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Metal abundances of subdwarf B stars from SPY - a pattern emerges

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Abstract. The formation of sdBs is still puzzling as well as the chemical composition of their atmospheres. While helium and other light elements are depleted relative to solar values, heavy elements are highly enriched. Diffusion processes in the hot, radiative atmosphere of these stars are the most likely explanation. Although several attempts were made, it was not yet possible to model all the observed features of sdB atmospheres. A setback of most prior studies was the small sample size. We present a detailed abundance analysis of 68 sdBs. From high resolution spectra obtained with the VLT/UVES instrument in the course of the ESO Supernova Progenitor Survey (SPY) we measured elemental abundances of up to 24 different ions per star. A general trend of enrichment was found with increasing temperature for most of the heavier elements. The lighter elements like carbon, oxygen and nitrogen are depleted irrespective of the temperature. Although there is considerable scatter from one star to another, the general abundance patterns in most sdBs are similar. An interplay between gravitational settling, radiative levitation and weak winds is most likely responsible. About 6% of the analysed stars show an enrichment in carbon and helium which cannot be explained in the framework of diffusion alone. Nuclear processed material must have been transported to the surface. The late hot flasher scenario may provide a possible explanation for this effect.

Key words. stars: atmospheres – subdwarfs

1. Introduction

Hot subdwarf stars are very important for the study of stellar atmospheres. The chemical peculiarities of their atmospheres are still puzzling although research has been done in this field for more than four decades. Sargent & Searle (1966) discovered the helium deficiency of sdB stars for the first time. Peculiar metal abundances were reported. While some metals showed solar abundances, others were depleted or even enriched. Theoretical diffusion models met with little success. Radiative levitation and mass loss caused by stellar winds counteract the gravitational settling (e.g. Unglaub & Bues 2001). Since the discovery of pulsating sdB stars the metal content in their atmospheres became important for asteroseismology as well. Several

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abundance studies of sdBs have been undertaken so far. Most of the data was obtained in the UV with different instruments (IUE, FUSE, HST/STIS, e.g. O'Toole & Heber 2006). Some optical spectra at high resolution were taken with large telescopes (e.g. Keck/HIRES). The samples analysed so far consisted of few stars only.

2. Observations and data analysis

68 sdBs were observed in the course of the SPY project with the high resolution spectrograph UVES at the ESO VLT. In order to derive the metal abundances we compared the observed spectra with rotationally broadened, synthetic line profiles using an automatic analysis pipeline. For a standard set of 69 metal lines from 24 different ions an LTE model spectrum with appropriate atmospheric parameters (Lisker et al. 2005) was automatically generated with LINFOR and fitted using the FITSB2 routine. Ionization equilibria have been checked to be consistent in general to within the error limits, except for a few notorious cases.

3. Metal abundances

We searched for trends of the metal abundances with atmospheric parameters and found correlations only with the effective temperature $T_{\rm eff}$ (see Fig. 1). The observed carbon abundances are subsolar and show a large scatter from star to star. Four exceptional sdBs show nearly solar to supersolar abundances up to +1.0 dex (see next section). The nitrogen and oxygen abundances range from −1.5 dex to solar. Neon and magnesium are also depleted. A trend with temperature is present in the aluminium and phosphorus abundances. Aluminium is enriched by 1.5 dex, phosphorus by 1.0 dex. In contrast, the silicon and sulfur abundances show a large scatter of 2.5 dex and no trend with temperature. Argon is enriched to +2.1 dex and shows a clear trend with temperature. Potassium is identified in an sdB for the first time. It is strongly enriched up to +2.9 dex and correlated with $T_{\rm eff}$. Doubly ionized calcium appears at higher temperatures with overabundances of up to +2.0 dex. Scandium, titanium, vanadium, and chromium are highly supersolar (+2.0 to +4.0 dex). Scandium and chromium show a clear trend with temperature, which is less pronounced for titanium and vanadium. The iron abundance shows no trend all over the parameter space and remains nearly solar. Cobalt could be measured in five stars only and upper limits are given for all others.

