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FUSE OBSERVATIONS OF GERMANIUM, ZIRCONIUM AND LEAD IN SDB STARS

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Abstract. We report the detection of the Ge III, Zr IV, Pb III and Pb IV resonance lines in Far Ultraviolet Spectroscopic Explorer (*FUSE*) spectra of hot subdwarf B stars (sdB). We analyze 18 stars that cover the effective temperature domain for this class of stars. We carry out an abundance analysis and demonstrate that Ge, Zr and Pb abundances are higher than the ones observed in the Sun's photosphere in almost every star. We perform radiative levitation calculations on Ge, Zr and Pb, and show that the theory predicts higher Ge and Zr abundances than the observations. Moreover, the large scatter of observed abundances cannot be explained by the radiative levitation alone. This suggests that other mechanisms must be taken into account for explaining the abundances of Ge, Zr and Pb in the atmospheres of sdB stars.

Key words: diffusion – spectroscopy – stars: abundances – subdwarfs

1. INTRODUCTION

The recent discovery of elements beyond the iron group in the atmospheres of hot subdwarf B stars (sdB) by O'Toole (2004) adds new pieces to the abundance anomaly puzzle observed at the surface of these relatively high gravity stars. O'Toole (2004) reported the detection of strong resonance lines of Ga III, Ge IV, Sn IV and Pb IV in the STIS and IUE spectra of many sdB and sdOB stars that cover a wide range of effective temperatures. Strong resonance lines of Ge III, Zr IV, Pb III and Pb IV are also formed in the far ultraviolet wavelength range. This is one of the last unexplored spectral windows in the study of sdB atmospheres. The Far Ultraviolet Spectroscopic Explorer (*FUSE*), which covers a spectral wavelength range of 905–1187 Å with a resolution of $R = \lambda/\Delta\lambda \simeq 18\,000$, is exploring in great details this important waveband. In this paper we present the results of an abundance analysis for the elements Ge, Zr and Pb observed in the atmospheres of 18 sdB stars. We also present results of radiative levitation calculations on Ge, Zr and Pb based on an approach developed by Michaud et al. (1976).

2. *FUSE* OBSERVATIONS

We retrieved the *FUSE* spectra from the Multimission Archive at STScI. All stars were observed through large apertures with exposure times of about 6000 s on average. The data were reduced using the program CALFUSE that processes the raw data into wavelength and flux calibrated 1-d spectra. Because each observation consists of several exposures, we co-added the individual exposures by cross-correlating them in order to remove any wavelength shifts. Figure 1 illustrates an example of merged *FUSE* spectra of the bright and cool sdB star HD 205805. The strongest lines observed in the spectrum are the hydrogen lines from Lyβ to the series limit, the He II 1084 and 992 Å lines, the C III 977 Å line and the C III 1175 Å multiplet.

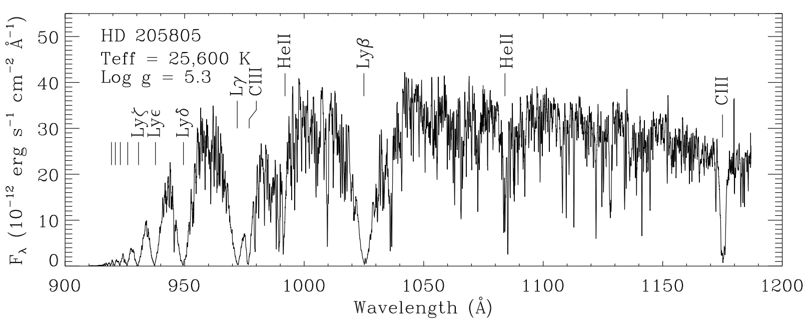

Fig. 1. *FUSE* spectrum of HD 205805.

The spectrum in Figure 1 seems noisy at this scale. In fact, this apparent noise is due to the huge number of photospheric and interstellar absorption lines that are observed in the *FUSE* spectra of almost all sdB stars. Interstellar lines such as H_2, C II, C III, N I, O I, Si II, P II and Fe II are observed along the lines of sight of many sdB stars. Photospheric lines come from elements such as C, N, O, Si, P, S, Cl and elements from the iron group such as V, Cr, Mn, Fe, Co and Ni. In addition to these elements, the *FUSE* wavelength range contains lines that are produced by elements beyond the iron group. Resonance lines from ions such as Ge III, Zr IV, Pb III and Pb IV are observed in the *FUSE* spectra of almost all sdB stars. Lines coming from excited levels of Pb III are also observed in a few stars. Table 1 summarizes the atomic properties of the Ge III, Zr IV, Pb III and Pb IV lines observed in the *FUSE* band.

