High resolution EUV spectroscopy of G191-B2B II: structure of the stellar photosphere and the surrounding interstellar medium


1Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH
2E.O. Hulburt Center of Space Research, Naval Research Laboratory, Washington DC 20375, USA
3Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT
4NOAO, Tucson, AZ 85726, USA
5Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
6Universitäts Sternwarte Göttingen, Georg-August-Universität Göttingen, Geismarlandstrasse 11, D-37083 Göttingen, Germany
7Lawrence Livermore National Laboratory, Livermore, CA 97550, USA

Accepted ??????. Received ?????; in original form 2004-07-30

ABSTRACT
We have continued our detailed analysis of the high-resolution (R=4000 fwhm) spectroscopic observation of the DA white dwarf G191-B2B, obtained by the J-PEX normal incidence sounding rocket-borne telescope, comparing the observed data with theoretical predictions for both homogeneous and stratified atmosphere structures. We find that the former models give the best agreement, in conflict with what is expected from previous studies of the lower resolution but broader wavelength coverage EUVE spectra. We discuss the possible limitations the atomic data and on our understanding of the stellar atmospheres that might give rise to this disagreement. In our earlier study (Cruddace et al. (2002)) we obtained an unusually high ionization fraction for the ionised HeII present along the line-of-sight to the star. In the present study we obtain a better fit when we assume, as suggested by STIS results, that this He II resides in two separate components. When one of these is assigned to the local interstellar cloud, the implied He ionisation fraction is consistent with measurements along other lines of sight. However, the resolving power and signal-to-noise available from the instrument configuration used in this first successful J-PEX flight is not sufficient to clearly identify and prove the existence of the two components.

Keywords: Stars: atmospheres – white dwarfs – ultraviolet: stars – ISM

1 INTRODUCTION
The hydrogen-rich DA stars constitute the most numerous group of white dwarfs, outnumbering helium-rich objects by approximately 7 to 1 in the Palomar Green survey (Fleming, Liebert & Green 1986; Liebert, Bergeron and Holberg 2004). The more recent, deeper, Sloan Digital Sky Survey appears to yield an even higher value of 9:1 for the ratio of DAs to the total number of DO and DB white dwarfs (Kleinmann et al. 2004). This division is qualitatively understood to arise from the number of times the progenitor star ascends the red giant branch and the amount of H lost through successive phases of mass loss. However, there are some significant remaining problems in understanding the evolutionary paths in detail. For example, the ratio of H-rich to He-rich progenitors (4:1) is lower than that of the white dwarfs into which they evolve (Napiwotzki 1999). Furthermore, a gap in the He-rich sequence, between ~45000 and 30000K, separating the DO and DB white dwarfs (Wesemael, Green & Liebert 1985; Liebert et al. 1986; Dreizler & Werner 1996) implies that He-rich white dwarfs must temporarily be seen as DA stars due to some physical process.

An understanding of the white dwarf evolutionary tracks and the relationship between H- and He-rich groups, as outlined briefly above, depends on accurate measurements of basic stellar parameters. Determination of effective temperature and surface gravity, from which luminosity, mass and radius can be estimated, positions stars in their evolutionary context. In particular, in the absence of any internal energy source, the age of a white dwarf can be estimated from the temperature, after applying the detailed physics related to the cooling process (see for example Wood 1992). However, the presence of metals in the white dwarf atmospheres can bias the determination of temperature and surface gravity (e.g. Barstow, Hubeny & Holberg 1998). Therefore, knowledge of the photospheric composition is needed to complete the picture.

It is now well known, from X-ray and EUV photometry, that elements heavier than H and He are ubiquitous in the
hottest white dwarfs, with $T_{\text{eff}}$ above ~50,000K (Barstow et al. 1993; Marsh et al. 1997). A number of stars are bright enough to be observed at high resolution in the far UV, revealing various heavy elements including C, N, O, Si, P, S, Al, Mg, Fe and Ni (e.g. Bruhweiler & Kondo 1983; Sion et al. 1992; Vennes et al. 1992, 1996; Holberg et al. 1994). Not all elements are detected in all stars, depending on the signal-to-noise of the available spectra and the specific wavelength ranges covered. For example, P and S are only detected in the ~912-1150Å range, covered by the ORFEUS and FUSE spectrographs but not by IUE and HST. On the other hand, the majority of published abundance measurements, mainly C, N, O, Si, Fe and Ni, are derived from observations made with the latter facilities.

From a physical point of view, the presence of heavy elements in white dwarf atmospheres can be explained by the effect of radiation pressure, which counterbalances the downward gravitational force. Detailed calculations carried out by several groups show that, when the radiative forces are sufficiently high these elements do not sink out of the atmosphere, but are supported in significant abundances in the outermost layers of the stellar envelope (e.g. Chayer et al. 1994; Chayer, Fontaine & Wesemael 1995). In their work, Chayer et al. (1994, 1995) compute the radiative forces from a flux distribution calculated from a homogeneous static stellar atmosphere. The equilibrium abundances are then determined from the balance of the radiative and gravitational forces. However, the effect of the new heavy element distribution is not then included in any further model atmosphere calculations and it is, perhaps, not surprising that the equilibrium abundances predicted by these calculations do not generally agree with the observed values. Furthermore, the abundance measurements used for comparison have generally been obtained through the far-UV observations discussed above, analysed using synthetic spectra derived from model atmospheres computed for homogeneous composition. Consequently, at best, the abundances can only be really representative of the region in which individual lines are formed within the stellar photosphere. When radiative forces are taken into account, the equilibrium conditions predict that the abundance distribution of any particular element is far from uniform. Hence, the abundance predicted at the line formation depth will be very sensitive to the accuracy of the treatment of the physics.

