

Beyond the iron group: Heavy metals in hot subdwarfs^{*}

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Abstract. We report the discovery of strong photospheric resonance lines of Ga III, Ge IV, Sn IV and Pb IV in the UV spectra of more than two dozen sdB and sdOB stars at temperatures ranging from 22 000 K to 40 000 K. Lines of other heavy elements are also detected, however in these cases more atomic data are needed. Based on these discoveries, we present a hypothesis to explain the apparent lack of silicon in sdB stars hotter than $\sim 32\,000$ K. The existence of triply ionised Ge, Sn, and Pb suggests that rather than silicon sinking deep into the photosphere, it is removed from the star in a fractionated stellar wind. This hypothesis provides a challenge to diffusion models of sdB stars.

Key words. stars: subdwarfs – stars: abundances

1. Introduction

Improving atomic data and access to high-resolution UV spectra through *HST* and *FUSE* have allowed abundance analyses of hot, degenerate stars to be undertaken (e.g. Ohl et al. 2000; Barstow et al. 2003). We have recently begun a project to measure the abundances of iron-group elements in hot subdwarf B stars (O'Toole et al. 2003; Chayer et al. 2003). These stars can be associated with models of hot, helium core-burning stars with hydrogen layers too thin to sustain nuclear burning. Analyses of high resolution *IUE* spectra of sdBs revealed peculiar chemical abundances. In particular, carbon varies greatly from star to star, nitrogen is essentially solar, while silicon is slightly underabundant up to $\sim 32\,000$ K, but at hotter temperatures it is very deficient – at least 5 dex below the solar value in some cases (e.g. Lamontagne et al. 1987; Baschek et al. 1982). These chemical peculiarities in sdBs are usually explained by invoking a complex balance of radiative levitation and gravitational settling combined with mass loss (Unglaub & Bues 2001; Bergeron et al. 1988), however, there have only been a few diffusion models published, with varying success (Unglaub & Bues 2001; Charpinet et al. 1997).

In this letter we present the discovery of strong resonance lines of several heavy elements in sdB (there will be no distinction made between sdB and sdOB stars here) based on high resolution UV spectra. Three of the elements discovered (germanium, tin and lead) have the same electronic configuration as silicon, and we discuss the implications of this in the context

of diffusion theory. A detailed abundance analysis is currently being carried out (O'Toole et al., in preparation).

2. Observations

Our original observations were made with *HST/STIS* as part of an ongoing project to measure metal abundances in pulsating and non-pulsating sdBs (proposal #8635, PI: U. Heber). We obtained data for five targets using the E140M grating, which in the far UV has a resolving power of $R = 45\,800$ and a useful wavelength range of 1165–1710 Å. Final results will be presented in a future paper, however a preliminary analysis can be found in O'Toole et al. (2003), while the serendipitous discovery of a white dwarf companion to one of the stars (Feige 48) using these data has been presented by O'Toole et al. (2004).

After our original discovery of heavy element resonance lines in our *HST/STIS* spectra, we searched for any other spectra of sdB/O stars in the *HST* and *IUE* archives. This resulted in high-resolution UV *HST/STIS* spectra of Feige 66 and CPD –64°481, a *HST/GHRS* spectrum of the sdO Feige 46, and the *IUE* spectra of 21 more stars, representing almost the entire range of effective temperatures and surface gravities for the sdB stars (see Fig. 1). In one case (Feige 110) the detection of the Pb IV line at 1313.072 Å was uncertain, so we looked for the second resonance line at 1028.611 Å using archival *FUSE* spectra.

3. Discovery of heavy element resonance lines

The analysis of the UV spectra of sdBs is complicated by the large number of absorption lines caused by iron-group elements. The wavelengths of these lines in the Kurucz database

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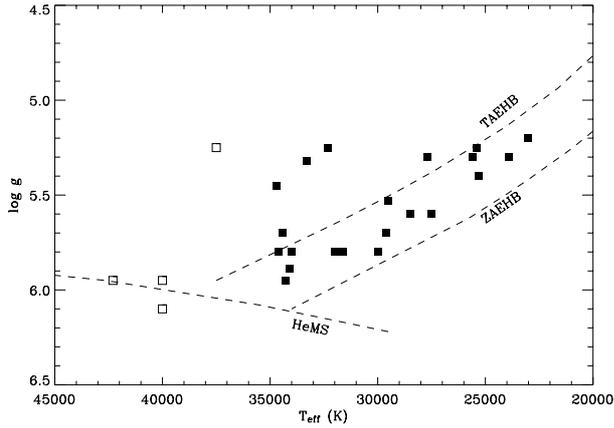


Fig. 1. $T_{\text{eff}} - \log g$ diagram of the sample stars. Filled squares show sdB stars, while open squares show sdOs. Two stars are not shown since they do not have temperature determinations.

