Extreme Ultraviolet Spectroscopy of White Dwarfs

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Abstract: It has long been predicted that Extreme Ultraviolet (EUV) observations of white dwarfs would be one of the principal keys to understanding the composition and structure of white dwarf atmospheres. Indeed, the ROSAT X-ray and EUV sky survey has revealed that most H-rich white dwarfs hotter than 40,000K contain significant quantities of heavy elements in their atmospheres. However, the ROSAT data are unable to say much about the role of helium in the hottest white dwarfs, which remains an important question. Spectroscopic observations with the Extreme Ultraviolet Explorer allow a direct and sensitive search for HeII absorption to be performed. Furthermore, they potentially reveal the detailed nature of the sources of EUV opacity. In most cases examined no trace of He is found but HZ43 and G191−B2B show tantalising evidence for the presence of He, which would have important implications for our views of white dwarf evolution.

1 Introduction

One of 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 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 about 3:1. Secondly, the absence of He-rich stars in the temperature range 30,000–45,000K would suggest that the two groups are not entirely distinct and that at least some He-rich objects must evolve into DA white dwarfs and vice versa. Several competing physical processes can affect the composition of a white dwarf atmosphere. He and heavier elements tend to sink out under the influence of the strong gravitational field, leaving a layer of H at the surface, but this process can be counteracted by radiation pressure. Convective mixing may also play a significant role.

A thorough understanding of the physical mechanisms and their influence on white dwarf atmospheres must be founded on a detailed knowledge of the actual composition and structure of white dwarf envelopes for a range of temperatures and spectral types. For the brightest stars, IUE echelle spectra have given us important insight through the detection of C, N, O, Si, Fe and Ni (eg. Vennes et al. 1992, Holberg et al. 1993 & 1994, Werner & Dreizler 1994). Similar studies have also been carried out with the HST GHRS instrument (Vidal-Madjar et al. 1994). However, these features are only visible in those objects with the most extreme abundances. Furthermore, the limits placed on the presence of He (He/H$< 10^{-3}$) by UV spectroscopy are too crude to be of physical significance. It has been realised for some time that extreme ultraviolet (EUV) spectroscopy provides the most sensitive search for the presence of photospheric He in DA white dwarfs. In addition, the effects of heavy element absorption are expected to be visible at abundances lower than in far UV observations, at least through their influence on the shape of the continuum flux if not by direct detection of lines.

In this paper, we review the development of EUV spectroscopy as a tool to study white dwarf atmospheres. We also consider the complementary role of broad band EUV photometry and observations in other wavebands in aiding our understanding of white dwarfs. Much of this work underpins the Extreme Ultraviolet Explorer (EUVE) spectroscopy programme, which is now yielding exciting new results.

2 Early EUV spectroscopy

The 1980s saw the first use of EUV spectroscopy in the study of white dwarf atmospheres, concentrating on He in particular as the dominant opacity source. Malina, Bowyer and Basri (1982) reported the detection of an HeII absorption edge at 228Å in a spectrum of HZ43 recorded by a sounding rocket borne spectrometer. The strength of the feature corresponded to a helium/hydrogen abundance ratio of $1-6\times10^{-5}$. Subsequently, more sensitive observations made with the EXOSAT transmission grating spectrometer, failed to confirm this report (Paerels et al. 1986a). With a peak effective area of about 0.5cm^2 and a spectral resolution of 6Å, the EXOSAT data were able to place an upper limit (90% confidence) on the He/H abundance ratio of 3×10^{-6}, based on the non-detection of an HeII 228Å edge. For technical reasons, associated with the deployment of the transmission gratings, only two other white dwarf spectra were obtained by EXOSAT. Helium was not detected in either of these (Feige 24 and Sirius B), an upper limit of 1×10^{-5} being obtained for the He abundance in Sirius B (Paerels et al. 1988). In just treating the He 228Å absorption as a simple edge rather than a series of lines, the abundance limits quoted might well be somewhat misleading. On the other hand, using the EXOSAT spectrum as the sole measure of temperature and gravity increases the number of unconstrained parameters in the study. Reanalysing the spectrum of HZ43 with LTE synthetic spectra which are fully line-blanketed and imposing T and log g contraints from optical data (Napiwotzki et al. 1993), we obtain an upper limit to the He abundance of 2×10^{-6}, just slightly improved (but better founded) compared to the earlier result (figure 1).