Important observational evidence concerning the heavy element distribution in white dwarf atmospheres is found when comparing the results of the UV studies with the EUV spectra. For example, synthetic spectra derived from homogeneous model atmospheres, based on the UV abundance measurements, are unable to reproduce the complete EUV energy distribution of G191-B2B (Barstow, Hubeny & Holberg 1999). In particular the models predict a flux significantly larger than observed at wavelengths below ~190Å. This problem can be rectified empirically, by treating the atmosphere as two slabs each having a different Fe abundance, with a higher value in the deeper layer. Dreizler & Wolff (1999) made further physical improvements beyond the Chayer et al. work by incorporating radiative levitation and diffusion self-consistently into the stellar atmosphere calculations. Interestingly, their predicted Fe abundance profile is quite similar to that assumed by Barstow et al (1999), but without the artificially sharp boundary between the two layers. The self-consistent approach has been able to reproduce the EUV spectra of many other white dwarfs (Schuh, Dreizler & Wolff 2002). However, the values of $T_{\text{eff}}$ and log g (which are the only free parameters in the models), derived from this work, do not agree very well with the results obtained from the published optical spectroscopy, analysed with homogeneous models (e.g. Barstow et al. 1998). Nor have the radiative levitation/diffusion models been compared to all of the available UV spectra in a systematic manner, as yet. Therefore, the question of whether or not the newer radiative levitation models are a complete treatment of the physics and the most appropriate to use across the complete white dwarf energy distribution remains to be answered.

As one of the brightest and best-studied hot white dwarfs, G191-B2B has been an important benchmark to test the physics incorporated into atmosphere models, which can then be applied to the study of other objects. Consequently, it was a natural first target for the rocket-borne Joint Plasmadynamic Experiment (J-PEX), a high resolution EUV spectrometer. In an earlier paper (Cruddace et al. 2002), we presented an analysis of the data, using a model which assumed a homogeneous stellar atmosphere and included interstellar absorption. The principal result was the clear detection of a low-density ionised He component along the line of sight, which had only previously been inferred from lower resolution observations with the Extreme Ultraviolet Explorer (EUV). However the inferred ionization fraction of He (~ 0.7) was unusually high. A homogeneous stellar atmosphere including a significant abundance of photospheric He yielded a best fit to the spectrum, and excluded at the 99% confidence level solutions in which He was absent. However, the implied He/H abundance of $1.6\times10^{-5}$ (by number) did not yield photospheric lines that were strong enough to be detected directly at the signal-to-noise of the J-PEX spectrum.

We present a new analysis of the J-PEX spectrum of G191-B2B, which considers a wider range of possible models developed in earlier studies. These include homogeneous atmosphere models, in which heavy element compositions have been updated in the light of recent UV studies (Barstow et al. 2003), and stratified structures determined from both empirical matches to the EUVE spectrum (Barstow et al. 1999) and a self-consistent treatment of the radiative levitation forces (Schuh et al. 2002). This work includes an improved treatment of the wavelength calibration, which takes into account second order errors in the solution that were not dealt with in our original work. Further, we re-examine the interstellar
absorption in the light of STIS results (discussed in section 4.2), which indicated that the low density ionised He material may in fact reside in two components at different locations along the line-of-sight, one being the He II in the local interstellar cloud.

2 THE JOINT PLASMA DYNAMIC EXPERIMENT (J-PEX)

The J-PEX spectrometer is a slitless, normal-incidence instrument, which for this mission employed a figured spherical grating in a Wadsworth mount. A large collecting area is achieved by using four ion-etched laminar grating segments, each 9 cm x 16 cm, the largest size which the makers of high-quality EUV/X-ray gratings can currently achieve comfortably. They have a focal length of 2 m and form four spectra on the MCP detector photocathode. Each grating has a line density of 3600 l/mm, operates in first order, and is coated with a Mo₅C/Si/MoSi₂ multilayer designed for the band 220-245 Å. The gratings are optimised to suppress the zeroth order and yield maximum efficiency in the first order at 235Å, at which the spectrometer achieves an effective area of 3.0 cm².

Figure 1 shows the optical layout of the spectrometer. EUV light from the target source enters a collimator, which minimises the EUV background flux into the spectrometer, and strikes the grating at an angle of incidence of 4.85 deg. The diffracted radiation is focused onto an MCP detector placed on the grating optical axis, a configuration that minimises aberrations. Any EUV and FUV background diffracted or scattered by the grating is trapped by baffles (not shown) and an aluminium filter attenuates residual background reaching the detector. Two telescopes measure the small target motions due to drift and jitter of the attitude control system (ACS). One has a CCD camera at the focus and operates at optical and UV wavelengths. The other has a multilayer-coated mirror, which focuses an EUV image of the target onto the MCP detector.

The structural design primarily comprises two concentric shells, a forward end closure and a motorised door covering the aperture, which is opened following separation of the payload from the Black Brant sustainer motor. The payload is pumped on the launch pad prior to launch to ensure that the MCP detector can operate in a vacuum environment (~10⁻⁶ mbar) after its own vacuum door opens in flight. The 22-inch outer shell is a standard Black Brant structure, which mates to the NASA payload systems. The inner shell forms the optical bench, upon which the optics and the detectors are mounted. The two joints between the shells incorporate compressed O-rings, providing dynamic and thermal isolation of the inner from the outer shell, and reduce bending loads. The grating and the optical mirror are mounted together rigidly at one end of the bench. The MCP and CCD detectors are likewise mounted together rigidly, but on a structure, which is connected to the optics plate by Invar tubes. In the presence of thermal expansion and slight flexing introduced by temperature changes, this design ensures stable co-alignment of the spectrometer and telescopes and maintains a fixed focal length. However, thermal deflections in the spectrometer, thought to be caused by detector heating during the lengthy calibration exposures hindered our ability to measure the instrument resolving power, giving an average measured value of \( R = 2750 \). Fortunately, this calibration problem should have a much smaller effect in a 5 minute rocket flight and we set reasonable bounds of \( 3000 < R < 4000 \) on the resolving power in flight.