in some cases can be quite inaccurate, especially at bluer wavelengths. This can mean that some lines in the spectrum appear to be unidentified. While analysing our *HST/STIS* spectra we noticed that the wavelengths of two very strong unmatched lines corresponded very well with the resonance doublet of Ge iv. The region around the line at 1189.028 Å is shown in Fig. 2 (the other line is at 1229.840 Å). There are no strong lines near these resonance lines that could lead to an incorrect identification. Using the line lists of Morton (2003, 2000), we discovered the resonance doublets of Ga iii at 1495.045 Å and 1534.462 Å and of Sn iv at 1314.539 Å and 1437.525 Å, as well as one resonance line of Pb iv at 1313.072 Å (the other line is at 1028.611 Å, lies in the wings of Ly β). The strongest Sn iii resonance line at 1251.387 Å may also be present, but is blended with an unknown feature. The three resonance lines of Zr iv, as well as Zn iv and possibly Cd iv are present in at least Feige 66, however no oscillator strengths for these lines could be found in the literature. We note that the only other report of these resonance lines in UV spectra was by Proffitt et al. (2001), who discussed the lead, tin and germanium abundances of the SMC main-sequence B star AV 304. They compared this star with the Galactic B star HD 46328. Both of these stars show the same Ge iv, Sn iv and Pb iv lines seen in our spectra. It is quite possible that these lines have been previously overlooked in the spectra of other main sequence O and B stars, although with many objects rapidly rotating, their identification might be difficult. This is one clear advantage that hot subdwarfs have: their rotation velocities are typically less than 5 km s⁻¹.

The discovery of the resonance lines of these heavy elements encouraged us to look for subordinate lines. These lines should be much weaker, but may still be detectable. We used the NIST Atomic Spectra Database¹ as well as the line list of Hirata & Horaguchi (1995). In the case of Ge iv, there are two strong lines around 1494.9 Å and 1500.6 Å that have listed oscillator strengths, however because the wavelengths are not very well known, we cannot claim a certain

¹ See http://physics.nist.gov/cgi-bin/AtData/lines_form

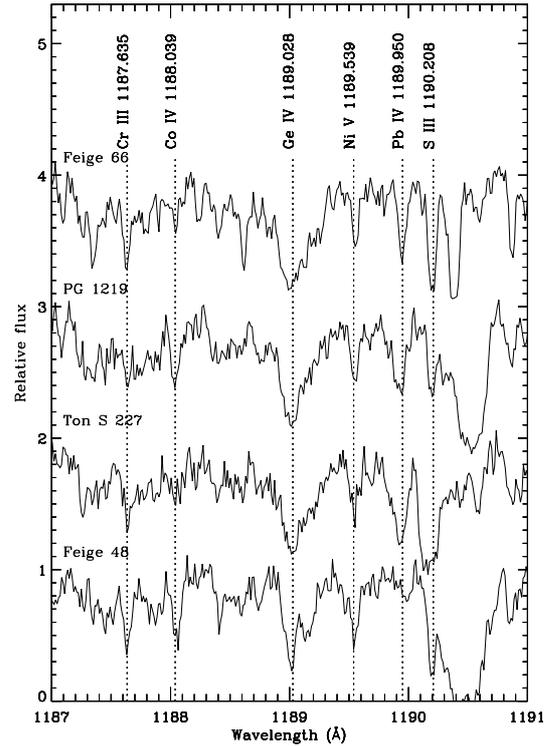


Fig. 2. *HST/STIS* spectra of 1187–1191 Å region showing the Ge iv 1189.028 Å line, as well as the Pb iv at 1189.95 Å. There is no atomic data for the latter. The strong feature around 1190.5 Å is due to interstellar Si ii. Several other strong lines are also marked.

detection. There are also a couple of strong Ga iii lines with published oscillator strengths, and these are detected at 1267.151 Å and 1293.446 Å. Several subordinate Pb iv lines with reasonably accurate wavelengths are seen, however once again there are no oscillator strengths available in the literature. The strongest appears to be the line at 1189.95 Å, which is clearly present in the three hottest stars Feige 66, PG 1219+534 and Ton S 227, but weak in Feige 48 (see Fig. 2). Other weaker Pb iv are possibly detected at 1343.06 Å, 1400.26 Å, and 1535.71 Å. There are no strong Sn iv lines other than the resonance lines detectable in our spectra.