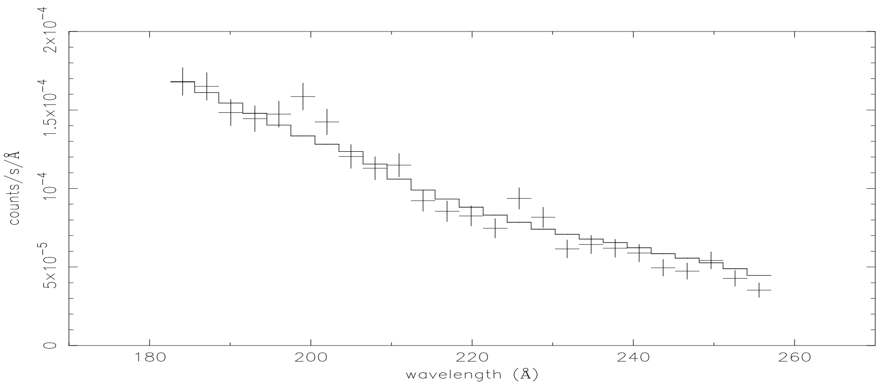

Fig. 1. EXOSAT TGS spectrum of HZ43 compared to the best fit model with T=47000K and log g=7.88 with He/H=2×10^{-6}, corresponding to the 90% upper limit discussed in the text

In contrast to HZ43 and Sirius B, the EXOSAT spectrum of Feige 24 could not be explained by a simple pure H or H+He model atmosphere (Paerels et al. 1986b). A plausible explanation of this result has been provided by Vennes et al. (1989), who find that introducing small traces of large numbers of heavy elements such as C, N, O, Ne, Si, Ar and Ca into a homogeneous model can qualitatively reproduce the spectrum. However, the precise abundance and composition (even which species were really present) could not be uniquely determined from the data. This explanation of the Feige 24 spectrum seems reasonable but it does require that, although only a few thousand degrees hotter than HZ43, is has a very different composition. Further evidence for the presence of heavy elements in at least a few DA is also found in IUE spectra. For example, C, N, Si and Fe have been observed in both Feige 24 and G191−B2B (eg. Vennes et al. 1992). In addition, a rocket EUV spectrum of G191−B2B (Wilkinson, Green & Cash, 1992) show features which the authors identify as OIII and FeIV absorption but again, no He.

3 EUV/X-ray photometry, IUE and optical spectroscopy

The combination of EXOSAT spectroscopic and photometric results (eg. Paerels & Heise, 1989; Koester 1989) led to rather uncertain conclusions concerning the general population of DA white dwarfs. It was not clear whether He, if present, was homogeneously distributed or in the more physically realistic stratified configuration (see eg. Vennes et al. 1988). Nor was it possible to determine whether

Feige 24 or HZ43 were most representative of DA atmospheres. The ROSAT EUV and X-ray all sky survey has been able to address the general properties of the population (Barstow et al. 1993). Although providing broadband data, like EXOSAT, the better spectral coverage and narrower bandpasses allowed tighter constraints to be placed on the possible atmospheric composition and structure of each star in the sample. This work demonstrated that *most* of the hottest DA white dwarfs ($T > 40,000$K) must have heavy elements in their atmospheres, whereas stars below 40,000K mainly seem to have little or no opacity in addition to that provided by hydrogen. For the hottest stars it is clear that He alone, in either configuration, is insufficient to account for the total opacity and heavier elements must be involved. However, the ROSAT data do to not allow us to decide whether He makes any contribution or not.

In addition to the above work, the ROSAT survey led to the discovery of a number of new white dwarfs. Several of these were sufficiently bright to be studied by the IUE echelle. RE2214−492 and RE0623−377 in particular were found to be very similar to Feige 24 and G191−B2B but contain even greater abundances of C, N, O and Fe (Holberg et al. 1993). More detailed work on these stars has also led to the detection of Ni ions (Holberg et al. 1994, Werner & Dreizler 1994).

While the role of He in DA white dwarf atmospheres has remained unclear, important results have emerged from an optical spectroscopic study of DAO white dwarfs by Bergeron et al. (1994). DAO stars, hybrid objects having a predominantly H envelope with spectroscopically detectable traces of He, have often been considered to represent a natural intermediate stage of evolution from DO to DA white dwarfs, where the proposed upward migration of residual H in the envelope is not yet complete. This hypothesis makes the important prediction that the atmospheric structure of DAO and DA stars should be stratified. However, it is clear from the work of Bergeron et al. that, at least in the optical line forming region, the majority of DAO stars have homogeneous atmospheres. As radiative levitation is unable to support the observed quantities of He (Vennes et al. 1988) an alternative, but as yet unknown, mechanism must be found to explain this result. Furthermore, we must remain open-minded about the structure of DA atmospheres, since a similar effect may exist in these stars.

