The Helium Content and Evolution of Subdwarf O Stars

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Introduction

Subdwarf O stars are faint blue stars that have luminosities 3–8 magnitudes below the main sequence. In the Hertzsprung-Russell diagram they occupy a region intermediate between normal dwarfs and hot white dwarfs. Phenomenologically they appear as an extension of the horizontal branch towards very high temperatures ($T_{eff} > 35\,000$ K). The link between the two classes form the subdwarf B stars.

Characteristic for their spectrum, besides being blue, are the unusually broad absorption lines which belong to hydrogen and helium. A prominent line that is always present – otherwise it is no sdO star – is the line λ 4686 of ionized helium.

The spectral characteristics though pronounced in high dispersion are less conspicuous otherwise, which makes the detection of an O subdwarfs not an easy task. The largest number of O subdwarfs has been found in surveys of regions around the galactic poles, often by making use of objective prism plates. So far some 100 such stars are known, and it is anticipated that a complete survey would yield a much larger number. With little exaggeration one may say that subdwarf O stars are a rather common feature in the sky and, if the life time of a star spent in this phase of evolution is not exceedingly long, that a substantial fraction of the stars will eventually pass through the sdO phase before they reach their final destiny, the white dwarf "cemetery". If so, then it means that sdO stars are in competition with central stars of planetary nebulae which are well known to form the main bulk of white dwarf progenitors.

To pin down the status of evolution, one has to have a good knowledge of the basic stellar parameters like effective temperature, gravity, and luminosity, two of which mark the location in the Hertzsprung-Russell diagram. This enables one (hopefully) to find a suitable evolutionary track that passes through the sdO domain and which may shed light on the past and future evolution. Further clues may come from the abundances of chemical elements, like the helium/hydrogen ratio and the nucleogenetically important elements C, N and O. In order to collect these data for a meaningful sample, a campaign was started in Kiel to analyse all available sdO spectra.

Spectral Analysis

There are two problems one faces when one wants to analyse spectra of sdO stars: first, they are faint. Except for a few bright stars, they are fainter than 12 mag, which makes the use of a big telescope unavoidable. Second, they are hot. Simple methods of analysis – those which are based on the local thermodynamic equilibrium (LTE) – fail because the intense radiation field upsets the atomic level populations which are otherwise in a Boltzmann equilibrium. An absorption line may appear strong not because the chemical element in question is abundant, but because the lower atomic level is overpopulated by radiative processes. Non-LTE effects (NLTE) may lead to distorted line profiles, and moreover, the entire structure of the atmosphere may be affected.

Even in the case of high gravity stars like subluminous O stars, the use of classical LTE methods yields gravities and hence masses which are too large by a factor of 5! The older analyses were suffering from the lack of adequate NLTE model atmospheres. The most complete analysis of subdwarf O stars is contained in the pioneering paper of Greenstein and Sargent (1974). Besides the problems with gravity and effective temperature, the helium to hydrogen ratio remains undetermined altogether in this analysis.

In the meantime, an extensive grid of NLTE model atmospheres for subluminous O stars became available (Kudritzki, 1976) plus the relevant line formation calculations (Simon, 1979). As a pilot project, three of the brightest O subdwarfs were analysed in detail, HD 49798 (Kudritzki and Simon, 1978, Simon et al. 1979), HD 127493 (Simon, 1979 and 1981) and BD + 75°325 (Kudritzki et al., 1980). For the first two objects, 20 Å/mm spectrograms have been obtained with the ESO 1.5 m telescope. In addition, a number of IUE high resolution spectrograms were secured. An elaborate scheme has been developed how to adapt a model atmosphere in order to reproduce the observed profiles of the Balmer-, He I and He II lines and also the spectral distribution of the continuum. The success of the method is demonstrated in Fig. 1 where for the close binary HD 49798 the observed and computed profiles of one line each of H I, He I and He II are compared. The profiles have been computed for the finally adapted model with $T_{eff} = 47500$ K, $\log g = 4.25$ and the helium number fraction $y = 50\,\%$. The model describes equally well the "optical" and the UV spectrum, as can be seen from Fig. 2, where the He II lines in the UV are compared with high resolution IUE observations.