Table 1. Atomic data for Ge, Zr and Pb.

Ion	Z	Wavelength (Å)	$\log gf$	g_l	E_l (cm^{-1})
Ge III	32	1088.463	0.264	1.0	0.0
Zr IV	40	1183.973	0.000	4.0	0.0
Pb III	82	1048.877	0.114	1.0	0.0
Pb IV	82	1028.611	0.086	2.0	0.0

3. ABUNDANCE ANALYSIS

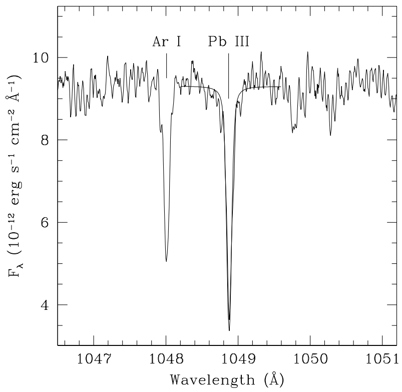

Fig. 2. *FUSE* spectrum of Feige 87 showing the Pb III 1048 Å line and our best fit.

We computed a set of LTE atmosphere models with the atmospheric parameters listed in Table 2 (the atmospheric parameters were derived by E. M. Green et al. 2006, in preparation; Edelmann 2003; M. Fontaine et al. 2006, in preparation; Kilkenny et al. 1987; Heber et al. 2002; Allard 1986 and Saffer et al. 1994). These models were computed for a hydrogen/helium chemical composition. We used two methods for determining the abundances of Ge, Zr and Pb. For stars that do not have numerous absorption lines and have a well defined continuum, we fitted each line by using a χ^2 minimization technique for which the abundance and a scaling factor are the free parameters. In this case we computed grids of LTE synthetic spectra by considering Ge, Zr and Pb as trace elements. The lines of Ge III, Zr IV, Pb III and Pb IV were computed for abundances ranging from $\log N(\mathrm{X})/N(\mathrm{H}) = -10.4$ to -6.0 in steps of 0.4 dex by assuming no microturbulent velocity. The calculations were performed by using the programs TLUSTY (Hubeny & Lanz 1995) and SYNSPEC (I. Hubeny 2004, private communication). The partition functions for the neutral, +1 and +2 ionization stages of Ge, Zr and Pb are calculated in the same manner as in the Kurucz's ATLAS9 code (Kurucz 1993; Proffitt et al. 2001). For the +4 ionization stage of Zr and Pb we adopted the ground-state statistical weights for the partition functions. The sdB star Feige 87 is a good example of a low-metallicity star for which this method gives excellent results (see Figures 2 and 3).

We cannot apply the χ^2 fitting technique for stars like the one illustrated in Figure 1 (see also Figure 1 of Blanchette et al. 2006). Instead we used the IDL (Interactive Data Language) program SYNPLOT developed by I. Hubeny. SYNPLOT is an interactive program that calculates and plots synthetic spectra using the program SYNSPEC. We can then overplot the observed spectrum and compare it to the model. If the model does not reproduce the observation, we can change the abundance and repeat the operation until the fit is acceptable, i.e., the comparison between the model and the observation is satisfactory. This is what we call fitting a spectrum by eye. The main difficulty encountered when fitting spectra with this method is the placement of the continuumm. For instance, Pereira et al. (2006) showed that LTE hydrogen-rich synthetic spectra computed in the *FUSE* band yielded continuum above the observed continuum. In their calculations they used T_{eff} and $\log g$ from a Balmer line analysis and normalized the synthetic spectra to the y magnitude. Their results indicate that the placement of the continuum may be one of the main sources of systematic error. When fitting a small portion of the spectrum we have a tendency to put the continuum close to what we believe is the real continuum. The study of Pereira et al. (2006) shows, however, that the continuum may be well above the one that we set for determining the abundances. Consequently, we may underestimate the abundances when fitting spectra that contain numerous absorption lines.

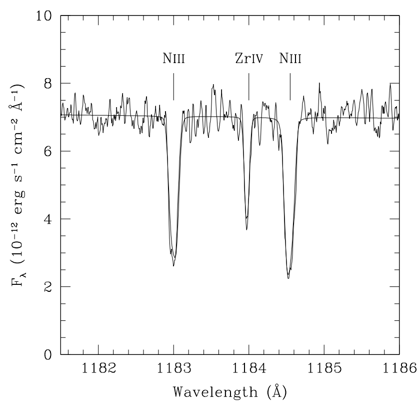

Fig. 3. *FUSE* spectrum of Feige 87 showing the Zr IV 1184 Å and N III 1183 and 1184 Å lines and our best fit.