Bergeron et al. also make a potentially important point concerning the effect of He on DA white dwarf atmospheres, finding that even small traces ($He/H > 10^{-5}$), at levels spectroscopically undetectable in the visible or UV bands, affect the Balmer line profiles. Consequently, the temperature measurements of the hottest white dwarfs may be erroneously high if trace He is present, but not accounted for in the models because it is not seen and, therefore, its abundance unknown. However, we note that Napiwotzki (these proceedings) finds that NLTE models do not show the dependency of the Balmer lines on the He abundance. Such a potential problem is not necessarily restricted to He. It has been demonstrated that similar effects may be caused by the presence of heavier elements (Lanz & Hubeny 1994, Werner & Dreizler 1993). Nevertheless, the importance of He abundance measurements in the EUV is increased, as they can potentially achieve a level of sensitivity where the possible effects on the Balmer lines become insignificant.

4 Spectroscopy of DA white dwarfs with EUVE

The launch of NASA's EUVE mission has provided us with a renewed opportunity of searching for He in DA stars and examining other sources of opacity. With a peak effective area about 20 times ($\approx 1\mathrm{cm}^2$) that of EXOSAT and a superior spectral resolution ($\approx 0.5 - 2.0$Å), EUVE allows us to obtain spectra throughout most of the EUV band, from $\approx 60 - 700$Å.

We have carried out an extensive search for photospheric He features in a number of hot DA white dwarfs. In these studies both a stratified H upon He configuration and, in the light of the work of Bergeron et al. (1994), a homogeneous mixture are considered. From an analysis point of view, the white dwarfs in question (drawn both from the EUVE archive and our own guest observer programme) 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 opacity 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 EUV spectrum near the HeII Lyman series, reproducing the general shape of the spectrum with an H+He model plus an exponential roll-off towards short wavelengths. A complete description of the data reduction and spectral fitting techniques used has been published elsewhere (Barstow, Holberg & Koester 1994a & 1994b).

Data obtained during the first year of EUVE observations are limited in signal-to-noise by a detector fixed pattern efficiency variation of $\approx \pm 20\%$. We find no evidence for any photospheric He in any of several DA white dwarfs studied (table 1). It is important to note that, in the homogeneous case the abundance limits are well below the level at which the He will significantly effect the Balmer line temperature determinations.

Table 1. Measured H layer mass and He abundance 90% limits in DA white dwarfs

Name	T($\pm 1\sigma$)	log g($\pm 1\sigma$)	H mass ($M_\odot$)	He/H
Feige 24	59,800(3,400)	7.5(0.51)	2.4×10^{-13}	3.0×10^{-6}
G191−B2B	57,314(750)	7.50(0.07)	2.6×10^{-13}	
GD71	32,045(148)	7.72(0.05)	1.0×10^{-12}	1.1×10^{-6}
GD246	54,987(931)	7.71(0.09)	9.7×10^{-14}	5.0×10^{-6}
HR8210	34,540(100)	8.95(0.06)	1.0×10^{-14}	
HD15638	46,000(+1,800/-850)	8.5(+0.1/-0.2)	4.1×10^{-14}	

Towards the end of the first year of EUVE spectroscopic observations, a technical remedy for the fixed pattern efficiency variation was implemented. The 'dither mode' divides each observation into a series of separate pointings to average out the fixed pattern, providing improved s/n by eliminating most of the spurious features. Figure 2 shows the complete spectrum of HZ43, recorded in this way. Comparing this with a smooth model spectrum indicates, from the excess scatter on the data points, that the residual efficiency variation has improved to an amplitude of $\pm 5\%$. Closer inspection of the HZ43 data, near the HeII Lyman series (figure 3) shows a weak, but distinct, absorption dip at the position of HeII 304Å, with an equivalent width of 200 ± 100mÅ. However, as there are other 'features' in the spectrum which are only a little weaker, that at 304Å may not be real. Even so, it gives a good indication of the sensitivity of the observation to the presence of photospheric He. If attributed to an interstellar component, the implied HeII column density would be $\approx 5 \times 10^{17}\mathrm{cm}^{-2}$. This would give rise to a large absorption edge, as illustrated in figure 3, which is not seen.