From the experience gained with high dispersion spectrograms it was concluded that if one restricts the analysis to the basic stellar parameters, T_{eff}, log g and the helium abundance, then medium resolution spectrograms would be of sufficient quality to obtain reasonable answers. It means that (partial) analyses of subluminous O stars could be extended to much fainter objects by making use of the 3.6 m telescope, the Boller and Chivens spectrograph in the dispersion range of 30–60

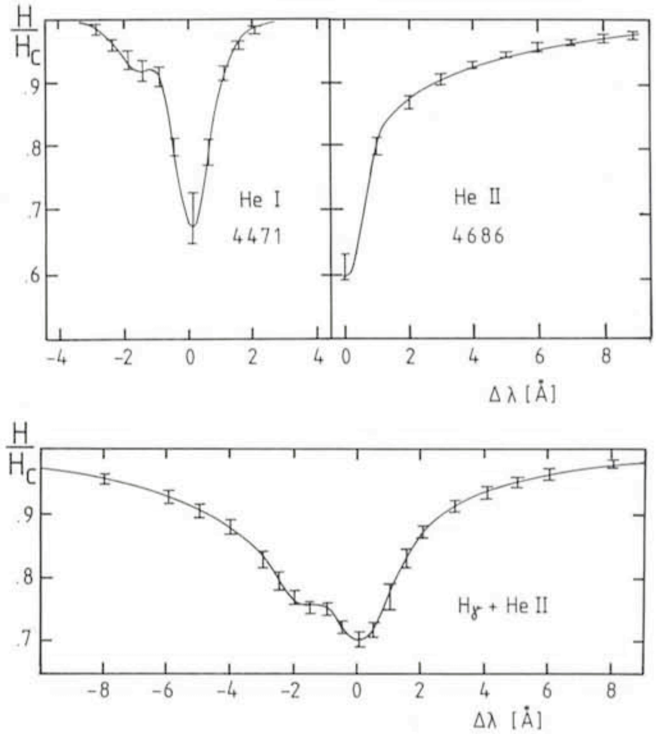

Fig. 1: *Observed profiles (with error bars) of visual hydrogen and helium lines of the sdO star HD 49798 compared with theory (flux in units of the continuum).*

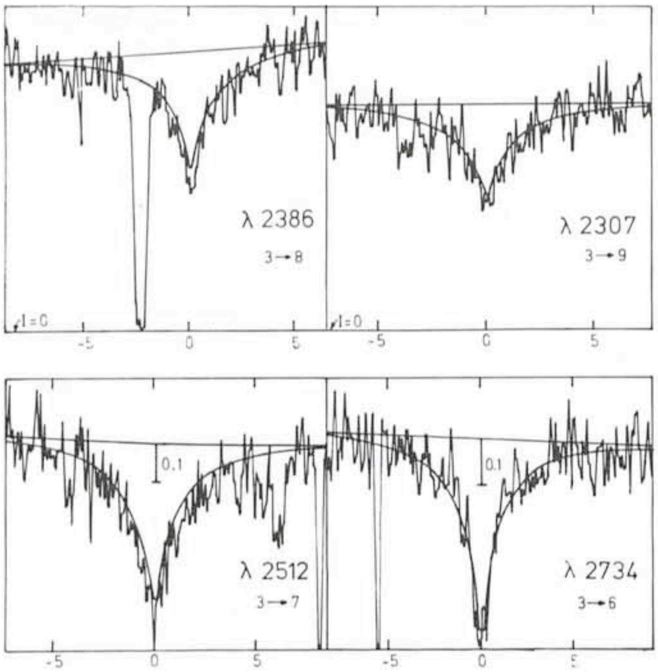

Fig. 2: *High resolution IUE observations of HD 49798: Observed profiles of He II lines compared with theory (the sharp saturated lines are of interstellar origin).*

Å/mm and the IDS. Meanwhile a larger number of objects has been observed by us.