In order to measure the zirconium abundance, we estimated the oscillator strength of the Zr IV 1184 Å line empirically, because no oscillator strength was available from the literature. We measured the Zr abundance in the atmosphere of the sdB star Feige 48 by using its ultraviolet spectrum obtained by the Space Telescope Imaging Spectrograph onboard HST (O'Toole et al. 2004). We analyzed the Zr III lines at 1790.113 Å, 1793.523 Å and 1798.048 Å and measured an abundance of $\log N(\mathrm{Zr})/N(\mathrm{H}) = -8.0$. Keeping this abundance constant, we fitted the Zr IV 1184 Å line observed in the *FUSE* spectrum by maximizing the oscillator strength gf in order to obtain the best fit for this line. This best gf value is given in Table 1. Because the Zr IV 1012 Å line is blended with the S III resonance line at 1012.498 Å, we only used the Zr IV 1184 Å line to estimate the Zr abundance. Figure 3 illustrates the best fit of the Zr IV 1184 Å and N III 1184 Å lines for the star Feige 87.

4. RESULTS

Table 2 summarizes the abundances for Ge, Zr and Pb observed in the atmospheres of our program stars. The first column is the name of the star. The second and third columns give the effective temperature in ascending order and the gravity, respectively. Columns 4, 6 and 8 are the measured abundances or upper limits ($\log[N(\mathrm{X})/N(\mathrm{H})]_\star$: $\star$ symbol). Columns 5, 7, and 9 are the observed abundances reported relative to the abundances in the Sun ($\log[N(\mathrm{X})/N(\mathrm{H})]_\star - \log[N(\mathrm{X})/N(\mathrm{H})]_\odot$: $\star - \odot$ symbol). The Ge, Zr and Pb abundances in the atmosphere of the Sun are −8.42, −9.41 and −10.00, respectively. They are taken from the review of Asplund et al. (2005). We estimate that the uncertainties (statistical and systematic) associated with the measured abundances vary from 0.1 dex to 0.3 dex. Table 2 shows that Ge, Zr and Pb are present in the atmospheres of almost all sdB stars. Although the average abundances relative to hydrogen are about the same for these three elements with a value of about $\log[N(\mathrm{X})/N(\mathrm{H})] \simeq -7.8$ and a dispersion of about 1.0 dex, the Ge, Zr and Pb abundances relative to the solar abundances are 0.62, 1.61 and 2.20 dex, respectively. The difference in the abundances relative to solar is due to the fact that

$$\log[N(\mathrm{Pb})/N(\mathrm{H})]_\odot < \log[N(\mathrm{Zr})/N(\mathrm{H})]_\odot < \log[N(\mathrm{Ge})/N(\mathrm{H})]_\odot. \quad (1)$$

Figure 4 illustrates the Ge, Zr and Pb abundances by number relative to hydrogen as a function of effective temperature. Filled circles and downward-pointing arrows correspond to abundances and upper limits. The horizontal dotted line in each panel is the solar abundance according to Asplund et al. (2005). The figure

Table 2. Abundance of Ge, Zr and Pb in the atmospheres of sdB stars compared to the Sun

Star	$T_{\rm eff}$	$\log g$	Ge		Zr		Pb	
	(10^3 K)	(cm s^{-2})	$\star$	$\star-\odot$	$\star$	$\star-\odot$	$\star$	$\star-\odot$
HD 4539	23.9	5.2	−7.7	0.7	−7.7	1.7	−8.1	1.9
JL 36	24.5	5.6	−7.8	0.6	−8.0	1.4	−7.7	2.3
HD 205805	25.6	5.3	−8.0	0.4	−7.4	2.0	−8.7	1.3
LB 1516	26.1	5.4	−8.0	0.4	−8.0	1.4	−8.7	1.3
Feige 48	29.6	5.5	−8.0	0.4	−8.0	1.4	−8.5	1.5
Feige 87	29.9	5.4	−10.3	−1.9	−8.4	1.0	−7.3	2.7
JL 236	29.9	5.7	−7.6	0.8	−7.5	1.9	−8.1	1.9
PG 0823+465	29.9	5.8	−9.0	−0.6	−7.4	2.0	<−9.0	<1.0
PG 1710+490	30.3	5.7	−7.9	0.5	−7.1	2.3	<−9.5	<0.5
PG 1206+165	30.5	5.6	−9.3	−0.9	−9.3	0.1	−6.7	3.3
PG 1610+529	31.0	5.8	−7.6	0.8	−7.1	2.3	−7.7	2.3
PG 1032+406	31.3	5.9	−6.7	1.7	−7.3	2.1	−7.1	2.9
Feige 91	31.3	6.0	−6.5	1.9	−7.3	2.1	−7.0	3.0
KPD2109+4401	31.4	5.6	−7.5	0.9	<−9.0	<0.4	−7.3	2.7
PG 1619+522	33.0	5.8	−6.7	1.7	−7.3	2.1	−7.2	2.8
PG 1538+401	33.5	5.9	−8.0	0.5	−8.8	0.6	−9.0	1.0
PG 1219+534	33.6	5.8	−6.6	1.8	−8.3	1.1	−7.0	3.0
PG 1255+547	33.9	5.8	−6.4	2.0	−7.1	2.3	−6.8	3.2