4. Abundance pattern in sdB atmospheres and diffusion

The metal abundances of the programme stars show a universal pattern, which could not been seen before. While the light elements carbon, nitrogen, oxygen, neon, magnesium as well as iron are not correlated with temperature, all heavier elements from aluminium to chromium are more abundant the hotter the star gets. Diffusion timescales are much shorter than the lifetime on the EHB hence an equilibrium abundance between radiative levitation, gravitational settling and a weak stellar wind should be reached. At higher temperatures, where radiative levitation plays a more important role, this equilibrium should be shifted to higher abundances of those heavy elements, which are not abundant in the sun. The lower the elemental abundance, the higher the UV photon flux and therefore the radiation pressure. An increase in the abundance leads to a decrease of the photon flux and a saturation effect (Vauclair & Vauclair 1982). This is exactly what can be seen in the data. While the equilibrium abundance does not change in case of the light elements (except helium) within the sdB temperature range, all elements heavier than magnesium are enriched. Since the primordial iron abundance is much higher than the abundances of the other heavy elements, saturation is more likely and seems to be the reason for the constant iron abundances. Although the general pattern may be qualitatively explained in this way, some questions remain open. All observed trends are superimposed by a scatter from star to star. The abundance difference between stars with similar temperature can be as high as 2.0 dex for some elements (e. g. silicon

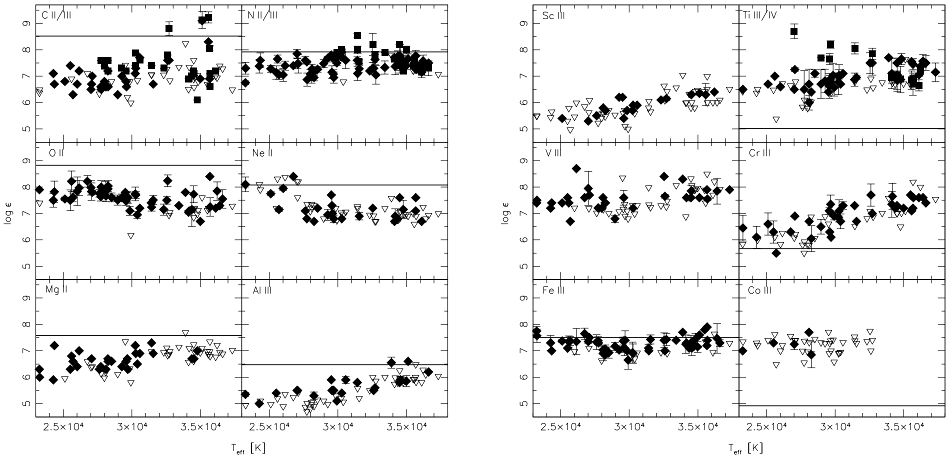

Fig. 1. The abundances of selected elements are plotted against the effective temperature. If two ionization stages are present, the lower one is marked by diamonds, the higher one by rectangles. Open triangles mark upper limits. Solar abundances (Grevesse & Sauval 1998) are drawn as horizontal lines. The solar abundances of scandium ($log\,\epsilon_{\rm Sc}$ = 3.17) and vanadium ($log\,\epsilon_{\rm V}$ = 4.00) are below the plotted range.

or sulfur). On the other hand there is little scatter for other elements (e.g. nitrogen or iron).

Four sdBs show a strong enrichment in carbon from nearly solar to ten times solar. Their helium abundance is high compared to the rest of the sample. They are situated at the hot end of the EHB, but this region is not exclusively occupied by these carbon rich sdBs. Subdwarfs with very similar atmospheric parameters don't show any carbon enrichment. If diffusion in the stellar atmosphere is the only reason for the observed abundance patterns, why do we see two different carbon abundances at the same atmospheric parameters? A mechanism is needed which constantly transports helium and carbon in the atmosphere and therefore counteracts diffusion at least to some extend. Weak photospheric convection could do. Non-canonical formation scenarios like white dwarf merger or late hot flasher (Lanz et al. 2004) may provide the initial enrichment of helium and carbon necessary to form a small convection zone (Groth et al. 1985). Carbon rich sdBs may therefore be formed in a similar way as He-sdB/sdOs (Ströer et al. 2007).

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