The IDS Spectrograms

As an example, three of the 29 Å/mm IDS spectra are shown in Fig. 3. Immediately evident is the large variety that sdO spectra present. SB 884 (middle) shows the typical broad lines due to $H\gamma$, He I and He II. In the upper tracing, $H\gamma$ is missing, which means that SB 21 is an extreme hydrogen-deficient star, while the bottom star, SB 38, is almost the opposite, a helium-deficient star.

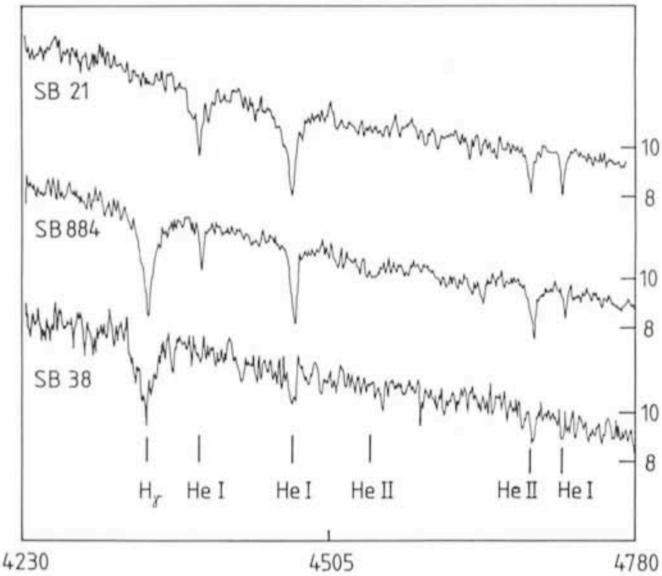

Fig. 3: *IDS spectra of three sdO stars. SB 21 (top) does not show $H\gamma$, which in SB 38 (bottom) is the most prominent feature. SB 21 is an extreme helium star, while SB 38 is helium poor. SB 884 has roughly a normal amount of hydrogen and helium.*

Quantitative results are obtained by means of fit diagrams in the (log g, log T_{eff})plane (Fig. 4) where the loci are plotted along which observed and computed equivalent widths agree for the indicated lines. The intersection of the various lines yields the atmospheric parameters, T_{eff} and g. The minimum scatter defines the number fraction of helium. A final check is made by comparing line profiles (Fig. 5) which proves that even IDS profiles (or the theory) can be trusted.

Before we describe the results, let uns briefly comment on the (g, T_{eff}) diagram because the evolution will be discussed on hand of this diagram.

(g, T_{eff}) Diagram

The above described spectral analysis automatically yields effective temperature T_{eff} and gravity g, besides the helium abundance. Stellar interior calculations also provide T_{eff} and g. Therefore, it is wise to discuss g and T_{eff} directly, rather than to make a poor guess of the distance and thereafter discuss the conventional H.R. diagram. The (g, T_{eff}) diagram is, morphologically spoken, a H.R. diagram containing the same information as the latter. The hydrogen main sequence transforms into a horizontal line, as g is nearly constant on the main sequence. A track with constant luminosity runs as

