J. B. HOLBERG,1,2 I. HUBENY,3 M. A. BARSTOW,1,4 T. LANZ,5,6 E. M. SION,1,7 AND R. W. TWEEDY,1,8
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ABSTRACT
We have co-added six recently obtained IUE echelle spectra of the hot DA white dwarf RE 2214 – 492 and 10 existing archive spectra of the well-known hot DA, G191-B2B. We find that both stars contain numerous weak features due to Ni v. Nickel is thus the second iron-group element to be found in the spectra of the very hottest DA white dwarfs. In addition to Ni v, we also observe Al iii in both stars and present evidence for the possible presence of Ni iv and Fe iv in RE 2214 – 492. The presence of Ni and Al, together with previously reported elements, will contribute significantly to both the EUV opacity and to the apparent complexity of the UV spectra of these stars. Using NLTE model atmospheres we estimate the Ni abundances in RE 2214 – 492 and G191-B2B to be log [Ni/H] = −5.5 ± 0.3 and −6.0 ± 0.3, respectively.


1. INTRODUCTION
The role that elements heavier than He may play in determining the strong opacities observed in the atmospheres of many H-rich DA white dwarfs is currently an issue of great interest. It has been evident for some time, beginning with Kahn et al. (1984), that many ostensibly pure-H DA white dwarfs have EUV and soft X-ray energy distributions which are strongly cut off at short wavelengths. The most comprehensive study of this effect is that of Barstow et al. (1993a) which employed ROSAT fluxes for some 30 DA white dwarves to demonstrate that at effective temperatures above 40,000 K virtually all DA stars possess EUV fluxes substantially lower than those predicted by appropriate pure-H atmospheres. Below this temperature, the fluxes for most DA were very close to those predicted by pure-H atmospheres. Barstow et al. further demonstrated that He alone could not be responsible for the observed EUV opacity, and suggested heavier elements as the likely source of this opacity. Prior to this, most soft X-ray and EUV observations had been interpreted exclusively in terms of EUV-inferred He abundances (see Paerels & Heise 1989) or alternately, in terms of the masses of thin H layers overlying He-rich zones in stratified atmospheres (see Koester 1989; Vennes & Fontaine 1992). Such interpretations, however, were based upon the limited information available from broad-band fluxes. In the two cases where actual EUV spectra of steeply cut-off sources were available, no evidence of He was seen and alternative explanations were presented. In the EXOSAT spectrum of Feige 24, Vennes et al. (1989) first showed that it was possible to model the data with an atmosphere containing trace amounts of numerous metals. Similarly, the EUV rocket spectrum of G191-B2B was interpreted by Wilkinson, Green, & Cash (1992) in terms of O iii and Fe vi features.

The first spectra of several hot DA white dwarves obtained from the Extreme Ultraviolet Explorer (EUV) are providing an initial view of the critical spectral regions where the opacity is most evident. Originally, it was hoped that such spectra would rapidly lead to the identification of the most important absorbers. Such identifications have not been forthcoming; rather, what is seen is that those DAs with strong opacity sources exhibit exponential-like roll-offs toward the shortest wavelengths with few, if any, distinguishing spectral features (Barstow et al. 1993b). These stars have been modeled with atmospheres containing arbitrary trace amounts of heavy elements (Finley, Koester, & Vauclair 1993). As there are few distinguishing spectral features, absorption edges, or lines, there is little to constrain the mixing ratios of heavy elements which are adopted. Standard assumptions, such as cosmic or solar abundances, are questionable since the processes likely to lead to the presence of heavy elements in a DA photosphere, such as radiative levitation, or accretion of interstellar material, are highly selective as to which ions and elements are favored. Under these circumstances, independent constraints on heavy element abundance are of great value. The primary source of such constraints continues to be high-resolution UV spectra, particularly those of International Ultraviolet Explorer (IUE).

Recently, Holberg, Wesemael, & Basile (1993) discussed the IUE echelle spectra of two hot metal-rich DA white dwarves, RE 2214 – 492 and RE 0623 – 377. They found a large number of features due to Fe v and Fe vi in the spectra of both stars. These stars, along with Feige 24 and G191-B2B, are among the most steeply cut off white dwarves in the ROSAT WFC survey. These latter two stars also contain significant amounts of Fe (Sion et al. 1992; Vennes et al. 1992). Also present in the IUE spectra of RE 2214 – 492 and RE 0623 – 377 were a number of features which appeared to be real but were too weak to reliably identify. Recently, four additional IUE echelle spectra of RE 2214 – 492 were obtained and have been co-added with the
two earlier spectra. This has resulted in a high signal-to-noise ratio (S/N) spectrum in which numerous previously unobserved features can now be confidently identified. In addition to RE 2214–492, we have also co-added 10 of the existing archive spectra of G191-B2B, a well-studied DA of similar temperature. In this Letter we present a preliminary analysis of these spectra.