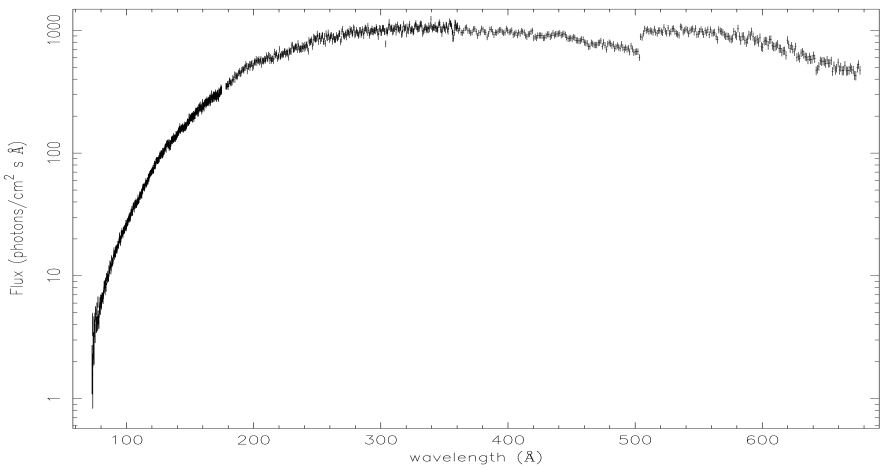

Fig. 2. Complete EUVE spectrum of HZ43 after deconvolution with the instrument response. The best fit model corresponds to T=50560K, log g=7.9, and log He/H=-5.9.

In fact, the best fit homogeneous model to the complete spectrum does require a small but finite amount of He, with an abundance of 1.3×10^{-6}, when the allowed temperature and gravity are constrained by the results of Napiwotzki et al. (1993). Forcing the He abundance down to 1×10^{-7} or lower leads to an increase in the value of χ^2 which is significant at the 95% confidence level. 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 result as a real detection of He in HZ43. Concentrating purely on the 180–260Å region covered in the EXOSAT analysis and on the limits placed on the strength of the HeII lines gives a much lower value for the He abundance

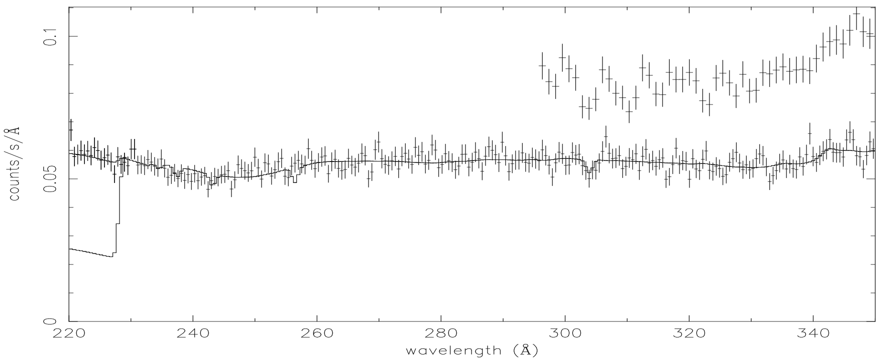

Fig. 3. Count spectrum of HZ43 between 220 and 310Å, showing a model with 10^{-7} of photospheric He and demonstrating the size of interstellar edge which would give the same 304Å line strength.

of $\approx 2 \times 10^{-7}$ or less. Whichever limit or value we adopt, it is at odds with the calculations of radiative levitation theory (Vennes et al. 1988), which predict an He abundance of at least 3×10^{-6} for a star with the mass and temperature of HZ43.

In contrast to HZ43, the spectrum of G191−B2B (figure 4) shows a large number of features, most of which can probably be attributed to the heavy elements which we already know to be present in the photosphere of this star (eg. Vennes et al. 1992, Holberg et al. 1994). However, we note that some of the absorption features correspond to the 304Å, 256Å, 237Å and 234Å lines of HeII, only the 243Å line appears to be absent from the series. This is illustrated in figure 4, where a homogeneous H+He model (T=57,300; log g=7.5; log He/H= −5) incorporating an exponential roll-off is compared with the observed spectrum, highlighting the line positions. There are two very strong features adjacent to the position of 243Å and it is possible that the line is comparatively too weak to be observed at the resolution of EUVE. Indeed, synthetic spectral models incorporating heavy elements and He demonstrate that this will happen. At the moment, it is necessary to add a strong note of caution to this interpretation. Although there do not appear to be any other strong lines coincident with the HeII wavelengths, G191−B2B has a complex EUV spectrum which we are not yet able to model in detail and there may be important lines which are omitted from our calculations. This is amply illustrated by the fact that incorporating all the elements detected by UV observations, we still fail to reproduce even the approximate shape of the EUV energy distribution. Furthermore, the large number of features observed, many of which will be blends of several lines at the resolution of EUVE, may give a false continuum. Coupling this with the possible effect of the heavy elements on the HeII level populations, compared to simple H+He models, the estimated He abundance, if He is really present, can only be regarded as very crude. However, if real, an abundance of 10^{-5} could affect the Balmer line profiles in this star, requiring a re-evaluation of its temperature.