The first successful flight of J-PEX, on-board NASA Black Brant IX rocket 36.195DG, took place at 05.45UT on 2001 February 22nd. The payload completed its mission flawlessly and obtained a 300s exposure on the target, G191-B2B, before being recovered safely. The flight data were transmitted to the ground station in real time and stored on a computer for subsequent analysis.
3 DATA REDUCTION

The stellar spectrum appears as four offset lines across the detector image, each covering a similar wavelength range. The image needs to be corrected for pointing drifts before the spectra can be extracted from it. A wavelength calibration is then applied, before all four spectra are co-added to yield the maximum signal-to-noise. We describe the process briefly below.

Aspect reconstruction was achieved by determining the centroid position of the EUV mirror image as a function of time, using the time tag attached to each MCP event. To facilitate the analysis, the corrected image in detector coordinates was rotated to align the X-axis of the new frame with the dispersion axis, so that the X location of each event was related directly to the wavelength. A suite of IDL routines was used to extract the accumulated photon events into spectral bins, over-sampling the spectral resolution by a factor 5 (bin size $\sim$0.01Å) to avoid any loss of information.

Using laboratory calibration images of a Penning discharge source, an approximate wavelength scale was established for each spectrum, which was fitted by a 3rd order polynomial. The four resulting “raw” spectra had common bin sizes, but slight offsets in the central wavelengths due to the differing start and end points of each extraction window. The final wavelength scale for each spectrum was established by cross-correlation with the G191-B2B EUVE medium wavelength spectrum. This process also allowed us to determine the wavelength scale offset for each grating. These offsets were refined by cross-correlating the individual spectra with each other to find common spectral features. Finally, the raw spectra were corrected for all offsets and re-binned to a common 0.02Å grid for co-addition and analysis.

Pre-flight dark exposures revealed a detector noise count rate of less than 5 counts s$^{-1}$ over the entire imaging area. Hence, the mean count per spectral bin accumulated during the 300s exposure is sufficiently low that the stellar spectra could be assumed to be free of background, apart from a single hotspot on the detector coinciding with one spectrum. This was removed by subtracting an estimate of the hotspot count rate, determined from adjacent pixels, from the spectrum. In addition, the EUV mirror image cut across one other spectrum. As this was too bright to subtract sensibly, the affected pixels were set to zero and an exposure correction applied to normalise that region when the spectra were co-added. Count errors were assigned on the basis of Poissonian statistics.

Figure 2 shows the final co-added, wavelength-calibrated spectrum obtained by J-PLEX, with the strongest predicted absorption lines annotated (except for Fe and Ni, which are too numerous to fit in the figure). The wavelength bin size has been doubled to 0.04Å to match the nominal spectral resolution and optimise the signal-to-noise per resolution element. The red histogram shows the best-fit model reported by Cruddace et al. (2002). A close inspection reveals that the predicted locations of some features (I deleted this because I think we need to be more specific, but I will deal with this later w.r.t section 4.2), and in section 4.2 we have taken these features into account to make describe small adjustments to the wavelength scale.

As a result of unexpected shifts, during launch, in the relative alignment of the spectrometer and the attitude control system star tracker, only two spectra were registered with the full wavelength range within the detector active area, while two were cut off by the detector boundary at $\sim$239Å. Hence, between 239 and 243Å only half the geometric collecting area of the telescope was used, effectively halving the exposure by comparison with the shorter wavelengths. To maintain a roughly constant signal-to-noise across the whole spectrum, data in this range were binned to 0.08Å, as shown in figure 2.

4 SPECTRAL ANALYSIS

4.1 Stellar Atmosphere Models

We have a very well established technique for the analysis of high-resolution spectra by comparing the observations directly with a model stellar spectrum (see e.g. Barstow et al. 2002, 2003). When working in the EUV, it is also necessary to take into account sources of interstellar opacity. We use the basic model of Hα, Hβ, and Hγ established by Rumph, Bowyer & Vennes (1994), but modified to treat the converging line series at high resolution near the Hγ edge. We utilised the programme XSPEC (Shafer et al. 1991) to fold model spectra through the J-PLEX instrument response, taking into account the nominal spectral resolution and instrumental effective area. This was determined using knowledge of the efficiency of each grating, combined with the efficiencies of other components in the instrument. These are discussed in detail elsewhere (Cruddace et al. 2002). XSPEC adopts a $\chi^2$ minimisation technique to determine the model that yields the best match between observational data and model spectrum. Uncertainties in any of the parameters can be evaluated from the change in $\chi^2$ as parameter values are systematically varied.