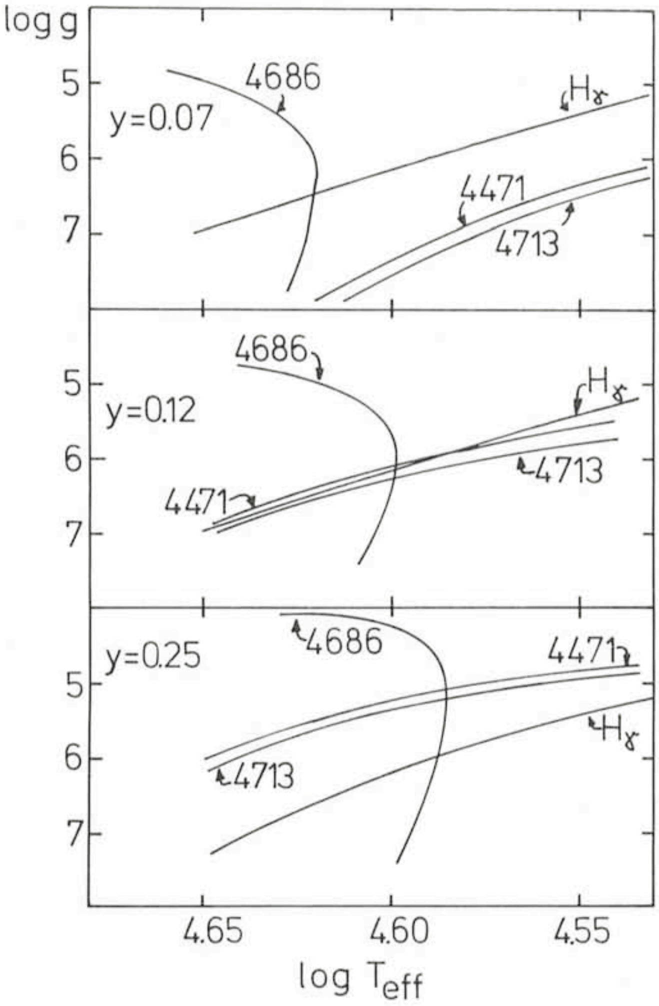

Fig. 4: *The fit lines along which the various equivalent widths agree with theory, for 3 assumed helium (number) fractions y. At y = 0.12, the scatter is smallest. The intersection with λ 4686 He II defines the basic stellar parameters: log T_{eff} = 4.6 and log g = 6.2, and hence the final model atmosphere. The example is SB 884.*

straight line from the upper r. h. corner to the lower l. h. corner. Giants are found at the upper part of the diagram, dwarfs at the lower part, etc. Late phases of stellar evolution proceed mostly at constant luminosity i. e. on tracks which run more or less parallel to the above described straight line.