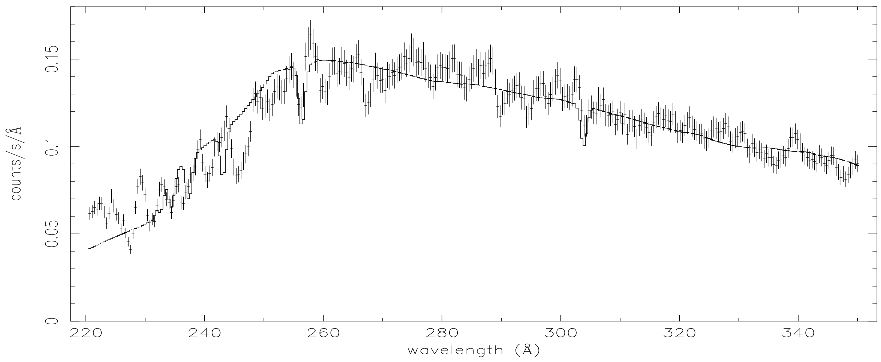

Fig. 4. Count spectrum of G191−B2B between 220 and 310Å. The best fit model for G191−B2B includes 1×10^{-5} of He.

5 EUVE studies of H deficient stars

One of the most interesting EUV sources discovered by the ROSAT sky survey is the DO white dwarf RE0503−289 (Barstow et al. 1994). The only DO white dwarf detected in the EUV surveys it lies along a very low column density line of sight, making it an ideal target for the EUVE spectrometers. With a temperature of 70,000K and log g $\approx$ 7 the dominant component in the atmosphere in addition to He is C, with an abundance $\approx 1\%$. The IUE high dispersion spectrum shows CIII, CIV, NV, OV and SiV, in addition to He, but little evidence for any other species. There is also good evidence for episodic mass loss, from variations in the line profiles (Barstow & Sion, 1994) The EUV spectrum (figure 5) is dominated by the HeII Lyman absorption series, which effectively reduces the flux to zero at wavelengths below 228Å. This illustrates why this is the only DO white dwarf detected in the EUV sky surveys, as a very low column density is needed to see out to 228Å. One ion not seen in the IUE data, but clearly detected in the EUV is NIV. In figure 5 we show, for comparison with the observed spectum, a synthetic spectrum calculated for a model atmosphere with T=70,000K log g=7.0, C/He=1% and N/He=0.01% . The general shape of the observational data is reproduced by the model but the NIV lines are clearly too strong, implying an abundance substantially lower than 0.1%. The absolute level of the model spectrum is scaled to match the EUVE data. However, this hides the most important discrepancy between the two, since the absolute flux predicted by the model atmosphere in the wavelength range 228–400Å is nearly an order of magnitude higher than observed. Hence, there must be significant sources of EUV opacity present in the atmosphere of the star which are not included in the model.

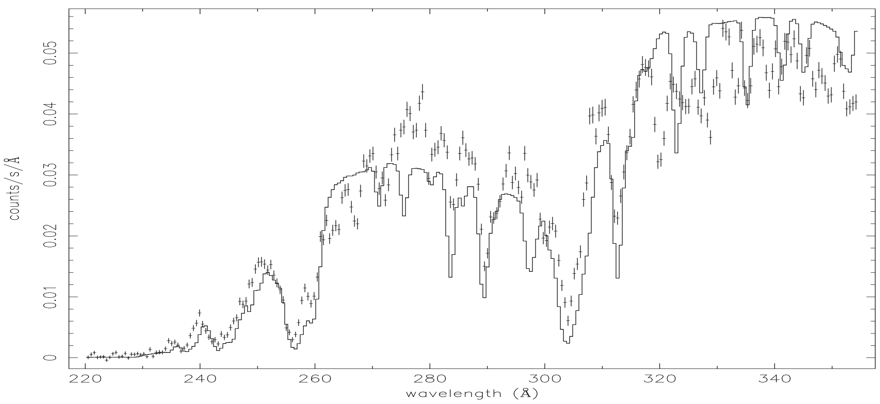

Fig. 5. EUVE spectrum of RE0503−289 compared to an HeCN model as discussed the text.