We use a variety of spectral models for the analyses reported in this paper. Table 1 lists all the these together with the relevant parameters. Models 1 through 3 were computed using the stellar atmosphere code TLUSTY and its associated spectral synthesis code SYNSTEL (Hubeny & Lanz 1995). The detailed models are based on work by Lanz et al. (1996) and Barstow et al. (1998, 1999), which consider homogeneous mixtures of He and heavy elements besides more complex stratified distributions of materials. We considered: a completely homogeneous mixture with variable abundances of helium and Fe (Model 1); a stratified hydrogen and helium atmosphere with varying
hydrogen layer mass and a homogeneous mixture of heavier elements (with varying Fe abundance, Model 2); the same stratified hydrogen and helium envelope with stratified Fe in a “slab” model as described by Barstow et al. (1999) and with all other elements in a homogeneous mixture (Model 3). Model 4 is a small grid of calculations using a variant of the PRO2 code (Werner & Dreizler 1999; Werner et al. 2003), where the balancing effects of radiative levitation and downward gravitational diffusion are taken into account in a self-consistent way (Dreizler & Wolf 1999; Schuh et al. 2002). These models should give a much better physical description of the atmospheric structure than the empirical “slab” type models (Model 3). $T_{\text{eff}}$ ranged from 53000K to 56000K and log $g$ from 7.4 to 7.6. Since the atmospheric structure and depth dependent abundances are a function of both $T_{\text{eff}}$ and log $g$, these parameters were allowed to vary freely within the limits during the analysis.

For all the TLUSTY models, we fixed the stellar temperature and surface gravity ($T_{\text{eff}}=54000K$, log $g$=7.5) at the grid points closest to the values determined from the Balmer and Lyman lines of G191-B2B (Barstow et al. 1998). Apart from the helium and Fe abundances, which were allowed to vary freely between the grid limits of $10^{-4}$ and $10^{-6}$ and $3.0 \times 10^{-5}$ and $3 \times 10^{-6}$ respectively, the homogeneous abundances of the heavy elements were fixed at values determined from far-UV data (Barstow & Hubeny 1998, C/H=4.0x10$^{-7}$, N/H=1.6x10$^{-7}$, O/H=9.6x10$^{-7}$, Si/H=3.0x10$^{-7}$, Ni/H=5.0x10$^{-7}$), to allow direct comparison with the results from our earlier analysis of the J-PEX spectrum. However, Barstow et al. (2003) have subsequently re-analysed the STIS spectrum of G191-B2B and revised these values. Therefore, we have included in this analysis another model, Model 5 in Table 1, a variant of Model 1 in which the atmosphere is uniform with variable He and Fe abundances, but uses the new STIS abundances for the other heavy elements.

### 4.2 Analysis procedures

For all this work, the interstellar HI and HeI column densities were fixed at values obtained from analysis of the broader band, lower resolution EUVE spectrum by Barstow et al. (1999). The values adopted for each model were those for the closest similar model used in the EUVE work. Columns of HI=2.15x10$^{18}$cm$^{-2}$ and HeI=2.18x10$^{18}$cm$^{-2}$, determined using a homogeneous atmosphere model were adopted for Models 1 and 5, while columns of Hr=2.05x10$^{18}$cm$^{-2}$ and HeI=2.00x10$^{17}$cm$^{-2}$, corresponding to the fe6 stratified model of Barstow et al. (1999), were used with all the stratified calculations (Models 2, 3 and 4). The HeII column density was always allowed to vary freely and independently of the other interstellar components. Our initial analysis of the J-PEX spectrum of G191-B2B, reported by Cruddace et al. (2002), made the assumption that the interstellar HeII present existed as a single component. However, far-UV spectroscopy has revealed that there are two components to the ISM. One of these is associated with the local interstellar cloud (LIC), while the other is designated Component I (see Sahu et al. 1999). Component I is very similar in velocity to highly ionized, possibly circumstellar, material revealed through the detection of a CIV doublet near 1550Å (Vennes & Lanz 2001, Bannister et al. 2003), which is blue-shifted with respect to the photospheric velocity. While the velocity separation of the LIC and stellar photosphere is small (~4.6 km s$^{-1}$) and well below the resolving power of the J-PEX spectrograph, the difference between Component I and the stellar photosphere is much larger at 16.6 km s$^{-1}$. We would not expect to resolve these components since this is still below the instrument resolution (equivalent to ~75 km s$^{-1}$ fwhm, 30 km s$^{-1}$ rms), but the quality of the agreement between model and observation could be affected, though broadening of the He lines, if not taken into account. Therefore, we treat the HeII opacity as being provided by two discrete components, each having a different velocity and column density. Both parameters of each component were allowed to vary independently during the spectral analysis.

### Table 1. Summary of theoretical model atmosphere calculations used for the analyses in this paper, giving details of temperature, gravity and abundances for each grid.