Our *HST/STIS* spectra are not the only high-resolution UV spectra available covering this wavelength range. There were a number of sdBs observed with *IUE*, and their resolution is good enough to be able to detect some of the lines we have discovered here, although in some cases low signal-to-noise makes things difficult. We show a list of all the stars in our sample in Table 1, and a selection of spectra around the Pb iv and Sn iv resonance lines in Fig. 3. In almost all stars the lines of Ge, Sn, and Pb are present. Low signal-to-noise is responsible in most cases for uncertainty, although in some stars the spectra are smeared by rotation (PG 1605+072, SB 290) or tidally-locked binary motion (HW Vir, PG 0113+114). The stars in Table 1 are grouped into sdOs at the top, “cool” sdBs in the middle, and “hot” sdBs (also known as sdOBs) at the bottom. The cool and hot sdBs are divided arbitrarily by the appearance of Si iv resonance lines (see Sect. 4). HZ 44 is an unusual object, since it is hot but shows the same heavy metal

Table 1. List of sdB/sdO stars with high-resolution UV spectra, comparing presence of G14 elements. Observations of stars marked with an asterisk were made with *HST/STIS*; all other observations were made with *IUE*. The spectra of HW Vir and PG 0133+114 are smeared by binary motion, while the PG 1605+072 and SB 290 spectra are smeared by rotation.

Star	Si	Ge	Sn	Pb	Binary
HZ 44	Y	Y	Y	Y	?
SB 884	Y	Y	?	Y	?
Feige 46*	Y	?	?	Y	?
Feige 110	N	Y	?	?	?
SB 290	Y	?	?	?	?
HD 4539	Y	Y	Y	Y	N
HD 171858	Y	Y	Y	Y	Y
HD 185510	Y	?	Y	Y	Y
HD 205805	Y	Y	Y	Y	N
FF Aqr	Y	Y	Y	Y	Y
HW Vir	Y	?	?	?	Y
Feige 48*	Y	Y	Y	Y	Y
Feige 65	Y	?	Y	Y	N
CPD-64°481*	Y	Y	Y	Y	?
PG 0133+114	Y	?	?	?	Y
PG 0342+026	Y	Y	Y	Y	N
PG 1605+072*	Y	Y	?	?	?
PG 1032+406	N	Y	Y	Y	Y
PG 1104+243	N	Y	Y	Y	Y
PG 1219+534*	N	Y	Y	Y	?
PG 1352-022	N	Y	?	Y	?
HD 149382	N	Y	Y	Y	N
Feige 66*	N	Y	Y	Y	N
Ton S 227*	N	Y	Y	Y	?
BD+34°1543	N	Y	?	Y	Y
PHL 932	N	Y	Y	Y	N
UVO 1758+36	N	Y	Y	Y	N

lines as cooler sdB stars. This may be due to convection related to the stars high helium abundance ($\log(\text{He}/\text{H}) \sim 0.4$). The sdO stars SB 884 and Feige 46 are peculiar and may not have evolved from the Horizontal Branch. The *IUE* spectrum of the hydrogen-rich sdO Feige 110 has several bad pixels in the 1310–1315 Å, making identification of lines in this region difficult. We note that the second Pb iv resonance line at 1028.611 Å may be present in the *FUSE* spectrum of Feige 110, however it appears to be blended, meaning that the presence of lead remains uncertain. The case of the Sn iv 1437.525 Å line is similar. The last column in Table 1 shows the binary status of the stars; the presence of heavy element lines appears to be independent of binarity. Finally, three of the stars in our sample are pulsating sdBs, and two of them clearly show the lines discussed, while the third (PG 1605+072) is rapidly rotating, making line identification difficult.

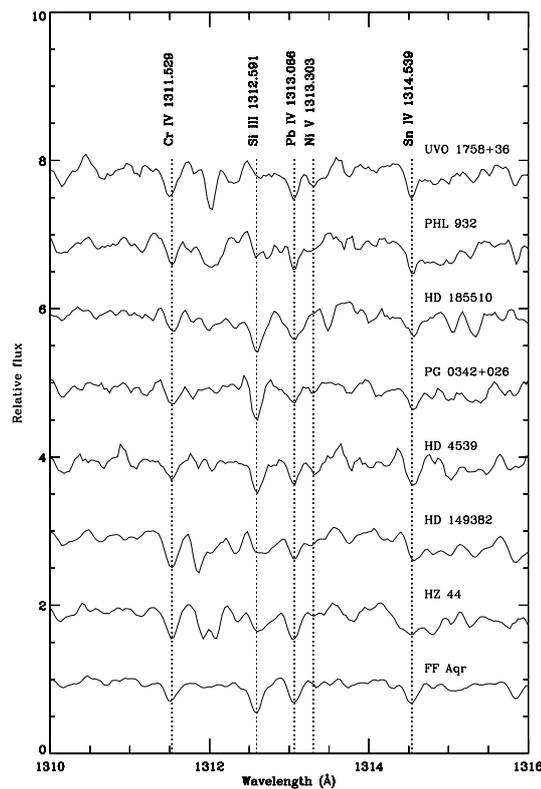


Fig. 3. *IUE* spectra of the 1311–1315 Å region showing the Sn iv and Pb iv resonance lines. The spectra have been offset for clarity and smoothed with a boxcar filter two pixels wide.

