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Research Article

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HST spectroscopy of chemically peculiar hot subdwarfs: PG 0909+276 and UVO 0512–08

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Abstract: High-resolution ultraviolet spectroscopy of two chemically peculiar hot subdwarfs, PG 0909+276 and UVO 0512–08, has been obtained using the Hubble Space Telescope. Chemical abundances in the stars' atmospheres were measured from previous optical spectra and from the new ultraviolet observations. Iron-group metals, including cobalt, copper and zinc, are highly enriched relative to typical subdwarf B (sdB) stars. Lead is also enriched, but with an abundance similar to other sdB stars. The surface chemistry of these two stars is quite distinct from both hydrogen-rich normal sdB stars and also from the intermediate helium-rich sdB stars which show heavy-element superabundances. A full explanation for exotic chemistries in hot subdwarfs remains elusive.

Keywords: stars: abundances – stars: fundamental parameters – stars: chemically peculiar – stars: individual (PG 0909+276) – stars: individual (UVO 0512–08) – stars: subdwarfs

1 Introduction

Stars with surface temperatures greater than 25 000 K and surface gravities higher than hydrogen-burning mainsequence stars but lower than white dwarfs are known as hot subdwarfs, or hot subluminous stars. Those with spectral type B, or sdB stars, have strong Balmer lines, weak neutral helium lines and no ionized helium lines. Evidence from parallaxes, sdB stars in binaries, and pulsating sdB stars, implies that most have masses $M < 0.5M_\odot$ Arguments from stellar structure theory imply that most comprise a helium burning core surrounded by an inert hydrogen skin that cannot sustain fusion. With effective temperatures $20 < T_{\rm eff}/{\rm kK} < 35$ and surface gravities $5.5 < \log g/{\rm cm\,s^{-2}} < 6.5$, the majority lie on or near the blue end of the extreme horizontal branch on a Hertzsprung-Russell diagram (Heber 2016) and are extremely helium-poor. With $35 < T_{\rm eff}/{\rm kK} < 45$, sdOB stars show showing both neutral and ionized helium lines and have surface chemistries ranging range from heliumweak to extremely helium-strong. Most lie close to the helium main sequence.

The formation and evolution of hot subdwarfs is not fully understood, with one problem being the number of subclasses observed. Several potential evolutionary tracks have been proposed, including a late helium flash in a post-giant star (Brown et al. 2001; Miller Bertolami et al. 2008), common-envelope binary evolution (Han 1998; Ivanova et al. 2013), or a white dwarf merger (Iben 1990; Saio & Jeffery 2002; Zhang & Jeffery 2012). Identifying to which track a given hot subdwarf belongs is not always possible. By measuring detailed photospheric chemistries from the large amount of spectropscopic information available at ultraviolet wavelengths, we aim to improve the diagnostics available to separate the otherwise degenerate tracks.

A previous analysis of two sdOB stars, PG 0909+276 and UVO 0512–08, showed them to be hydrogen-weak, with extreme super-solar abundances of metals with atomic number $Z \geq 18$ (Edelmann 2003; Geier 2013). Both being bright in the ultraviolet, new high-resolution ultraviolet spectra have been obtained with the Hubble Space Telescope (*HST*) in order to better determine the surface chemistries of these two stars. A key goal was to identify and measure species additional to those measure from optical spectra. A detailed analysis of these spectra will be published elsewhere (Wild & Jeffery 2017). This poster paper presents preliminary results.

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Table 1. Observations used in analysis of PG 0909+276 and UVO 0512−08

Star	Instrument	Date	R	$\lambda\lambda/\text{Å}$	n	$t_{\rm exp}/\text{s}$	S/N	Image
PG 0909+276	DSAZ FOCES	2000.01	30 000	3900 – 6900	3	5400	30	
	HST STIS E140M	2015.04.24	45 800	1140 – 1740	1	2989	20	OCKS02020
	HST STIS E230M	2015.04.24	30 000	1740 – 2500	1	2019	50	OCKS02010
	IUE SWP LORES LAP	1986.01.07	260	1150 – 2000	1	300		SWP27469LL
	IUE LWP LORES LAP	1986.01.07	320	1850 – 3350	1	450		LWP07464LL
UVO 0512−08	DSAZ FOCES	2000.01–02	30 000	3900 – 6900	2	7200	30	
	HST STIS E140M	2015.02.25	45 800	1140 – 1740	1	1006	20	OCKS01010
	HST STIS E230M	2015.02.25	30 000	1740 – 2500	1	696	30	OCKS01020
	IUE SWP LORES LAP	1980.02.28	260	1150 – 1950	1	235		SWP08075LL
	IUE LWR LORES LAP	1980.02.28	320	1900 – 3200	1	330		LWR07043LL

Table 2. Atmospheric parameters.