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>log $g$</th>
<th>Helium treatment</th>
<th>Heavy element treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fully homogeneous</td>
<td>54000</td>
<td>7.5</td>
<td>He/H = 10$^{-6}$ - 10$^{-4}$</td>
<td>Fe/H from 3x10$^{-6}$ to 3x10$^{-2}$, others with fixed uniform abundances (see text)</td>
</tr>
<tr>
<td>2</td>
<td>Stratified H+He</td>
<td>54000</td>
<td>7.5</td>
<td>H mass 10$^{-14}$ - 10$^{-13}$</td>
<td>As for model 1</td>
</tr>
<tr>
<td>3</td>
<td>Barstow et al. (1999) stratified Fe</td>
<td>54000</td>
<td>7.5</td>
<td>H mass 10$^{-14}$ - 10$^{-13}$</td>
<td>Fe from fe4 to fe6 models, others with fixed uniform abundances (see text)</td>
</tr>
<tr>
<td>4</td>
<td>PRO2 self-consistent rad.lev. &amp; diffusion</td>
<td>53000 – 56000</td>
<td>7.4 - 7.6</td>
<td>Determined by self-consistent calculation of radiative levitation and diffusion effects for given $T_{\text{eff}}$ and log $g$</td>
<td>Fe/H from 3x10$^{-6}$ to 3x10$^{-5}$, others fixed at STIS values (see text)</td>
</tr>
<tr>
<td>5</td>
<td>Fully homogeneous</td>
<td>54000</td>
<td>7.5</td>
<td>He/H = 10$^{-6}$ - 10$^{-4}$</td>
<td>As for model 1</td>
</tr>
</tbody>
</table>
Figure 5. The high resolution EUV spectrum of G191-B2B, obtained with the J-PEX spectrometer, spanning the wavelength range 221-244 Å (error bars). The red histogram is the best-fit theoretical model of the star and ISM, as described in the text. The strongest predicted lines of He, C, N, O, and P are labeled with their ionization state and wavelength. Lines of Fe and Ni are too numerous to include here and account for the unlabelled individual features and broader absorption structures.
An inspection of the original analysis of the J-PEX spectrum (figure 2), shows that the match between the wavelengths of detected features with their predicted location is not always very good. For example, this is apparent near the He II Lyman series limit near 228Å, where an apparent emission feature appears about 2-wavelength bins (0.1Å) shortward of its location in the model (note that the appearance of emission is an artifact of a number of overlapping He II interstellar absorption features superposed on the photospheric continuum). Similar discrepancies are found elsewhere, but in a different sense, indicating that there is an uncorrected residual ripple in the wavelength calibration. Since we do not have any additional calibration information to deal with this, we have assumed that the predicted wavelengths of the major absorption features are correct and adjusted the wavelength calibration accordingly. In doing this, any absolute velocity information is compromised, but relative velocities (say between photospheric and ISM components) are preserved. It is important to note that most published EUV wavelengths are calculated rather than measured and are not necessarily accurate. This is particularly true of complex atoms having millions of EUV lines, such as Fe or Ni. However, for low Z elements this is much less of a problem and we have used lines of HeII (λλ 228.06, 228.54, 230.14Å), CIV (λλ 238.25Å), NIV (λλ 238.07, OIV (λλ 231.7, 231.25, 233.47, 233.56, 238.57Å) and Ov (λλ 227.51, 231.82Å).

As reported in our original paper, some strong absorption features do not have any readily identifiable counterparts. Along with some other features they are not reproduced detail in the models but, in these specific cases, no lines of any description are predicted to be present at those wavelengths. Since, they can potentially alter the fit between model and data by forcing the procedure to average out the flux differences across the line, which might yield some erroneous results, we have excluded those regions of the spectrum where the strongest such features occur from the analysis. Specifically, these are at 229.3Å and 232.7Å and appear as gaps in figures 3(a-d). In addition, we have not used the very shortest wavelength part of the spectrum below 226Å (or a section near 227.5Å), where there are many bins containing zero counts, since these cannot be handled by the fitting algorithm. In other regions of the spectrum where similar discrepancies can be seen we have not excluded the data points because a feature is predicted at the specific wavelength, but not as strong/weak as actually observed. These limitations of the models are discussed later in section 5.

4.3 Spectral analysis results

Figures 3 and 4 show the results of the spectral analyses carried out using the different model types described in section 4.1. Each figure shows the best match between model and data determined by the χ² minimization. For clarity of presentation and comparison between the various models, the total spectral range of J-PEX is split into two, with figure 3 covering 226Å to 236Å and figure 4 236Å to 246Å. Table 2 lists the values of all the parameters for the best-fit models along with the χ² and reduced χ².

In general, all the models give a reasonably good agreement with the data, as all the values of the reduced χ² lie below ~3.0. However, formally a “good fit” should have a reduced χ² less than ~2.0, indicating that the fits to the stratified models are not acceptable. This is illustrated further by calculating the value of the F-statistic, compared to the overall best fit, which was obtained with Model 5 (homogeneous atmosphere with revised heavy element abundances). Two of the three stratified models (Models 3 and 4) can be excluded with high probability. All the best-fit models include opacity from both photospheric and interstellar helium, the levels of photospheric opacity being consistent with our inability on this flight to achieve positive detections in the 237.331 and 243.026Å HeII lines. Furthermore, no significant change in the quality of the fit is noted if the photospheric component is forced to zero and all the HeII opacity assumed to be interstellar and/or circumstellar. Compared to our initial analysis, the match between the locations of absorption features in the observed spectrum and those of the models is much improved. Particularly good agreement is obtained in the ~228Å to 230Å wavelength range. Apart from the HeII Lyman series, no strong absorption lines are predicted by the models in this range. We can clearly identify 228.54Å (left hand arrow in fig 3a), and blends of He lines down to the series limit (marked by the bracket in fig 3a). The apparent emission feature at 227.9Å is an artifact of the HeII line series opacity on the stellar emission, which was predicted by our modeling before the J-PEX flight. The absorption line at 229.0Å is coincided with predicted HeII and OIII features and is probably a blend of both (right hand arrow in figure 3a). We also note that the homogeneous model that incorporates the revised heavy element abundance estimates of Barstow et al. (2003) yields a better fit to the data than the model with the original abundances. However, the difference is not significant at a high confidence level, unlike the differences between the homogeneous models and those with stratified heavy elements.
Figure 3. Comparison of the best-fit spectral models for each atmosphere type (blue histograms) with the 226Å to 236Å region of the J-PEX spectrum of G191-B2B (black error bars). From the top a) Homogeneous mixture of all elements – Model 1, b) Stratified H + He envelope with homogeneous Fe mixture – Model 2, c) Stratified H + He envelope with Fe stratified “slab” distribution – Model 3, d) Self-consistent radiative levitation/diffusion PRO2 model – Model 4. In a) the bracket identifies the converging HeII Lyman series lines and the series limit, the left arrow marks HeII 228.54Å and the right arrow a blended feature of OIII and HeII at 229.0Å.
Figure 4. Comparison of the best-fit spectral models for each atmosphere type (blue histograms) with the 236Å to 246Å region of the J-PER spectrum of G191-B2B (black error bars). From the top a) Homogeneous mixture of all elements – Model 1, b) Stratified H + He envelope with homogeneous Fe mixture – Model 2, c) Stratified H + He envelope with Fe stratified “slab” distribution – Model 3, d) Self-consistent radiative levitation/diffusion PRO2 model – Model 4.
Table 2. Summary of the results of the various analyses of the J-PEX spectrum of G191-B2B as discussed in the text, for each of the five model structures/compositions available. All rows labelled +1σ or –1σ list the formal error bars for the parameter above, when these have been derived. The parameter \( z \) is the measured red-shift for the various opacity components considered.

