The Composition and Structure of White Dwarf Atmospheres Revealed by Extreme Ultraviolet Spectroscopy

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The *ROSAT* and *EUVE* all-sky surveys have resulted in an important change in our under-standing of the general composition of hydrogen-rich DA white dwarf atmospheres, with the photospheric opacity dominated by heavy elements rather than helium in the hottest stars ($T > 40,000$ K). Most stars cooler than 40,000 K have more or less pure H atmospheres. However, one question, which has not been resolved, concerned the specific nature of the heavy elements and the role of helium in the hottest white dwarfs. One view of white dwarf evolution requires that H-rich DA stars form by gravitational settling of He from either DAO or He-rich central stars of planetary nebulae. In this case, the youngest (hottest) DA white dwarfs may still contain visible traces of He. Spectroscopic observations now available with *EUVE* provide a crucial test of these ideas. Analysis of data from the *EUVE* Guest Observer programme and *EUVE* public archive allows quantitative consideration of the sources of EUV opacity and places limits on the abundance of He which may be present.

1. Introduction—The View from EUV Surveys

Among the most significant problems in the study of hot white dwarf evolution has been the existence of two distinct groups having either H or He dominated atmospheres and the possible relationships between them and their proposed progenitors, the diverse types of central stars of planetary nebulae (CPN). While the very hottest H-rich DA white dwarfs outnumber He-rich DOs by a factor 7 (Fleming, Liebert & Green 1986), the relative number of H- and He-rich CPN is only about 3:1. In addition, there is an apparent absence of He-rich stars in the temperature range 30,000–45,000 K, the so-called DB gap, suggesting that H- and He-dominated groups are not entirely distinct. Several competing processes can affect the composition of a white dwarf atmosphere. He and heavier elements tend to sink out of the photosphere under the influence of gravity but this can be counteracted by radiation pressure. Convective mixing, accretion or mass loss via a weak wind may also play a significant role.

The first soft X-ray and EUV studies of hot DA white dwarfs made the simplifying assumption that He was the sole photospheric opacity source, although the He in these stars was never identified spectroscopically. However, current evidence indicates that heavier elements have an important role to play. The *ROSAT* EUV/X-ray sky survey data demonstrated that the hottest stars ($T > 40,000$ K) must have heavy elements in their atmospheres to explain the observed fluxes, but stars below 40,000 K seem to have little opacity other than that provided by hydrogen (Barstow et al. 1993). For the hottest stars, it is clear that He alone is insufficient to account for all the opacity and even heavier elements must be involved. Unfortunately, none of the available data permit

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us to decide whether or not He does play a role in DA atmospheres. Optical and *IUE* data typically only allow upper limits of a few $\times 10^{-4}$ to be placed on the He content and the broadband photometric *ROSAT* data do not allow separation of the possible opacity contributions from He and the heavier elements.

2. The Role of Helium in DA White Dwarfs

The availability of *EUVE* spectroscopy has provided us with an opportunity of resolving some of these issues, in particular searching for He with considerably greater sensitivity than has been possible in the past. *EUVE* allows spectra to be obtained throughout most of the EUV band, from $\approx$ 60–700 Å, but the crucial region is that of the He II lyman absorption series between 304 Å and the limit at 228 Å.

From an analysis point of view, the white dwarfs studied (drawn from both GO programme and *EUVE* archive) divide into two distinct groups—those with and those without significant heavy element opacity. EUV spectra of the latter category can be described completely by a synthetic spectrum calculated for an H+He model atmosphere, together with a suitable model of the interstellar medium (Rumph, Bowyer, & Vennes 1994). If heavy elements are present, the stars can only be properly studied using complex line-blanketed models with a comprehensive selection of opacity sources. However, it is possible to study just the region of the spectrum near the He II lines, reproducing the general shape of the spectrum with an H+He model plus an exponential roll-off towards short wavelengths. A complete description of our data reduction and analysis techniques has been published elsewhere (Barstow, Holberg, & Koester 1994a, 1994b, 1995).