	UVO 0512−08	PG 0909+276
$T_{\rm eff}/\text{K}$	37 290±650	36 670±1 430
$\log g/\text{cm}\cdot\text{s}^{-2}$	6.10±0.20	5.75±0.16
$n_{\rm He}$	0.126±0.008	0.159±0.062
$E(B-V)$	0.05	0.05
$v \sin i/\text{kms}^{-1}$	2	2
$v_{\rm turb}/\text{kms}^{-1}$	5	5

2 Aim

It has been suggested in the analyses of other chemically peculiar, hydrogen-poor sdB stars (Naslim et al. 2013) that extreme over-abundances of heavy elements are primarily due to enrichment of the stellar atmosphere by selective radiative levitation of specific ions such that these ions form layers (strata) of high concentration in the line forming region of the photosphere. We analyse data from three spectroscopic regions (optical, and the near and far UV), and extract chemical abundances from each. Our primary aim is to measure abundances for as many elements as possible with the atomic data available by applying local thermodynamic equilibrium (LTE) stellar atmosphere models. UV analysis is not typically performed on hot subdwarfs, as the UV spectra are extremely blended, with many unidentified lines having no atomic data. This makes abundance measurement from either single lines or blends a difficult process.

3 Observations

Observations were obtained with the Hubble Space Telescope' *HST* Imaging Spectrograph (STIS) under Guest Observer programme #13800 in both near ultraviolet (NUV) and far ultraviolet (FUV) wavelength ranges. Pipeline reduced data products were obtained from the Space Telescope Science Institute online archive.

We also used low-resolution ultraviolet spectrophotometry from *IUE*, and high-resolution optical (OP) spectra from the Fiber-Optics Cassegrain Echelle Spectrograph (FOCES) mounted on the 2.2m telescope of the Deutsch-Spanisches Astronomisches Zentrum at the Calar Alto Observatory, Spain. The latter were obtained and analysed by Edelmann (2003); Geier (2013). Details are given in Table 1.

4 Modelling Techniques

We generated a grid of model atmospheres with typical sdB metallicity and varying effective temperature ($T_{\rm eff}$), helium number fraction ($n_{\rm He}$), and surface gravity (g). This was used to fit the basic parameters for each star (Table 2). The package used for computing model atmospheres and theoretical spectra and for fitting these to the observations is LTE-CODES (Jeffery 2003; Winter 2006), which includes STERNE (Behara & Jeffery 2006), SPECTRUM (Jeffery et al. 2001a), LTE_LINES (Jeffery 1991) and SFIT (Jef-

Table 3. Elemental abundance (log ϵ_i) by spectral region, the number of lines (N) contributing to each measurement and the mean weighted by the square of the errors.