<table>
<thead>
<tr>
<th>Model Number and Description</th>
<th>1. Fully homogeneous</th>
<th>2. Stratified H+He, homogeneous heavy elements</th>
<th>3. Stratified H+He, stratified “slab” Fe, other self-consistent levitation/diffusion</th>
<th>4. Stratified with STIS heavy element abundances</th>
<th>5. Fully homogeneous with STIS heavy element abundances</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2 )</td>
<td>686</td>
<td>690</td>
<td>940</td>
<td>1161</td>
<td>613</td>
</tr>
<tr>
<td>Reduced ( \chi^2 )</td>
<td>1.74</td>
<td>1.75</td>
<td>2.38</td>
<td>2.94</td>
<td>1.55</td>
</tr>
<tr>
<td>F test (%conf)</td>
<td>75</td>
<td>75</td>
<td>99.99775</td>
<td>99.99999</td>
<td></td>
</tr>
<tr>
<td>( T_{\text{eff}} ) (K)</td>
<td>54000</td>
<td>54000</td>
<td>54000</td>
<td>53000</td>
<td>54000</td>
</tr>
<tr>
<td>log ( g )</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>7.6</td>
<td>7.5</td>
</tr>
<tr>
<td>He II ISM A (LIC?) (cm(^{-2}))</td>
<td>3.57E+17</td>
<td>1.66E+17</td>
<td>4.68E+17</td>
<td>3.20E+17</td>
<td>2.58E+17</td>
</tr>
<tr>
<td>-1σ</td>
<td>1.64E+17</td>
<td>9.20E+16</td>
<td>4.68E+17</td>
<td>1.47E+17</td>
<td>1.47E+17</td>
</tr>
<tr>
<td>+1σ</td>
<td>1.43E+17</td>
<td>1.42E+17</td>
<td>1.95E+17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He II ISM B (LB?) (cm(^{-2}))</td>
<td>3.62E+17</td>
<td>5.23E+17</td>
<td>3.46E+17</td>
<td>2.70E+17</td>
<td>4.55E+17</td>
</tr>
<tr>
<td>-1σ</td>
<td>1.69E+17</td>
<td>1.53E+17</td>
<td>1.85E+17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1σ</td>
<td>1.39E+17</td>
<td>1.42E+17</td>
<td>1.55E+17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He/H (number) or H mass (M(_{\odot}))</td>
<td>1.00E-05</td>
<td>1.00E-13</td>
<td>1.25E-13</td>
<td>n/a</td>
<td>3.00E-05</td>
</tr>
<tr>
<td>-1σ</td>
<td>1.78E-14</td>
<td>7.60E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1σ</td>
<td>2.00E-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe/H (number)</td>
<td>5.20E-05</td>
<td>3.00E-06</td>
<td>n/a</td>
<td>n/a</td>
<td>8.26E-07</td>
</tr>
<tr>
<td>-1σ</td>
<td>1.03E-05</td>
<td>0.00E+00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+1σ</td>
<td>1.26E-05</td>
<td>1.60E-07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_{\text{LIC}} )</td>
<td>1.54E-05</td>
<td>1.27E-05</td>
<td>1.56E-05</td>
<td>-4.77E-05</td>
<td>1.51E-05</td>
</tr>
<tr>
<td>+/-1σ</td>
<td>9.00E-07</td>
<td>1.50E-06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_{\text{ISM}} )</td>
<td>-6.22E-05</td>
<td>-6.22E-05</td>
<td>-6.22E-05</td>
<td>-1.00E-04</td>
<td>-6.23E-05</td>
</tr>
<tr>
<td>+/-1σ</td>
<td>1.00E-06</td>
<td>9.50E-07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_{\text{Phot}} )</td>
<td>7.39E-05</td>
<td>2.02E-05</td>
<td>7.07E-05</td>
<td>3.49E-04</td>
<td>8.80E-05</td>
</tr>
<tr>
<td>+/-1σ</td>
<td>1.89E-05</td>
<td>1.16E-05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_{\text{ISM-LIC}} ) (km s(^{-1}))</td>
<td>-23.28</td>
<td>-22.47</td>
<td>-23.34</td>
<td>-15.69</td>
<td>-23.22</td>
</tr>
<tr>
<td>+/-1σ</td>
<td>0.40</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_{\text{Phot-LIC}} ) (km s(^{-1}))</td>
<td>17.55</td>
<td>2.25</td>
<td>16.53</td>
<td>119.01</td>
<td>21.87</td>
</tr>
<tr>
<td>+/-1σ</td>
<td>5.66</td>
<td>3.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5 DISCUSSION

5.1 Homogeneous vs. stratified heavy element distributions

Since it has been accepted for some time that the presence of significant quantities of heavy elements in the atmospheres of hot DA white dwarfs such as G191-B2B is a result of radiative levitation, it is a surprise that the models that give the best agreement in comparison with the J-PEX spectrum are those with a homogeneous distribution of material. In particular, this result contradicts the analyses of the EUVE spectrum of G191-B2B, which require a stratified atmospheric structure to reconcile the overall spectral shape across the full ~100-600 Å wavelength range, in particular at wavelengths below 190 Å, as reported by both Barstow et al. (1999) and Dreizler & Wolff (1999). This result was reinforced by the subsequent work of Schuh et al. (2002) for a sample of G191-B2B-like stars.

