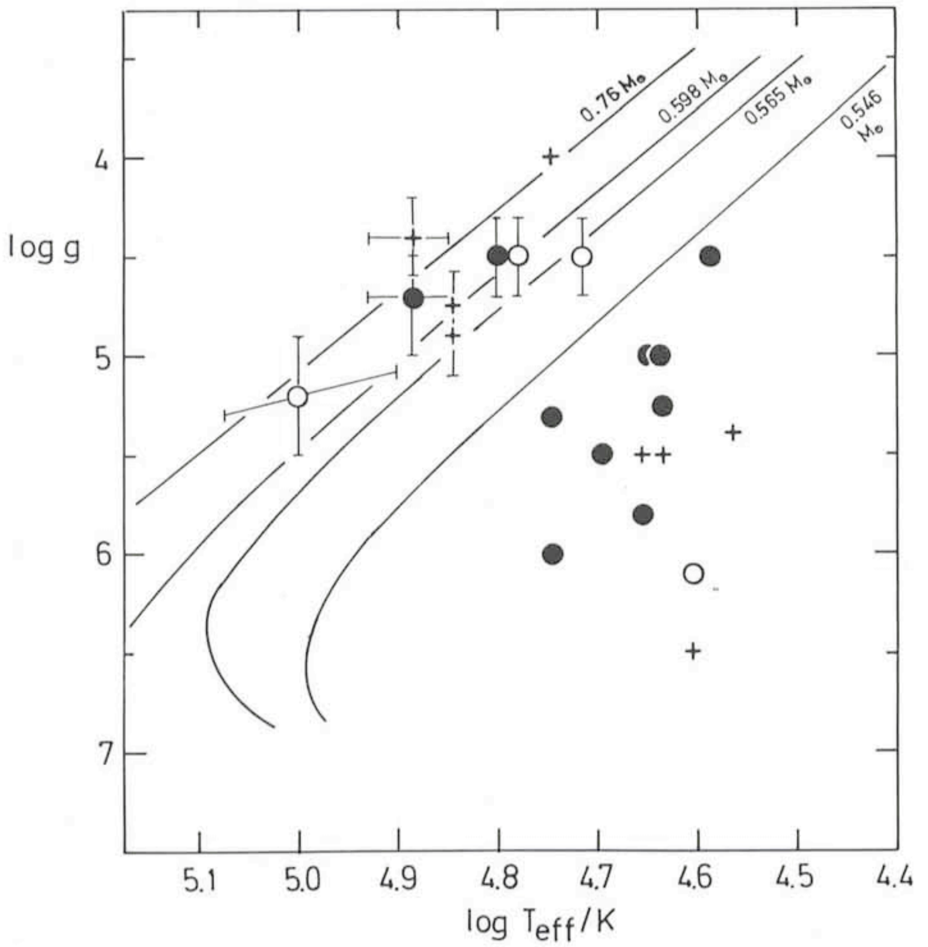

Figure 4: *Position of subluminous stars in the (g, T_{eff})-diagram. The programme stars are marked by error bars. The dashed lines are theoretical evolutionary tracks for stars of 0.546 $M_\odot$, 0.565 $M_\odot$, 0.598 $M_\odot$ (Schönberner, 1979, 1983) and 0.76 $M_\odot$ (Faulkner and Wood, 1984) descending from the asymptotic giant branch.*