Z	FUV	NUV	OP	N (FUV/NUV/OP)	Mean
PG 0909+276					
C	8.620±0.175	8.780±0.200	8.609±0.300	30/12/32	8.676±0.121
N	7.800±0.475	7.770±0.250	8.023±0.165	2/5/15	7.935±0.132
Si	5.950±0.200	-	-	9/0/0	5.950±0.200
S	8.589±0.250	8.500±0.300	7.809±0.200	36/36/8	8.196±0.139
Ar	8.292±0.275	8.414±0.150	8.300±0.200	34/35/2	8.360±0.110
Ca	8.300±0.265	8.366±0.125	7.734±0.200	25/30/15	8.204±0.098
Sc	7.641±0.250	7.300±0.300	7.750±0.150	9/28/39	7.656±0.118
Ti	-	7.500±0.225	7.754±0.125	0/14/24	7.694±0.109
V	6.300±0.250	7.490±0.175	8.000±0.250	6/58/5	7.421±0.124
Cr	7.450±0.225	7.750±0.250	-	79/150/0	7.584±0.167
Mn	-	7.020±0.150	-	0/46/0	7.020±0.150
Fe	7.100±0.200	-	-	67/0/0	7.100±0.200
Co	7.730±0.225	8.250±0.250	-	160/328/0	7.963±0.167
Ni	7.850±0.150	8.000±0.325	-	277/186/0	7.876±0.136
Cu	6.900±0.275	7.300±0.175	-	56/7/0	7.185±0.148
Zn	6.500±0.150	-	-	14/0/0	6.500±0.150
Pb	4.40±0.15	4.10±0.20	-	1/1/0	4.29±0.12
UVO 0512−08					
C	8.386±0.129	9.030±0.220	8.468±0.283	22/40/49	8.540±0.104
N	7.905±0.380	7.675±0.215	7.478±0.308	7/13/13	7.663±0.160
Ne	-	8.907±0.531	8.150±0.289	0/13/9	8.323±0.254
Mg	-	8.518±0.725	-	0/9/0	8.518±0.725
Al	5.503±0.583	-	-	1/0/0	5.503±0.583
Si	4.911±0.399	-	-	3/0/0	4.911±0.399
S	7.191±0.265	7.722±0.416	8.135±0.310	19/24/26	7.615±0.181
Ar	8.310±0.184	8.573±0.225	8.323±0.300	55/67/14	8.398±0.129
Ca	8.770±0.200	8.549±0.262	7.874±0.296	59/82/34	8.506±0.140
Sc	6.907±0.387	6.680±1.357	7.393±0.303	2/2/7	7.192±0.235
Ti	7.762±0.452	7.755±0.297	8.323±0.300	17/34/9	7.865±0.191
V	6.721±0.200	7.142±0.323	-	40/19/0	6.838±0.170
Cr	8.200±0.703	8.683±0.118	-	331/317/0	8.670±0.116
Mn	7.519±0.343	7.476±0.332	-	53/13/0	7.497±0.239
Fe	8.491±0.045	8.697±0.093	7.996±0.294	348/342/15	8.520±0.040
Co	7.600±0.277	8.564±0.098	-	221/354/0	8.457±0.092
Ni	7.000±0.093	8.259±0.183	-	119/117/0	7.258±0.083
Cu	6.350±0.150	7.300±0.175	-	53/6/0	6.752±0.114
Zn	7.251±0.158	7.300±2.228	-	101/4/0	7.251±0.158
Pb	4.95±0.30	4.04±0.15	-	1/1/0	4.22±0.13

fery et al. 2001b). These assume that the atmosphere is semi-infinite, plane parallel, and in radiative, hydrostatic, and local thermodynamic equilibrium. A new model with the appropriate parameters was generated and used to synthesise high-resolution synthetic spectra in which different chemical abundances could be varied. These spectra were used to fit metal abundances to the data, using a Levenburg-Marquardt downhill simplex algorithm. A value of 5 kms^{-1} was adopted for the microturbulent velocity, representing a maximum allowed by the line profiles. Similarly, the metal lines are sufficiently sharp that they constrain the projected rotation velocity $v \sin i < 2kms^{-1}$.

5 Atomic data

To supplement atomic data used in the analysis of other chemically peculiar subdwarfs (Jeffery et al. 2017), we used the University of Kentucky atomic database (Aggarwal et al. 2017), augmented to include data on Zn, Ga, Ge, Sr, and Ba from Rauch et al. (2015). Where duplicate lines were found, the latter was preferred due to being a database specific to those elements. The resulting data set was then merged with the atomic database maintained by Kurucz (Smith et al. 2016) and again, when duplicate lines were found, data from the latter were preferred. We

