

## Heavy Elements in DA White Dwarfs

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### **Abstract.**

We present a series of systematic abundance measurements for a group of hot DA white dwarfs in the temperature range  $\approx 20,000 - 75,000\text{K}$ , based on far-UV spectroscopy with STIS on *HST*, *IUE* and *FUSE*. Using our latest heavy element blanketed non-LTE stellar atmosphere calculations we have addressed the heavy element abundance patterns for the hottest stars for the first time, showing that they are similar to objects like G191–B2B. The abundances observed in the cooler ( $< 50,000\text{K}$ ) white dwarfs are something of a mystery. Some of the patterns (e.g. REJ1032) can be explained by self-consistent levitation-diffusion calculations but there is then a serious difficulty in understanding the appearance of the apparently pure H atmospheres. We also report the detection of photospheric HeII in the atmosphere of WD2218+706.

### **1. Introduction**

The existence of two distinct groups of hot white dwarfs, having either hydrogen-rich or helium-rich is now, qualitatively at least, understood to arise from the number of times the progenitor star ascends the red giant branch and the amount H (and He) lost through the successive phases of mass-loss. Consequently, it seems clear that each group descends from their respective proposed progenitors,

the H-rich and He-rich central stars of planetary nebulae (CSPN). Nevertheless, there remain several features of the white dwarf cooling sequence that cannot be readily explained. For example, while the hottest H-rich DA white dwarfs outnumber the He-rich DOs by a factor 7 (Fleming et al. 1986), the relative number of H- and He-rich CSPN is only about 3:1. In addition, there exists a gap in the He-rich track between  $\approx 45000\text{K}$  and  $30000\text{K}$  between the hot DO and cooler DB white dwarfs, confirmed by a detailed spectroscopic analysis of all the then known hot He-rich objects by Dreizler and Werner (1996).

To understand white dwarf evolution, we need to know accurately several physical parameters for each star. For example, a measurement of effective temperature ( $T_{eff}$ ) establishes how far along its evolutionary sequence the star has progressed. A key result has been the establishment of the temperature scale for DA stars through the determination of  $T_{eff}$  from the Balmer line profiles in optical spectra. The reliability of this work depends on the assumption that the Balmer line profile technique is a reliable estimator of  $T_{eff}$  in all cases. However, Barstow Holberg & Hubeny (1998) have shown that the presence of substantial blanketing from photospheric heavy elements does significantly alter the Balmer line profiles at a given effective temperature. Hence, the temperature scale of the hottest, most metal-rich DA white dwarfs, realised by studies using only pure H photospheric models, cannot be viewed as reliable and must be revised taking into account the photospheric composition of each star.

Until recently very few DA white dwarfs were known to have effective temperatures above  $\approx 70000\text{K}$ . Therefore, the proposed direct evolutionary link between H-rich CSPN and white dwarfs has hardly been explored. In particular, there have been no measurements of the photospheric composition of what might be termed super-hot DAs, to distinguish them from the cooler ranges studied in detail. Using a new grid of non-LTE, heavy element-rich model atmospheres and a combination of *HST* STIS and *FUSE* spectra, we have made the first measurements of photospheric abundance for a sample of very hot DA white dwarfs. For comparison, we have also re-examined the archive data of the cooler DA stars.

## 2. Observations

All the new far-UV spectroscopic observations were obtained as part of a joint *HST* STIS (cycle 8) and *FUSE* (cycle 1) programme. The *FUSE* observations are discussed elsewhere in these proceedings (Barstow et al. 2000), with examples of typical spectra. Our STIS data were all obtained with the E140M grating and cover the wavelength range from 1150 to  $1700\text{\AA}$ . Figure 1 shows sample regions of the STIS spectrum of REJ0558–371 (for which we also have *FUSE* data), illustrating the detection of NV, OV, SiIV and FeV. The STIS spectra are typically more sensitive to Fe and Ni than the *FUSE* observations and N is not detected by *FUSE*. On the other hand, P and S which are detected in the *FUSE* range cannot be seen by STIS. Hence, the two instruments acquire complementary information.