4. Implications

The effects of diffusion hamper any meaningful discussion about the origin of the heavy elements discussed in this letter (i.e. whether they are formed by the *r*- or *s*-process). Clearly they can not be formed in these hot subdwarfs, but their presence can, however, be used to shed some light on some of the other chemical peculiarities found in these stars.

It has long been known that silicon in sdB stars show peculiar behaviour. Above a certain temperature ($\sim 32\,000$ K) there is almost no silicon left in the upper photosphere. Previous studies suggested that above this temperature silicon might exist in a noble gas configuration (e.g. Baschek et al. 1982), and that it should sink deep into the photosphere since these atoms would absorb little radiative flux, and hence momentum. Calculations by Michaud et al. (1985) and Bergeron et al. (1988) have found, however, that diffusion alone cannot account for the large silicon underabundances, and that a competing particle transport mechanism, i.e. a weak stellar wind, must be present. The discovery of strong Ge, Sn and Pb resonance lines can be used to confirm this. Consider that Si, Ge, Sn and Pb occupy the same column in the periodic table (Group 14, hereafter G14), i.e. they each have 4 electrons in their outer shell. (Note that Cr iv, the lowest mass G14 element, has a significantly higher ionisation potential (64.492 eV), and is also produced by the triple- α process, meaning that it is somewhat independent of the other G14 elements.) This means that we can expect their susceptibility to absorb radiative momentum to be quite similar. In other words, to a first approximation,

the elements' initial abundances and relative masses will be the only things that affect the outcome of their acceleration by radiative flux. As a consequence, the velocity of Pb atoms will be seven times lower than Si atoms, since Si is seven times lighter than lead. Consider that the escape velocity of a typical sdB is $\sim 1200 \text{ km s}^{-1}$; if $v(\text{Si}) = 2000 \text{ km s}^{-1}$ (not an unrealistic value), then $v(\text{Pb}) = \sim 270 \text{ km s}^{-1}$, $v(\text{Sn}) = \sim 475 \text{ km s}^{-1}$, and $v(\text{Ge}) = \sim 770 \text{ km s}^{-1}$. In other words, silicon will escape the star, but the heavier elements will not. A similar qualitative argument was put forward by Leckrone et al. (1999) to explain the abundance peculiarities of the HgMn star χ Lupi.

An implication of the hypothesis presented here is that this wind must be fractionated, rather than uniform, since Coulomb coupling is inefficient in extremely thin winds. Fontaine & Chayer (1997) investigated the effects of a weak stellar wind on helium in sdBs and found that the observed abundances can be explained if the mass-loss rates are between about 10^{-14} and $10^{-13} M_{\odot} \text{ yr}^{-1}$. Unglaub & Bues (2001) found that the CNO elements could show strong deficiencies as well as enrichments when they considered the effects of such a wind with these kinds of mass-loss rates. Detecting such a wind directly would be difficult for most sdBs, but Heber et al. (2003) discovered four luminous objects that show weak $\text{H}\alpha$ emission cores, and suggested that these may be the signature of a stellar wind. Preliminary calculations by Vink (2004) show that the mass-loss rates for these stars may be as high as $10^{-11} M_{\odot}$. Because none of sdB stellar wind studies mentioned here have done so, we suggest that future calculations include silicon.

Naively one might expect atoms with similar mass to be affected in the same way as silicon. For lighter elements this appears to be the case, with aluminium also at least significantly depleted in hotter sdBs (e.g. Baschek et al. 1982). The presence of Ga III , with a similar ionisation potential, suggests that Al III should be present in these stars, rather than Al IV . For the main ionisation stages of the other elements (Mg III , P III/IV , S III/IV , Ar III) in Period 3, however, most flux is absorbed by lines below the Lyman limit, where very little is emitted by sdB stars. As a consequence, these elements will not be as strongly driven as aluminium or silicon, meaning they should be present in the spectra of sdB stars. This is the case for all species except Mg III , which has very few strong lines at observable wavelengths.

5. Summary

We have discovered strong resonance lines of lead, tin, germanium and gallium in many sdB stars. The presence of these lines is independent of binarity, and they are present in both

pulsating and non-pulsating sdBs. Other heavy elements may also be present, however lists of laboratory wavelengths and oscillator strengths are missing or incomplete. The lines should also be present main sequence O and B stars. We suggest that the presence of heavy Group 14 elements, but the near absence of silicon in the hotter sdBs, implies that rather than sinking deeping into the photosphere, silicon may have been carried out of the star by a fractionated stellar wind. This hypothesis is supported by measurements of aluminium resonance lines, which also show strong depletion in hotter sdB stars. These discoveries provide a challenge for future diffusion and stellar wind models of hot subdwarfs.

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