The issue here seems to be one of detail versus global coverage. The EUVE spectrum covers a broad wavelength range (~500 Å) and with much better signal-to-noise than the J-PEX spectrum, but has limited (~0.5 Å) spectral resolution. In contrast, J-PEX has a much narrower band (~25 Å) but a factor 10 better resolving power. Inspection of figures 3 and 4 reveals that, over the J-PEX waveband, the stratified models have too much opacity, particularly at the longer wavelengths above 235 Å. In fact, this is also the case in the EUVE analyses. Although this instrument can only resolve broad absorption complexes rather than individual lines (or small groups of lines), the individual features present at that resolution are generally stronger than in the data (see all of Barstow et al. 1999; Dreizler and Wolff 1999; Schuh et al. 2002). Hence, even before the J-PEX flight the particular problem of reconciling the predicted detailed line opacity with that observed already existed, but was given secondary consideration compared to the reproduction of the overall spectral shape by the models.

This is an interesting discrepancy since, for a realistic model stellar atmosphere, we would expect to obtain consistency between the two instruments. Hence, this is probably an indication of current limitations in the models. It is well known that there are likely to be deficiencies in the atomic data used since the wavelengths and oscillator strengths are largely calculated rather than measured. Any inaccuracies in these computations would be reflected in incorrect opacities and implied abundances. This is particularly true for Fe and Ni lines, the dominant sources of photospheric opacity. Furthermore, the fact that the models are unable to account for some of the stronger lines that we do detect is an indication that the input data are incomplete. For the stratified models, their main observational deficiency is that the photospheric lines and complexes are typically predicted to be stronger than observed across the whole J-PEX waveband. Of particular note are the broad regions 234.5-236 Å (see figs 3c and 3d) and 236-237 Å, besides narrow complexes at ~238.3 Å and 239.3 Å (see figs 4c and 4d). These are all associated with groups of Fe and Ni lines. It is possible that revised atomic data might rectify this. Alternatively, if the atomic data is satisfactory, we may need to consider the inclusion of other physical effects in the calculations, such as mass-loss, to provide more realistic models. If the opacities are realistic, the homogeneous results indicate that the actual element abundances are lower, at the line formation depth, than the radiative levitation calculations predict. Mass-loss could contribute to such a relative depletion of the heavy element material and modify the stratification, bringing the EUVE and J-PEX analyses into closer agreement.

With the documented uncertainties in the stellar atmosphere model calculations we are unable to draw any particular conclusions about the physics of the stellar atmospheres from this work. Nevertheless, we have shown that, even with limited signal-to-noise, the J-PEX spectrum can in principle distinguish between different model calculations and so highlight the issues that we might need to re-examine. This is also a demonstration of the importance of high resolution EUV spectroscopy and provides a foretaste of what could be achieved with higher signal-to-noise spectra obtained through the longer exposures available on a satellite platform.

5.2 Interstellar and/or circumstellar He II

A feature of all EUV studies of G191-B2B is the requirement for a component (or components) of He II opacity to explain the observed spectra, in combination with either homogeneous or stratified models. At the resolution of EUVE and in the presence of absorption from many other species, this material could not be directly detected. However, the J-PEX data clearly reveal the interstellar He II Lyman series lines and imply that there is a contribution from photospheric He. In our original analysis (Crudace et al. 2002), we treated the interstellar He as belonging entirely to a single component. However, in view of the strong evidence from the far-UV data that there are multiple interstellar components, we have divided the ionised He into two independent contributions. We notionally identified these with the LIC and ISM Component I. The fitting procedure naturally separates these two components in velocity space, the velocity difference of ~ -23 km s\(^{-1}\) being similar to the ~ -14 km s\(^{-1}\) reported by Sahu et al. (1999). However, the formal error in the velocity is unrealistically small (~0.5 km s\(^{-1}\)), compared to the rms velocity resolution of ~30 km s\(^{-1}\) (75 km s\(^{-1}\) fwhm).
Nevertheless, in the light of the clear far-UV evidence that earlier analyses is the high He II ionization fraction two components. One problem that has been noted in observe being divided in an appropriate way between these components is not conclusive. Therefore, as we would expect, the evidence in the J-PEX spectrum for the presence of two interstellar/circumstellar components is not conclusive.

Nevertheless, in the light of the clear far-UV evidence that two ISM components are present, it is interesting to consider the implication of the EUV opacity that we observe being divided in an appropriate way between these two components. One problem that has been noted in earlier analyses is the high He II ionization fraction obtained from a single absorbing component, in comparison with other lines of sight in and around the Local Interstellar Cloud and the Local Bubble. Combining the two He II components treated here into a single one, as they would be viewed by EUVE, yields a similar result to earlier analyses, with an ionization fraction (N\text{He}\text{II}/[N\text{He}+N\text{He}]) of 0.77 for the best homogeneous model (Model 5), similar to that obtained in the earlier analysis (Crudace et al. 2002). Similar fractions (within ±0.04) are obtained for the other models studied, well within the ±10% uncertainty of the estimate (based on the HeII column uncertainties alone, the uncertainty in the HeI measurement has not been quantified).