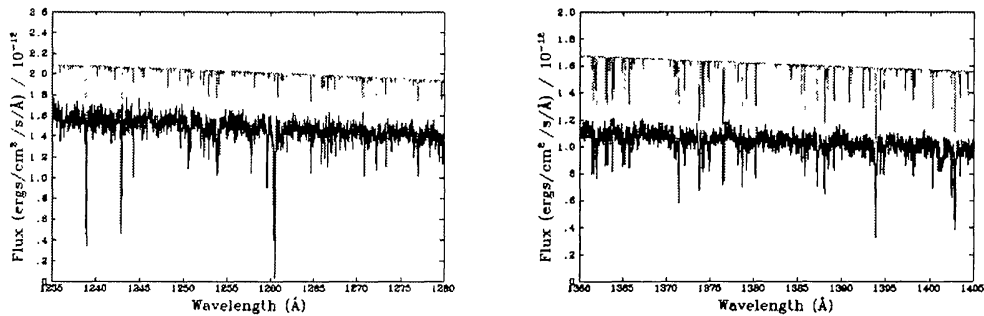


Figure 1. Left: 1230Å to 1280Å region of the STIS spectrum of REJ0558–371, showing photospheric absorption lines of NV (1238.821/1242.804Å) and large numbers of Ni lines. Right: 1360Å to 1405Å region of the the STIS spectrum of REJ0558–371, showing photospheric lines of OV (1371.296Å), SiIV (1393.755/1402.770Å) and FeV. In both cases the best-fit synthetic spectrum is shown offset for clarity.

### 3. Abundance measurements

We have calculated a new grid of model stellar atmospheres using the non-LTE code TLUSTY. These are based on work reported by Lanz et al. (1996) and Barstow, Hubeny & Holberg (1998, 1999). In this case we have extended the temperature range of the calculations up to 90,000K, to deal with the hotter DA stars included in this analysis. To take account of the higher element ionization stages that are likely to be encountered in these objects, we have added new ions of OVI, FeVII/VIII and NiVII/VIII to the model atoms as well as extending the data for important ions such as CIV to include more energy levels. As before, all the calculations were performed in non-LTE with full line-blanketing. We initially fixed the abundances of the heavy elements at the values determined from our earlier homogeneous analysis of G191–B2B ( $\text{He}/\text{H}=1.0 \times 10^{-5}$ ,  $\text{C}/\text{H}=4.0 \times 10^{-7}$ ,  $\text{N}/\text{H}=1.6 \times 10^{-7}$ ,  $\text{O}/\text{H}=9.6 \times 10^{-7}$ ,  $\text{Si}/\text{H}=3.0 \times 10^{-7}$ ,  $\text{Fe}/\text{H}=1.0 \times 10^{-5}$ ,  $\text{Ni}/\text{H}=5.0 \times 10^{-7}$ ). but taking into account that the CIV lines near 1550Å have subsequently been resolved into multiple component by STIS.

Abundances were estimated for each element in each star of the sample by matching the data to a synthetic spectrum calculated from the TLUSTY non-LTE model nearest in  $T_{\text{eff}}$  and  $\log g$  using SYNSPEC. Abundances were then varied within a narrow range within SYNSPEC to obtain the formal values that give the best representation of the data, summarised in Table 1. For the hot group of stars (REJ0457 and above), gaps in the abundance data arise mostly from the absence of data in the appropriate spectral range, rather than a true absence of these elements. For GD246 and PG1123, which are of similar temperature to REJ0457, the situation is not completely clear cut. STIS observations are available for both these stars, but at higher dispersion with the E140H grating and over a narrower wavelength range than the E140M. Hence, the 1550Å CIV resonance lines are not covered while NV, SIV and OV are. For the cooler stars

gaps in the table are indicative that the element is not present at abundances detectable by STIS or *IUE*.

Table 1. Photospheric heavy element abundances determined from far-UV spectroscopy of the hot DA white dwarf sample.