shows that the abundances are higher than the solar abundances in almost every star, and that these overabundances can reach 3 orders of magnitude in a few cases. The analysis of several stars provides the opportunity to uncover some trends in the abundance patterns. Can we observe such trends with the data that we have in hand? There may be a slight increase in the abundance as the temperature increases. The large scatter of the abundances, however, is really the most striking result. For instance, stars with $T_{\rm eff} \geq 29\,500$ K show a scatter of the abundances on a scale of 2 to 3 orders of magnitude for the three elements.

Three stars in our sample are EC 14026 pulsators: Feige 48, KPD 2109+4401 and PG 1219+534. The Ge, Zr and Pb abundances in Feige 48 are about the same and are close to the cooler stars. KPD 2109+4401 and PG 1219+534 display the same abundance pattern. Although they show relatively high Ge and Pb abundances, their Zr abundance is much lower. By comparison with other stars in general, the pulsators do not show any abundance enhancement. Two stars in our sample are out of the ordinary: Feige 87 and PG 1206+165. The two stars show low Ge and Zr abundances but high Pb abundance. Moreover, their *FUSE* spectra show very low abundances of iron peak elements, although their C, N and O abundances are relatively high. The hot PG1538+401 star is another interesting object. Its Ge, Zr and Pb abundances are systematically lower than the other hot stars.

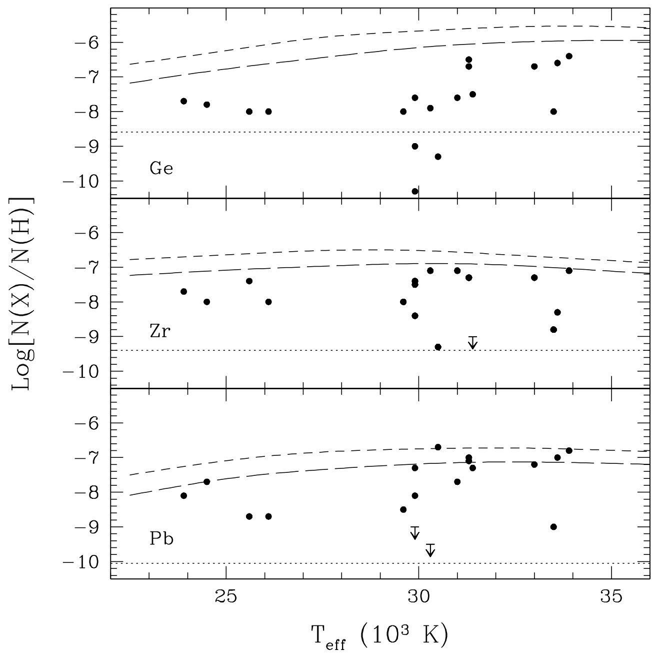

Fig. 4. Ge, Zr and Pb abundances (*filled circles*) and upper limits (*downward-pointing arrows*) observed in the *FUSE* spectra of sdB stars. The dotted line in each panel is the solar abundance according to Asplund et al. (2005). The dashed and long-dashed lines are predicted abundances computed within the framework of the radiative levitation theory according to Michaud et al. (1976) for models with $\log g = 5.5$ and 6.0, respectively.