During the first year of *EUVE* spectroscopic observations the signal-to-noise was limited to $\approx \pm 20\%$ by the detector fixed pattern efficiency variation. Subsequently, this problem has been largely diminished by implementation of the 'dither mode' to average out the fixed pattern and leave a residual efficiency variation of $\pm 5\%$. Figure 1 shows the complete *EUVE* spectrum of the EUV brightest DA white dwarf HZ43. Although it has a temperature above 40,000 K, the star is known to have a remarkably pure H atmosphere. It is well fitted by a pure H model, within the range of temperature and gravity determined by Napiwotzki et al. (1993) and the systematic uncertainties in the models and instrument calibration, although the best fit does require a finite He abundance of 1.3×10^{-6}. However, since the shape of the continuum flux is quite sensitive to possible systematic effects in the models and instrument calibration, we are cautious about interpreting this as a real detection of He in HZ43. Concentrating on the region spanned by the He II Lyman series (Figure 2) allows a 90% upper limit of 3×10^{-7} to be placed on the He abundance (Barstow, Holberg, & Koester 1995).

Table 1 summarises the He abundance limits determined for several stars, with their effective temperatures, gravities and noting whether or not the observation was dithered. The value obtained for HZ43 is substantially lower than any of the others. However, more importantly it is well below the He abundance predicted by diffusion theory (see Vennes et al. 1988), which should be $\approx 3 \times 10^{-6}$ for a star with the temperature and mass of HZ43. This has important consequences for our understanding of the physical mechanisms that determine the photospheric composition of white dwarfs.

3. Heavy Elements in DA White Dwarfs

Recently, Marsh et al. (1995) have extended the analysis of *ROSAT* observations begun by Barstow et al. (1993) to a much larger sample of stars, including most of the new white dwarfs discovered in the survey. While the general conclusions that may be drawn
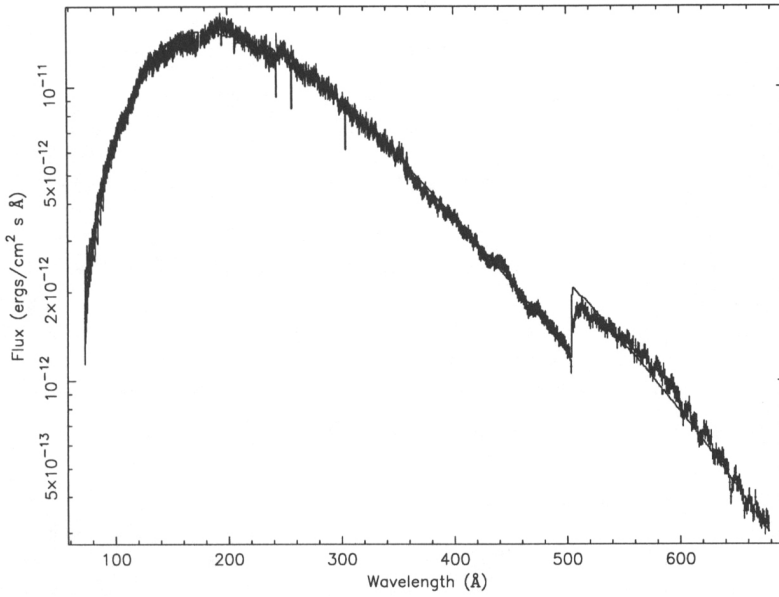
FIGURE 1. Complete *EUVE* spectrum of the DA white dwarf HZ43 after deconvolution with the instrument response (error bars). The model histogram corresponds to the best fit homogeneous H+He model with T=50,560 K, log g=7.9, and He/H= 1.3×10^{-6}.
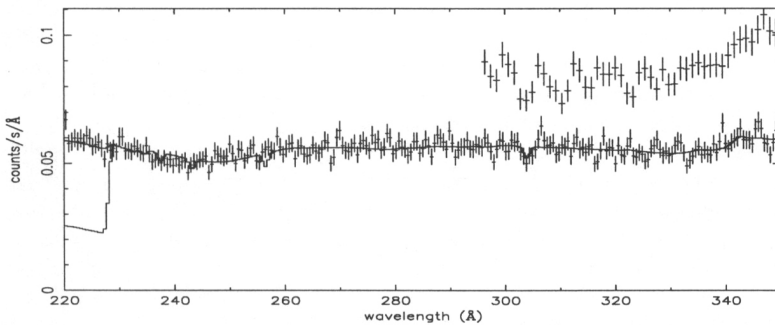

FIGURE 2. Count spectrum of HZ43 between 220 and 310 Å, showing a model with 3×10^{-7} of photospheric He and demonstrating the size of the interstellar 228 Å edge which would be present if the weak 304 Å "feature" was completely accounted for by an interstellar component.