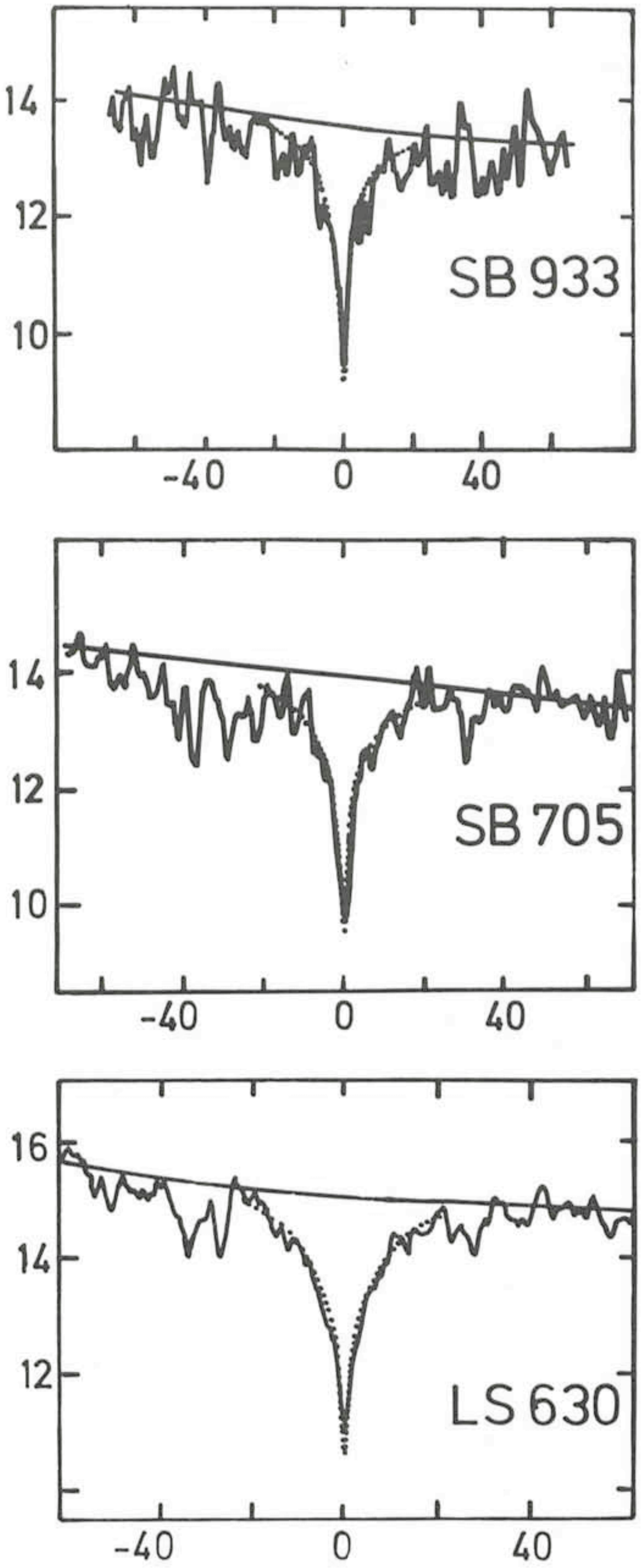

Fig. 5: *From the finally adapted model atmospheres (see Fig. 4), profiles are computed (dotted) and compared with observation, to check the validity of the model atmospheres. The example is* λ *4686 of He II.*

The Helium Content

The relevant portion of the (g, T_{eff})diagram is shown in Fig. 6. The observed sdO stars are marked by symbols which shall indicate if the star consists of helium only (filled circles), if it is a mixture of equal numbers of helium and hydrogen (half filled circle), or if it is helium poor (open circle). Please note that these abundances refer only to the photosphere and that the interior probably contains carbon and oxygen. It is striking that there exists a sharp boundary between helium rich and helium poor, the critical temperature being 40,000 K. The helium poor sdO stars are better called sdOB stars because they appear as intermediate between the SdB stars which are also known to be helium deficient and the SdO's.

It is hard to conceive of a stellar evolution that could lead to a subdivision with respect to helium. Moreover, the SdOB stars have a helium content of as little as 1 – 2 %, which is far below the primordial helium abundance. The answer to this is diffusion. All sdO's plus sdOB's are helium enriched presumably, the strong gravity however dragging the heavier helium ion below the photosphere, whenever $T_{eff} > 40,000$ K. The prerequisite for gravitational settling is an atmosphere that is quiet. Mass loss – which is being observed in some low gravity subdwarf O stars – and convective instability might work against diffusion. In fact, for temperatures just above 40,000 K, a helium convection zone occurs, which is too weak, though, to upset the radiative atmosphere, but which may nevertheless impede diffusion.

The Supernova Remnant SN 1006 and the Binary LB 3459

In Fig. 6 the location of the recently identified blue star near the center of a supernova is also shown. Amazingly, it turns out to be a typical sdOB star of which so far only five are known.

If it is really the remnant of a star that exploded in A.D. 1006, and which presumably lost its hydrogen rich atmosphere, why is it not helium rich or even metal rich? The answer again may be diffusion. The time scales for diffusion are rather short for these high gravity objects and probably less than the time which elapsed since the supernova exploded.

Another interesting object shown in Fig. 6 is the close binary LB 3459. It consists of a primary with $0.5_\odot$ (LB 3459) and a secondary with 0.07 $M_\odot$ (Kilkenny et al., 1979, Kudritzki et al., 1981). If mass transfer and mass loss have produced this strange system then one should expect a helium rich rather than a helium poor object. The fact that LB 3459 appears as sdOB star with helium down to 0.1 % again points to diffusion as the "demixing" agent.