5. RADIATIVE LEVITATION

In order to confirm the role of the radiative levitation for maintaining traces of heavy elements, we carried out radiative levitation calculations on Ge, Zr and Pb. Figure 4 illustrates radiative equilibrium abundances computed at $\tau_{\mathrm{R}} = \frac{2}{3}$ for models with $\log g = 5.5$ (dashed lines) and 6.0 (long-dashed lines). Because of lack of atomic data for Ge, Zr and Pb, we used the approximate method developed by Michaud et al. (1976) to compute the equilibrium abundances illustrated in Figure 4. Bergeron et al. (1988) showed that the approach of Michaud et al. (1976) yields good agreement with more detailed radiative levitation calculations carried out in sdB models for C, N and Si. Bergeron et al. (1988) added that this approximate formalism overestimates the radiative acceleration by no more than a factor of ~ 3 in the line-forming regions, and concluded that this method could be applied to other elements. Following the findings of Bergeron et al. (1988) and in order to better match the observed abundances, we reduced the radiative acceleration on Ge, Zr and Pb by a factor of 3. Figure 4 shows that the radiative levitation provides more than enough support for our elements of interest.

The predicted abundances are in general greater than the observed abundances. In a few cases the predictions are consistent with the observations. It is difficult to explain, however, the large scatter of the observed abundances. For instance, stars with $T_{\rm eff} \geq 29\,500$ K show abundances that vary over two to three orders of magnitude. According to the parameter-free diffusion model, which consists of a strict equilibrium between the gravitational and radiative accelerations, stars with similar atmospheric parameters should show similar abundances. The large scatter of the abundances for $T_{\rm eff} \geq 29\,500$ K cannot be interpreted only in terms of the atmospheric parameters.

6. DISCUSSION AND CONCLUSION

A weak stellar wind at the surface of sdB stars is one of the mechanisms that was proposed for opposing gravitational settling and at the same time affecting the equilibrium abundances predicted by the radiative levitation. Although the proposed mass loss rates are too low to be detected directly, their effect on the surface abundances may be quite important. Michaud et al. (1985) and Bergeron et al. (1988) put forward the wind hypothesis to explain the Si underabundance observed in a handful of sdB stars. Bergeron et al. (1988) demonstrated that detailed radiative levitation calculations predicted large Si abundances, even though observations showed that Si was underabundant as much as five orders of magnitude in stars with $T_{\rm eff} \geq 27\,000$ K. Michaud et al. (1985) suggested that an outward velocity field produced by a weak stellar wind could decrease the Si abundance at the surface of a sdB star.

By trying to explain the He underabundance in sdB stars, Michaud et al. (1989) demonstrated that the radiative forces were in fact too small to support the observed He abundance. This result prompted Fontaine & Chayer (1997) and Unglaub & Bues (1998) to compute time dependent diffusion calculations that included mass loss. Both groups showed that mass loss rates of the order of 10^{-13} to 10^{-14} $M_{\odot}\,{\rm yr}^{-1}$ could maintain He abundances similar to those observed in the atmospheres of sdB stars. The wind hypothesis was also assumed by Chayer et al. (2004) to explain the presence of EC 14026 pulsators and non-pulsators in the empirical instability region. Chayer et al. (2004) showed that weak stellar winds could disrupt the Fe reservoir, which is responsible for driving the pulsations in EC 14026 stars, and explain why a star pulsates while another does not.

All the diffusion calculations that we have just reviewed involve weak stellar winds that assume an outward velocity that is provided by the continuity equation. This velocity depends on the mass loss rate, the density of matter, and the position where the velocity is calculated. This means that at a given radius all elements have the same outward velocity. This velocity is low in the deeper layers of the atmosphere, and is large in the upper layers. O'Toole (2004) proposed that this velocity could be different for elements with different atomic mass. He suggested that a fractionated wind could explain the Si underabundance and the presence of Ge, Sn and Pb in the atmospheres of sdB stars. O'Toole (2004) argued that Si, Ge, Sn and Pb should have similar susceptibility to absorb radiative momentum given that they occupy the same column of the periodic table and should have in principle similar atomic properties. He added that the atomic mass should be the parameter that could be involved in the separation of the elements in the wind. Consequently, a light element such as Si could be removed preferentially from the atmospheres of sdB stars in a fractionated stellar wind, while the heavier elements Ge, Sn and Pb should lag behind.

This interesting hypothesis can be tested by comparing the abundances of Si, Ge, Sn and Pb in a sample of stars with atmospheric parameters that cover the whole range of possible values for sdB stars. The present study is the first step in this direction. The *FUSE* observations provide the spectral window to identify not only Ge and Pb, but also Si. We are in the process of completing the Si abundance analysis and hope to test the hypothesis of the fractionated wind put forward by O'Toole (2004).

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