TABLE 1. He abundance 90% upper limits in DA white dwarfs

Star	$T(\pm 1\ \sigma)$	$\log g\ (\pm 1\ \sigma)$	He/H	Dithered?
GD659	35,300(500)	8.00(0.20)	1.3×10^{-6}	Y
Feige 24	59,800(3,400)	7.50(0.51)	3.0×10^{-6}	N *
GD 71	32,045(148)	7.72(0.05)	1.1×10^{-6}	N
HZ43	49,000(2,000)	7.70(0.20)	3.0×10^{-7}	Y **
RE J2156−546	49,800(3,300)	7.75(0.18)	2.0×10^{-6}	N *
GD246	54,987(931)	7.71(0.09)	5.0×10^{-6}	N *

** This upper limit is *below* the level of the He abundance predicted by diffusion theory for a star of this T and $\log g$.
* Close to the predicted value.

TABLE 2. Limits on heavy element abundances in "pure H" DA white dwarfs

Element Abundance	HZ43		GD659	
	IUE high res	*EUVE*	*IUE* high res	*EUVE*
log C/H	−8.5	−5.5	−7.7	−4.6
log N/H	−5.0	−6.0	−4.2	−5.4
log O/H	−6.0	−6.5	—	−6.0
log Si/H	−8.0	−6.0	−9.0	−7.0
log Fe/H	−4.5	−4.5	—	—

remain unaltered, more detail is seen in the 40,000–60,000 K region. The increase in photospheric opacity is gradual in the 40,000–50,000 K range but becomes dramatic above 50,000 K. However, it is also apparent that the dispersion in opacities is considerable within a selected narrow temperature range and any theory which seeks to explain the composition of DA white dwarf atmospheres must be able to account for this. EUV spectroscopy can contribute to the solution of this problem through direct study of the sources of EUV opacity in those stars having significant heavy element abundances and measurement of upper limits in stars with near pure H envelopes.

As an example, upper limits to the abundances of C, N, O, Si, and Fe have been estimated from the *EUVE* spectra of HZ43 (T=49,000 K) and GD659 (T=35,300 K; see also Holberg et al. 1995). The strengths of EUV absorption lines were calculated for a range of abundances, using the TLUSTY and SYNSPEC non-LTE codes (Hubeny 1988; Hubeny & Lanz 1992, 1995), and compared with the data. Any lines with a depth approximately twice the amplitude of the signal-to-noise of the spectra should be readily detected and the upper limits are defined as the abundance at which the strongest features just reach this threshold. These results are summarised in Table 2 and compared with limits, derived in a similar way, for coadded *IUE* high dispersion spectra. While *IUE* provides the best constraints on C and Si, the EUV data are much more sensitive to N and O. At the effective temperatures in question, NIV and OIV are the most populated ionisation states and most of their bound-bound transitions are found in the EUV rather than the far-UV.

Currently, analysis of *EUVE* spectra of white dwarfs containing large quantities of
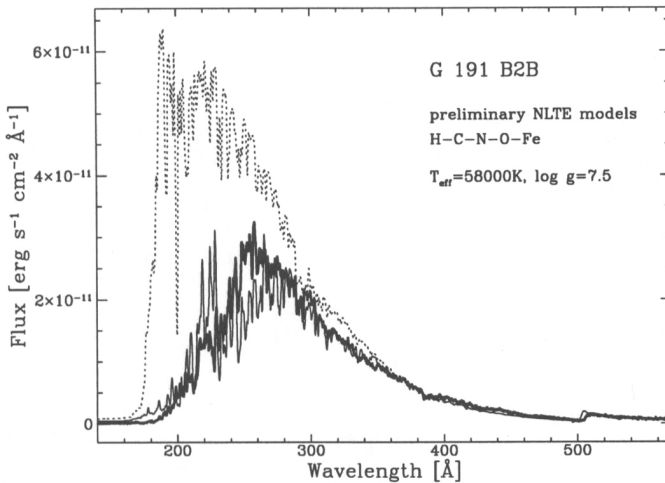
FIGURE 3. *EUVE* spectrum of G191–B2B (thick solid line) compared with two non-LTE line blanketed models for T=58,000 K, log g=7.5, C/H= 2×10^{-6}, N/H= 1.75×10^{-7}, O/H= 1.0×10^{-6}, and Fe/H= 6.5×10^{-5}. Dashed line—6,000 lines; thin solid line—300,000 lines. Interstellar absorption is included with H I= 2.5×10^{18} cm^{-2}, He I/H I=0.09 and HeII/HI=0.01