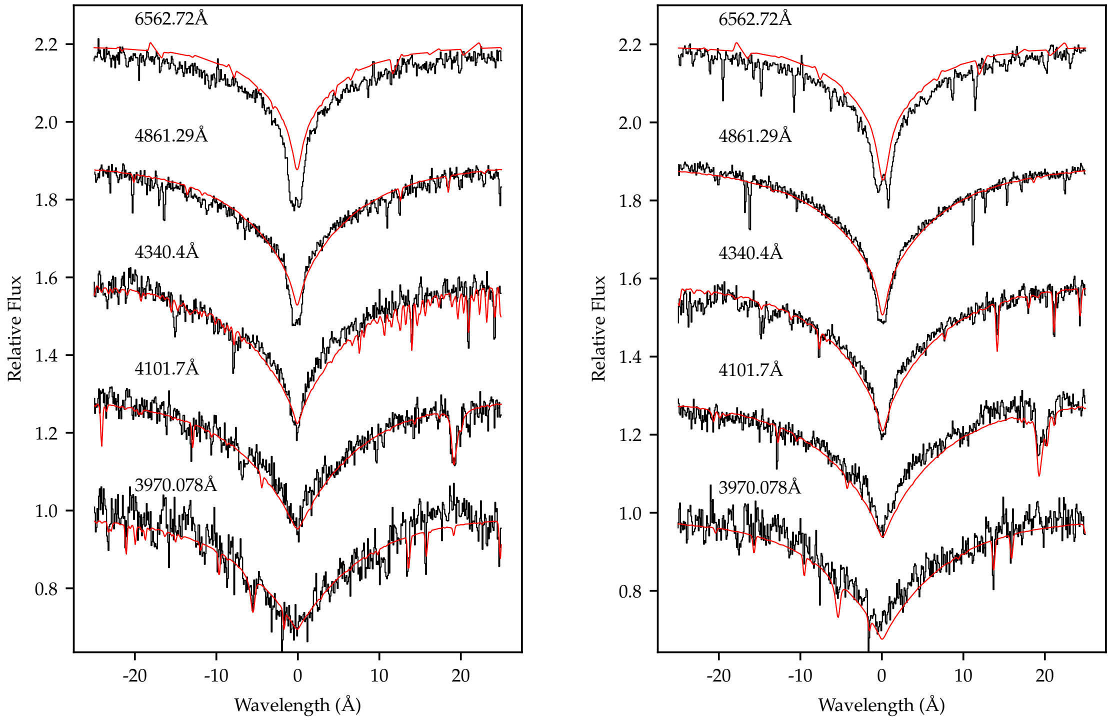

Figure 1. The Balmer series of PG 0909+276 (left) and UVO 0512–08 (right). Adapted from Wild & Jeffery (2017).