Star	$T_{\text{eff}}$	C/H	N/H	O/H	Si/H	P/H	S/H	Fe/H	Ni/H
PG1342	72000	100		20	10	0.10	20	100	
REJ1738	71300	0.2	3.0	3.0	10			40	5.0
REJ0558	63000	8.0	3.0	30	20	0.2	2.5	100	15
REJ2214	62100	10	0.75	9.6	7.5			100	10
REJ0623	59700	10	1.6	9.6	3.0			100	10
WD2218	56900	4.0	10	100	6.5			200	5.0
Feige 24	56400	1.0	3.0	5.0	3.0			100	20
REJ2334	54600	0.2	5.0		3.0			100	5.0
G191-B2B	54000	4.0	1.6	9.6	3.0	0.25	3.2	100	5.0
GD246	53700				1.0				
REJ0457	53600	4.0	1.6	9.6	1.0	0.25		100	5.0
PG1123	52700								
HZ43	49000								
REJ1032	46300	4.6	500		0.56				
REJ2156	45900								
PG1057	39600								
REJ1614	38500	4.8	25		0.10				
GD394	38400				0.80				
GD153	37900								
GD659	35300	2.0	63		0.16				
EG102	20200				1.0				
Wolf1346	20000				0.32				

Note: All abundances are  $\times 10^{-7}$ .

#### 4. Discussion

It is no surprise that significant quantities of heavy elements are present in the majority of stars with  $T_{\text{eff}}$  in excess of 50,000K. What is particularly interesting for these hot objects is that the abundances seen in the hottest object are quite similar to those seen in the temperature regime near G191–B2B, the prototypical star of this group. However, it is also clear that the abundances are not identical from object to object. This variation may well be explained by small differences in  $T_{\text{eff}}$  and  $\log g$  altering the precise balance of the radiative levitation and diffusion processes. Schuh (2000) has shown that including these effects self-consistently within the model atmosphere calculations can give a good match to the observed EUV and UV spectra of several of these stars. However, this agreement may break down in the hotter objects if a wind is present and Schuh's analysis should be extended to PG1342, REJ0558 and REJ1738.

The cooler white dwarfs ( $T_{\text{eff}} < 50,000\text{K}$ ) can be divided into two broad categories, those where heavy elements (typically C,N and Si, e.g. REJ1032) are detected and those where the atmospheres seem to be devoid of such material (e.g. REJ2156). Where heavy elements are detected in the far UV, the EUV spectra appear to arise from a pure H envelope, indicating that the atmospheres

are highly stratified, with the heavy elements residing in the outermost regions (see Holberg et al. 1995, Holberg et al. 1999). In the case of one of these stars (REJ1032) Schuch has demonstrated that the stratification (and resulting spectra) is a natural consequence of the balance between radiative levitation and downward gravitation. However, it is difficult to reconcile this picture with the increasing abundance of N towards lower temperatures in REJ1614 and GD659. Furthermore, it is difficult to explain the dramatic difference between objects at similar temperature and gravity, such as REJ1032 and REJ2156 which has no heavy element content.

One or two objects appear to be anomalous in some way. While they fit within the broad categories outlined above, the abundance of at least one element is extreme compared to any other object. For example, the C abundance measured from the *FUSE* spectrum of PG1342 is by far the greatest value in the entire sample, by at least one order of magnitude. Similarly GD394 contains a Si abundance well in excess of any other star. In this case, Dupuis et al. (2000) have found the star to be peculiar in other ways, exhibiting a 1.15d EUV photometric modulation. The data suggest that GD394 is accreting material, but a possible source has not yet been identified.