heavy elements poses some difficulty. Some progress has been made for objects with less extreme abundances, such as PG1234+482 (see Jordan et al. these proceedings), using LTE models. However, with considerable blanketing from Fe group lines contributing to the overall opacity, non-LTE effects are expected to be important. Unfortunately, non-LTE models of stars like G191–B2B have been completely unable to match the observations whereas LTE models can yield a reasonable representation (see Koester, these proceedings). The problem seems to stem from the difficulties of dealing with a large enough number of heavy element lines in non-LTE. Recent state-of-the-art calculations (Lanz & Hubeny 1995) have typically used the Kurucz line list, considering only the 36,000 lines between observed levels with some 6,000 contributing to the EUV opacity in the range from 25 to 600 Å, but cannot match the steep fall in the spectrum below 250 Å (thin dashed line, Figure 3). Taking all the lines predicted by Kurucz for the higher levels of Fe IV, Fe V, and Fe VI increases the total number of lines to about 730,000. About 300,000 of these contribute significantly to the opacity and the new calculation yields a large improvement in the level of agreement between model (thin solid line) and data (thick solid line). Reworking of the codes to deal more easily with such large numbers of lines should allow progress to be made in this area in the near future.

4. The Composition of RE J0503−289

The hot helium-rich DO white dwarf RE J0503−289 lies in a region of extremely low interstellar hydrogen density (Barstow et al. 1994). As the only DO white dwarf detected
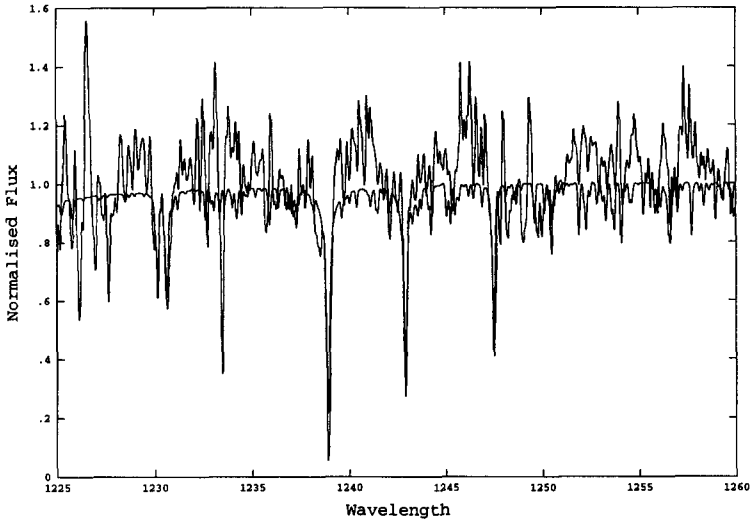
FIGURE 4. Region of the *IUE* high dispersion spectrum of RE J0503−289 showing N V, C IV and C III features compared to a 63,000 K model with C:He=0.1%, N:He=0.01%, O:He=0.01%, Si:He=0.01% and Ni:He=0.001%.

in both *ROSAT* WFC and *EUVE* sky surveys, it is a very important target for further study with the *EUVE* spectrometer. The star is also bright enough to be observed at high dispersion with *IUE* and we have acquired four spectra during the past two years. Detection of weak P Cygni profiles in one of these is evidence for the presence of an episodic weak wind in this object (Barstow & Sion 1994).