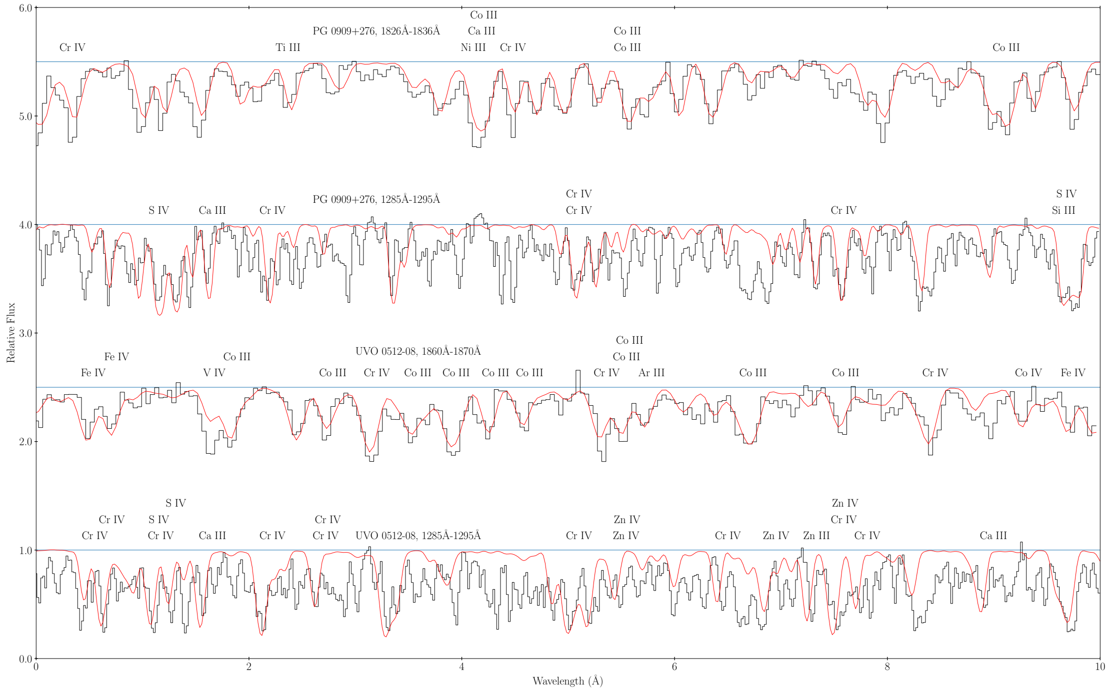

Figure 2. Samples of the normalized FUV and NUV spectra of PG 0909+276 and UVO 0512–08. For PG 0909+276, lines with equivalent widths more than 0.04Å are labelled. For UVO 0512–08, lines with equivalent widths more than 0.05Å are labelled. The segments are all plotted to the same scale and offset vertically by 0, 1.5, 3 and 4.5 units respectively. The estimated continuum is marked as an horizontal line.

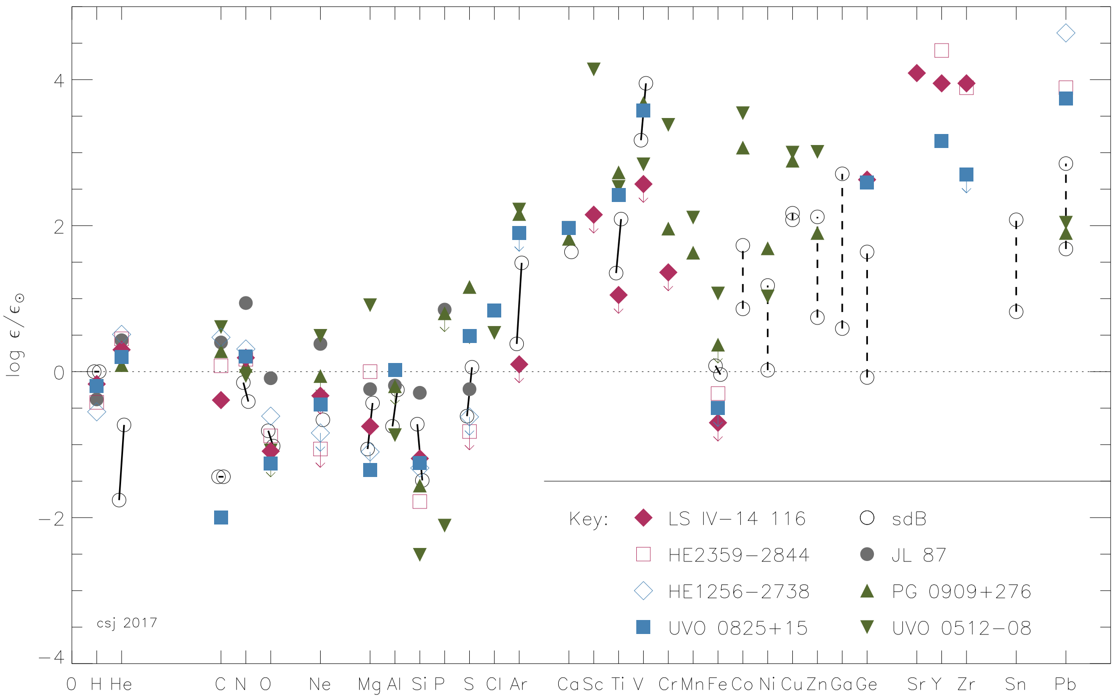

Figure 3. Surface abundances of super metal-rich hot subdwarfs, including the pulsating stars LS IV−14°116 and UVO 0825+15, and the two stars considered in this paper; PG 0909+276 and UVO 0512−08. Abundances are shown relative to solar values (dotted line). Mean abundances and ranges for the helium-rich subdwarf JL 87 (Ahmad et al. 2007) and for normal subdwarfs are also shown. The latter are shown by connected open circles as (i) $Z \leq 26$ (solid lines): the average abundances for cool and warm sdBs (Geier 2013) and (ii) $Z \geq 27$ (broken lines): the range of abundances measured for five normal sdBs from UV spectroscopy (O'Toole & Heber 2006). Adapted from Jeffery et al. (2017).