What then means the helium content of a subluminous star? If it were a characteristic for the outer shell then it could serve as an indicator for the evolution of the star in question. But now it appears as if, for these objects, the helium content merely describes the momentary state of the atmospheres, more or less independent of the past history; the interplay of mass loss, gravitational settling and convective instability probably being the determining factors.

The Evolution

Among the sdO's there are some binaries. Their evolution can be understood as a result of mass transfer. The majority, however, appears single. How can they have enriched helium?

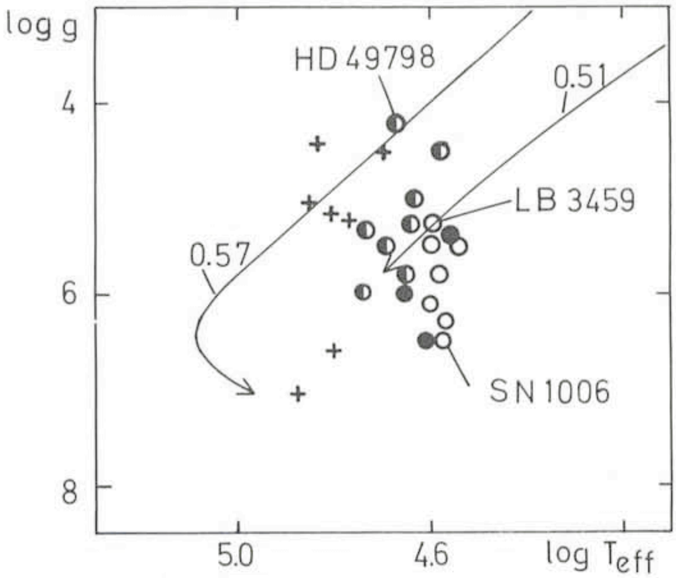

Fig. 6: *The (g, T_{eff}) diagram of subdwarf O stars, the equivalent to the conventional Hertzsprung-Russel diagram. The helium poor sd OB stars are marked by open circles. The supernova remnant suspect SN 1006 as well as the close binary star LB 3459 are also sd OB's. The extremely helium rich objects have full circles, while the intermediate helium rich have half filled circles. Crosses denote the locations of 7 recently analysed central stars of planetary nebulae. The evolutionary tracks belong to stars with 0.51 and 0.57 solar masses (Sweigert et al., Schönberner) that evolve from the horizontal branch to the white dwarfs.*

A further problem arises from the mass. For some sdO's fairly reliable distances exist and hence luminosities. From the effective temperature and gravity, the mass can be derived. For single sdO's the mass turns out to be 0.5 $M_\odot$. How can a star with that little mass have evolved, without having experienced a substantial mass loss?

The scenario may be the following: stars with masses of more than say 1.2 $M_\odot$ lose mass at the top of the first giant branch, at a rate which in some cases may be much stronger than the usually accepted wind – possibly through the helium flash which, after all, is not as harmless as one thinks? After mass ejection the stars are found on the horizontal branch: some with little mass left (~ 0.5 $M_\odot$), on the blue side – these are the helium rich stars – and some with larger masses (~ 0.8 $M_\odot$), on the red side – they have normal photospheric composition. The red HB stars have enough mass left in their outer shell to climb up a second time the (now asymptotic) giant branch, at the top of which they expel a shell, the planetary nebula. The evolution is described in Fig. 6 (Schönberner, 1979). The track with 0.57 $M_\odot$ beautifully matches the position of 6 recently analysed central stars of planetary nebulae – these are the first direct spectral analyses, without recourse to the Zanstra method (Méndez et al., 1981, Kudritzki et al., 1981). The majority of white dwarfs also have 0.57 $M_\odot$. The blue helium rich stars have too little mass left in their shell. They do not reach the asymptotic giant branch and hence are not capable of ejecting a shell. They reach the position of the sdO's on a track which is sketched according to Sweigart et al. (1974). They are likely to form the low mass component of white dwarfs.

If this scenario is correct, then the switch, whether planetary nebula or subdwarf O star, is turned at the top of the first giant branch.

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