If we consider the two components individually, we have to make some assumptions about how the He is distributed between the two regions, the LIC and Component I, since the wavelength coverage of J-PEX does not include the 206Å He I line. Bannister et al. (2002) have pointed out the association of the latter with highly ionized material seen in the STIS spectrum. Hence the most extreme case we can consider, with all the neutral helium residing in the LIC and the medium outside the LIC associated with Component I being completely ionized, would seem to be a good approximation to the existing conditions. The best fits for Models 1 through 5 yield a large spread in the ionization fraction of the LIC, ranging from 0.43 for Model 2 (see table 1) to 0.68 for Model 3. Model 5, the homogeneous model with revised heavy element abundances yields a value of 0.54. In figure 5, which shows the calculated ionization fraction as a function of stellar distance (estimated photometrically), we compare our results for G191-B2B (open diamonds) with those of Barstow et al. (1997, filled diamonds), who reported EUVE observations of stars with pure H atmospheres. For G191-B2B, the upper symbol is the ionization fraction estimate for the total He II column, while the lower of the two is that calculated for the LIC, assuming all the neutral helium resides there, as discussed above. This lower value is consistent with the Barstow et al. (1997) results, within the overall uncertainties, and supports the argument that there are two HeII components in the line-of-sight to G191-B2B.

![Figure 5](image_url)

Figure 5. Comparison of our results for G191-B2B (from Model 5, open diamonds) with those of Barstow et al. (1997, filled diamonds), showing the calculated ionization fraction as a function of stellar distance. For G191-B2B, the upper symbol is the ionization fraction estimate for the total HeII column, while the lower of the two is that calculated for the LIC, assuming all the neutral helium resides therein, as discussed in the text.

6 CONCLUSION

We have presented a detailed analysis of the high-resolution EUV spectrum of G191-B2B, obtained with the sounding rocket-borne J-PEX spectrometer. This new work confirms the basic results of the initial analysis, published.
by Cruddace et al. (2002), but incorporates an improved treatment of the wavelength calibration, considers a wider range of possible atmosphere models and examines multiple interstellar components.

The most important, but also rather surprising result is that the models which give the best agreement with the \textit{J-PEX} spectrum are those with homogeneous rather than stratified heavy element compositions. This is in contradiction to what we expected, based on the results of several analyses of the broader band, but lower resolution, \textit{EUVE} spectra. These broad band data require a stratified distribution of material (Fe in particular) to reproduce the overall spectral shape at the shortest wavelengths (below ~200Å). However, when the homogeneous models (1 and 5) which reproduce best the fine detail in the \textit{J-PEX} spectra are used to predict flux at wavelengths below 200Å, the results exceed the levels measured by \textit{EUVE} significantly. It is likely that the atmosphere of G191-B2B really does have a stratified structure, but that some combination of deficiencies in the atomic data and/or the model physics is leading to incorrect detailed abundance profiles or erroneous opacities in the lines. Of particular note are the broad regions 234.5-236Å and 236-237Å, besides narrow complexes at ~238.3Å and 239.3Å where the stratified models predict stronger absorption than is observed. These features are all associated with Fe and Ni complexes, elements for which the atomic data likely to be the most problematic. Clearly, further work is required to determine whether or not there are deficiencies in the atomic and opacity data used, to consider the necessity of including additional physical processes, such as mass loss, and to
evaluate at what level such effects may alter the predicted heavy element stratification. While we are unable to draw any particular conclusions about the physics of the stellar atmospheres from this work, we are able to demonstrate that, even with limited signal-to-noise, the \textit{J-PEX} spectrum can in principle distinguish between different model calculations and so highlight the issues that we might need to re-examine. This is also a demonstration of the importance of high resolution EUV spectroscopy and implies that what could be achieved with higher signal-to-noise spectra obtained through the longer exposures available on a satellite platform.

One of the major breakthroughs of the \textit{J-PEX} instrument has been the direct detection of low density ionized HeII along the line-of-sight to G191-B2B, which using STIS data we have been able to separate into one or more interstellar or circumstellar components. Cruddace et al. (2002) treated this material as a single absorber. In our new analysis we have separated this into two interstellar absorbers associated with the LIC and “Component I”. This interpretation is consistent, in that we get a slightly better fit for two components rather than one and the velocity differences between them are more or less in agreement with what is observed at high resolution with \textit{HST}/STIS. However, with the relatively limited signal-to-

\section*{ACKNOWLEDGEMENTS}

MAB and NPB were supported by PPARC, UK. The Naval Research Laboratory (NRL) was supported in this work by NASA under grant NDPR S-47440F and by the Office of Naval Research under NRL work unit 3641 (Application of Multilayer Coated Optics to Remote Sensing). SS was supported by DFG grants DR 281/13-1 and DR 281/13-2 to the University of Tübingen. SS also acknowledges PPARC and the Schuler Stiftung for travel support in association with this work.

\section*{REFERENCES}

Barstow M.A., Good S.A., Holberg J.B., Burleigh M.R.,
Barstow M.A., Good S.A., Holberg J.B., Hubeny I.,
Barstow M.A., Bruhweiler F.C., Burleigh M.R.,
Chayer P., LeBlanc F., Fontaine G., Wesemael F.,
Liebert J., Wesemael F., Hansen C.J., Fontaine G.,
Vennes S., Chayer P., Thorstensen, J.R., Bowyer C.S.,
Vennes S., Thejll P.A., Wickramasinge D.T., Bessell M.S.,
Werner K., Dreizler S., 1999, Journal of Computational
and Applied Mathematics, 109, 65
Werner K., Deetjen J.L., Dreizler S., Nagel T., Rauch T.,
Schuh S.L., 2003, in “Stellar Atmosphere Modeling”,
eds. I. Hubeny, D. Mihalas, K. Werner, ASP Conference
Proceedings Vol 288, 31