also investigated Pb IV lines using theoretical oscillator strengths from Alonso-Medina et al. (2011). These data were extracted and merged into our customized atomic line database. Because both target stars have $T_{\mathrm{eff}} \approx 40\,000$ K, there are substantial contributions from highly ionized species. Since the conditions that produce these ions are difficult to recreate in the laboratory, there is often either little or no data available for their spectra. Therefore, in both stars, there are large numbers of observed lines for which there is no match in our database. For example, when analysing the far UV region of PG 0909+276, a total of 736 lines were successfully used to extract abundances. This is only 20% of an estimated 3,600 lines seen in the spectrum (Figure 2). This leaves the majority of the information we could potentially extract unknown, and an obvious gap in knowledge for atomic physics to target in future research.

6 Results

For both stars, optical spectra show large sections that have either weak or no lines, although Edelmann (2003) notes that the optical spectrum of UVO 0512–08 contains many more lines than expected from a hot subdwarf. With several strong hydrogen and helium lines, and isolated lines of other species, the optical spectra provide the most robust means to determine basic parameters (Figure 1, Table 2) and to estimate abundances of some key elements. However, ultraviolet spectra are required to measure the abundances of most iron-group elements. So far, we were able to determine the abundances of 17 species heavier than helium, in PG 0909+276, and 20 in UVO 0512–08 (Table 3, Figure 3).

Elemental abundances are given in logarithmic form as:

$$\log \epsilon_i = \log \frac{n_i}{\Sigma_i n_i} + c \qquad (1)$$

where c is determined such that $\log \Sigma_i \mu_i \epsilon_i + c = \log \Sigma_i \mu_i \epsilon_{i\odot} + c' = 12.15$ and μ_i is the atomic mass of element i. On this scale, the log solar abundance of hydrogen is 12.00 (by definition), and of iron is 7.50. Abundances relative to solar are denoted by square brackets: e.g. [C] = $\log(\epsilon_{\mathrm{C}}/\epsilon_{\mathrm{C}\odot})$.

In both PG 0909+276 and UVO 0512–08, all observed elements with $Z \geq 18$ have abundances that are enriched compared to solar, and elements with $Z < 16$ were seen to be within ±1 dex of solar, except for silicon ([Si] = -1.56 ± 0.20 and -2.51 ± 0.40 in PG 0909+276 and UVO 0512–08, respectively) and phosphorous. However, the overall trend in abundances at $Z < 18$ is unclear, since several elements with $Z < 14$ show no lines at observed wavelengths. We observe roughly solar carbon and nitrogen, consistent with the majority of sdB stars.

Although most sdB stars have elevated iron-group abundances, iron itself is generally very close to solar (Geier 2013). This anomaly also extends to the chemically-peculiar sdBs analysed so far, although this is the first time that measurements have been possible from the ultraviolet. In contrast, we find that UVO 0512–08 appears to be enriched in iron, with a mean [Fe] = $+1.07 \pm 0.04$.

We observed two Pb IV lines in each star, yielding lead abundances of $\log \epsilon_{\mathrm{Pb}} = 4.29 \pm 0.12$ in PG 0909+276 and 4.22 ± 0.13 in UVO 0512–08. These values are ~ 2 orders of magnitude enriched relative to solar ($\log \epsilon_{\mathrm{Pb}\odot} = 1.75 \pm 0.10$), and roughly typical of values observed in normal sdB stars. Neither star may therefore be described as lead-rich as, for example, UVO 0825+15 (Jeffery et al. 2017).

7 Conclusion

We have carried out an atmospheric fine analysis of two hot subdwarfs known to be strongly enriched in some iron-group elements. This analysis uses new high-resolution ultraviolet spectroscopy in order to measure abundances of elements not seen at optical wavelengths. The interim result is that lead is enhanced relative to solar, but no more that in other "normal" hot subdwarfs, while other iron-group elements are confirmed to be over-abundant by 1 - 4 dex. Additional elements have been investigated and are discussed in detail by Wild & Jeffery (2017). Evidence for how these over-abundant species are distributed vertically through the photosphere has still to be obtained.

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