H1504+65 is a peculiar pre-white dwarf object, which appears to be completely devoid of H or He (Nousek et al. 1986). A recent optical analysis, using NLTE models, gives a temperature of $170,000 \pm 20,000$K and log g= 8 ± 0.5 (Werner, 1991). The atmosphere is solely made up of C and O by equal parts with less than 1% He. It appears to be an extreme PG1159 star, a pre-white dwarf which has lost its entire H and He envelopes as a consequence of a late He shell flash. As the naked core of a former AGB red giant this gives us, in principle, a unique opportunity to study the thermonuclear $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. H1504+65 is the second brightest EUV source in the ROSAT WFC survey but, having a relatively high interstellar column density of 6×10^{19}cm^{-2}, is only visible at the shorter EUV wavelengths. H1504+65 is only detected in the EUVE short wavelength spectrometer (figure 6). The whole spectrum covers the range 80–180Å and is dominated by absorption from OVI. A 180,000K model spectrum matches the positions of the lines accurately but fails to match the data in a number of respects. As for RE0503−289 the predicted level of the continuum flux is about an order of magnitude higher than that observed. A number of prominent absorption lines are not accounted for by the model and, at the time of writing, these remain unidentified. There is clearly some source of opacity which decreases the flux between 100Å and 115Å more rapidly than the OVI line series alone. Furthermore, there is a signficant tail of continuum emission below the OVI edge, which is not predicted by the model. Neither C nor N have any important transitions which contribute to the opacity in this region of the EUV but Ne does, although this has not been detected spectroscopically at other wavelengths. The detection of Ne would be an indication that H1504+65 may have burned carbon in the past.

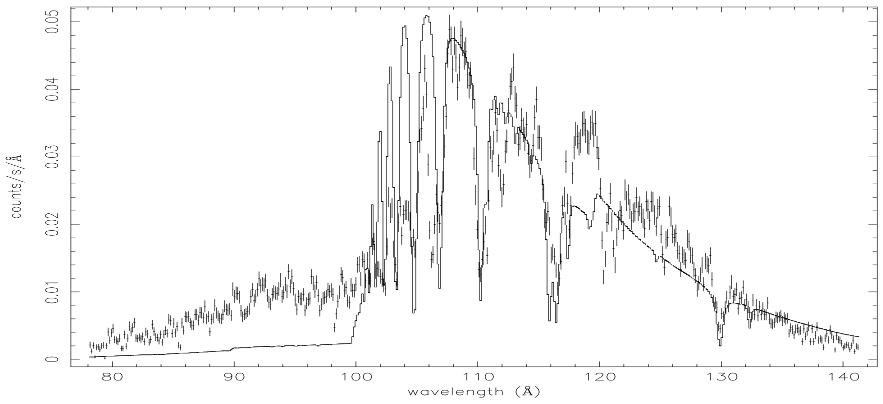

Fig. 6. EUVE spectrum of H1504+65 with a 180,000K C/O model for comparison.

6 Conclusions

It is clear that spectroscopy with EUVE is already making significant contributions to our understanding of white dwarf atmospheres, based on a firm foundation from EXOSAT, ROSAT, IUE and ground-based results. In particular, important progress has been made in understanding the role of He in DA stars. Limits placed on the abundance of He in white dwarf spanning a temperature range from 30,000K to 50,000K are 2-3 orders of magnitude below the values typical of DAO white dwarfs, supporting the growing view that DAOs do not form a direct link between DO and DA stars. However, this does not rule out the possibility that DOs still evolve into DAs by upward migration of residual H, but with the process being too rapid for a significant population of intermediate objects to build up. With the exception of (possibly) G191−B2B, the allowed abundances of He present are all below a level where the Balmer line temperature measurement becomes problematic. Therefore, it seems likely, that there is no general problem with the DA temperature scale as established so far as the effects of He are concerned. However, the contribution of heavier elements has not yet been addressed in detail.

Although DA white dwarfs are by far the largest population which can be studied by EUVE, the few H (and He) deficient stars, while rare, are very important. Since only two such objects have been discussed here it is difficult to draw any general conclusions. What is clear is that even the best state-of-the-art NLTE models are unable to completely explain either of the spectra presented here. Further work in this area is required before the EUVE data will yield the promised results.

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