## 5. Helium in WD2218+706

All the above work deals with measured abundance of elements heavier than H or He. However, the absence of He in the hot DAs remains a mystery. CSPN typically have significant abundances of photospheric He but this seems to disappear before the central star appears as a white dwarf. One key aim of the STIS observations of the hottest white dwarfs was to search for the presence of the HeII 1640Å in the spectra. He was not detected in either REJ1738 nor REJ0558, but is clearly present in WD2218+706 (figure 2) and lies at the photospheric velocity. The implied abundance of  $3 \times 10^{-5}$  is well below previous optical and UV limits and less than predicted theoretically for  $T_{\text{eff}}=56900\text{K}$  and  $\log g=6.9$ , appropriate for this star. It is tempting to mark this as the first detection of photospheric He in an isolated hot DA (all other detections appear to be associated with binary systems or possible merged DAs). However, the gravity is rather low for an isolated star, suggesting a binary origin, even though there is no companion known. In addition, this star is associated with a known planetary nebula (DeHt5).

## 6. Conclusion

We have reported a series of systematic abundance measurements for a group of hot DA white dwarfs in the temperature range  $\approx 20,000 - 75,000\text{K}$ , based on far-UV spectroscopy with STIS on *HST*, *IUE* and *FUSE*. Using our latest heavy element blanketed non-LTE stellar atmosphere calculations we have addressed the heavy element abundance patterns for the hottest stars for the first time, showing that they are similar to objects like G191-B2B. The abundances observed in the cooler ( $< 50,000\text{K}$ ) white dwarfs are something of a mystery. Some of the patterns (e.g. REJ1032) can be explained by self-consistent levitation-diffusion calculations but there is then a serious difficulty in understanding the

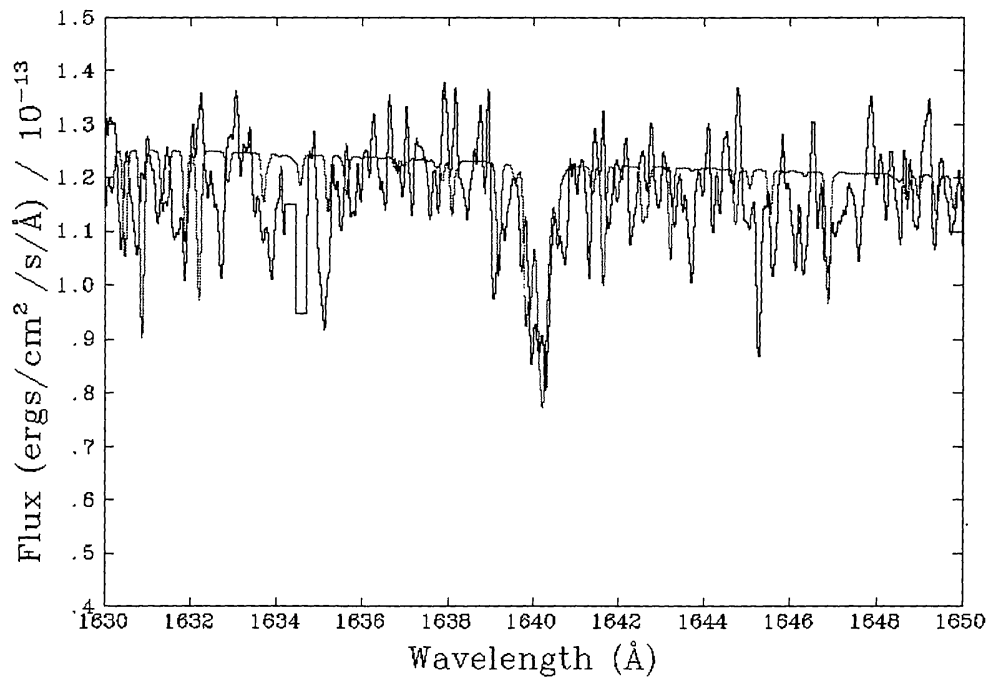


Figure 2. STIS spectrum of WD2218+706 in the region of the HeII 1640Å line, showing its clear detection. The smooth curve is a synthetic spectrum calculated for an abundance (He/H) of  $3 \times 10^{-5}$ .

appearance of the apparently pure H atmospheres. New observations of other stars lying in this temperature range are needed to test the self-consistent model calculations.

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