The *IUE* and *EUVE* data show that, in addition to the carbon already discovered in our earlier optical and low dispersion *IUE* observations, the atmosphere of the star contains significant quantities of nitrogen, oxygen and silicon. There is no sign of any Fe, found in DA white dwarfs of similar temperature, but many of the weaker features in the spectrum coincide with Ni V transitions. More detailed analysis of the photospheric composition of RE J0503−289 has proved difficult. It is possible to estimate photospheric abundances by comparing non-LTE model spectra with the measured UV line strengths. However, the EUV fluxes predicted by the same models which match the UV data are up to an order of magnitude greater than observed. In an attempt to reconcile the EUV and far-UV data, we constructed a grid of non-LTE spectra for a range of temperature and composition and fit both spectral ranges simultaneously. A consistent solution is achieved with a temperature of 63000 K (cf. 70000 from earlier work) and a C abundance of 0.1%, a factor 10 below that originally estimated. Abundances of N, O, and Si are all about 0.01% and that of Ni 0.001%, with respect to helium. Figure 4 shows a section of the *IUE* spectrum spanning the wavelength range from 1225 to 1260 Å, including N V, C IV and C III features compared to a non-LTE model computed for these abundances. The EUV model spectrum is now a very good match to the data (Figure 5), although the predicted He II line profiles are rather broader than observed. This probably arises from the absence of a satisfactory broadening theory for the He II Lyman series. We hope to address this problem with theorists working on the atomic data.
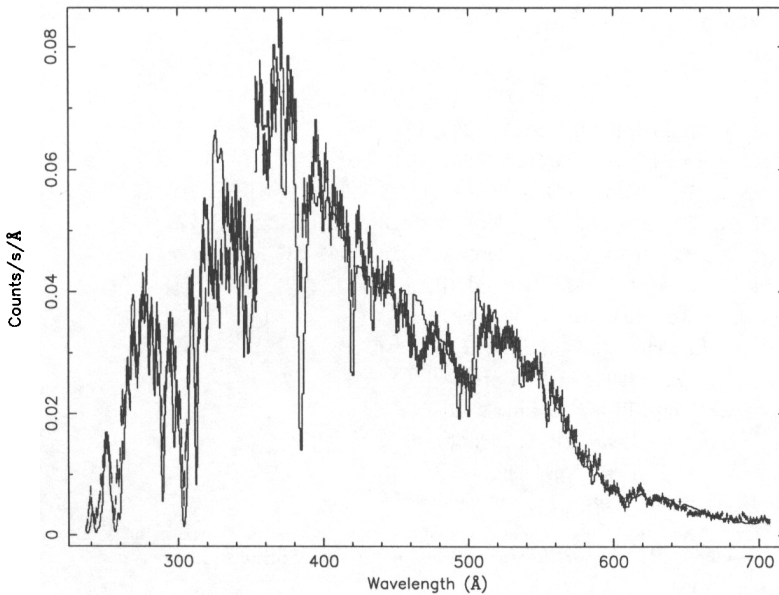
FIGURE 5. *EUVE* spectrum of RE J0503−289 compared to the best fit model discussed in the text.

5. Conclusion

It is clear that EUV spectroscopy is already making significant contributions to our understanding of white dwarf atmospheres. For example, important progress has been made in understanding the role of helium in DA stars. Limits placed on the He abundance of a number of typical DAs, spanning a temperature range from 30,000 to 60,000 K are 2 to 3 orders of magnitude below the values typical of DAO white dwarfs. Furthermore, the allowed abundances of He are below a level where the Balmer line temperature measurement becomes problematic. In those DA stars which have low levels of heavy element abundances in their atmospheres, the *EUVE* spectra can also be used to place limit on their abundances. The higher spectral resolution of the *IUE* echelle gives the best limits on carbon and silicon but the most populated ions of nitrogen and oxygen, N IV and O IV, have their strongest transitions in the EUV. Hence, *EUVE* data give more stringent limits on these elements.

Study of the very hottest DA white dwarfs such as G191−B2B, which contain significant quantities of heavy elements, has proved difficult because it has not been possible to calculate detailed model spectra which can match even the general shape of the spectral data. However, it seems that this is a result of not including sufficient numbers of detailed line transitions, mainly for iron ions, in the non-LTE calculations. We hope that imminent improvements in the computer programmes will solve this problem. In contrast, we have been able to make significant progress in understanding the atmosphere of the DO white dwarf RE J0503−289, which contains significant quantities of carbon, nitrogen, oxygen, and silicon but shows no evidence for iron.

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