2. OBSERVATIONS

The procedures followed in co-adding the spectra are similar to those described in Holberg et al. (1993). Briefly, in each image we have measured the apparent wavelengths of the major C, N, O, and Si stellar features and the low-ionization interstellar features in order to determine the relative wavelength shifts between each of the spectra. We attribute the small wavelength shifts between individual spectra of each star to differing placement of the star within the IUE large aperture and to differing SWP wavelength calibrations rather than any real Doppler shifts due to stellar motion which might have occurred between images. In this process we have also corrected the wavelength scales for incorrect IUESIPS processing of the spectra according to Garhart (1993). We then select an average of several spectra to define a reference wavelength scale and linearly shift each spectrum to match the reference. These small differential wavelength shifts serve to mutually register common spectral features among all the spectra. Individual spectra are then co-added over the entire 1150–1950 Å wavelength range and averaged to improve S/N. In order to aid in proper identification and measurement of the large number of weak features, we have defined IDL data reduction procedures to automatically locate and measure wavelength centroids and equivalent widths of all the features, real and otherwise, which are present above a chosen equivalent width threshold. In each case we have chosen that threshold to be 12 mÅ. At this stage we have also Doppler-shifted the co-added spectra to the laboratory frame which we have defined from the observed radial velocities of the stronger easily identified CNO stellar features.

2.1. Velocities

For both stars we observe two distinct sets of features: interstellar and stellar. The interstellar features are the predominately ground-state transitions due to C II, N I, O I, and Si II seen in many white dwarfs. For RE 2214–492 and G191-B2B the observed mean velocities of 12 ISM features in each star are $-4.5 \pm 0.9$ km s$^{-1}$ and $+9.7 \pm 1.0$ km s$^{-1}$, respectively.

A single velocity component is observed to characterize all of the observed C, N, O, Si, Fe, and Ni features in each star. The mean velocity of 29 features in G191-B2B is $+22.1 \pm 0.6$ km s$^{-1}$, a result in agreement with the value of $+18.3 \pm 4.2$ km s$^{-1}$ for the strongest C IV, N V, and Si IV features first reported by Bruhweiler & Kondo (1983). (The uncertainties in the IUE velocities reported here reflect the variance of the mean computed from internal statistics.) This velocity is also quite consistent with the observed photospheric velocity of G191-B2B of $+22 \pm 2$ km s$^{-1}$ from Reid & Wegner (1988). For 26 features in RE 2214–492 we observe a radial velocity of $+28.9 \pm 0.8$ km s$^{-1}$ for all photospheric features. We are not aware of any independent measures of the photospheric velocity for RE 2214–492 which can be compared with the above IUE velocity. The arguments presented in Holberg et al. (1993) concerning the high ionization states and excited levels of the Fe transitions leave little doubt, however, that these features arise in the photospheres of both stars. It should be noted here that the above radial velocity differs from the value of $+38.9$ km s$^{-1}$ quoted in Holberg et al. (1993). The difference is due to the application of the procedures described in Garhart (1993) to correct the erroneous IUESIPS wavelength scale.

2.2. Identified Features

The reduction procedures described above result in a list of possible features present in the observed spectra. This list can be compared with the spectral features predicted to exist in the photospheres of white dwarfs containing CNO and Fe group elements. We have employed NLTE model atmospheres computed with the TLUSTY code (Hubeny 1988; Hubeny & Lanz 1992) in order to identify the large numbers of features in our RE 2214–492 and G191-B2B spectra and to estimate the abundances of Fe and Ni in the atmospheres of these stars. In Table 1 we present the adopted parameters of the model atmospheres used to analyze the spectra of RE 2214–492 and G191-B2B. Since we are primarily concerned here with the presence of Ni and Fe, we have fixed the $T_{\text{eff}}$ and $\log g$ for each star at values determined previously. For RE 2214–492, we use $T_{\text{eff}} = 63,500$ K and $\log g = 7.5$ (Holberg et al. 1993) and for G191-B2B we use $T_{\text{eff}} = 58,000$ K and $\log g = 7.5$ (Kidder 1991; Holberg et al. 1986).

In constructing model atmospheres, we have initially assumed a pure hydrogen composition. The first eight levels of H I are taken into account explicitly; all the remaining levels, considering their occupation probabilities, were taken into account by means of a “merged level,” as described by Hubeny, Hummer, & Lanz (1994). Once the model atmosphere (basically the run of temperature, electron density, and hydrogen level populations with depth) was constructed, we have calculated a detailed synthetic spectrum, taking into account all lines from the Kurucz (1990) line list for C, N, O, Fe, and Ni, assuming various abundances of metals. In principle, it is more consistent to take into account the metal opacities (CNO, Fe, Ni) for lines and continua (the so-called metal line–blanketed models). Such models will certainly be necessary for deriving accurate metal abundances, but for our present purposes, where our estimated accuracy of derived abundances is about 0.3 dex, the pure-H models, with metal lines considered for spectrum synthesis only, are satisfactory.

In Table 2 we provide a list of some isolated, unblended Ni ν features present in both stars. Here we have used Raassen & van Kleef (1977) for the laboratory wavelengths and line identifications. Observed wavelengths are measured in the laboratory frame after applying the stellar Doppler shifts discussed in § 2.1. Observed wavelengths and equivalent widths were obtained using the IUEDAC procedure FEATURE. For RE 2214–492 and G191-B2B the mean difference between the laboratory and observed wavelengths in Table 2 are $-2.1$ mÅ.

<table>
<thead>
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<th>Parameter</th>
<th>RE 2214–492</th>
<th>G191-B2B</th>
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<tr>
<td>$T_{\text{eff}}$</td>
<td>63,500 K</td>
<td>58,000 K</td>
</tr>
<tr>
<td>$\log g$</td>
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<td>-4.5</td>
</tr>
<tr>
<td>$\log [\text{Ni/H}]$</td>
<td>-5.5</td>
<td>-6.0</td>
</tr>
</tbody>
</table>

TABLE 1

ADOPTED MODEL ATMOSPHERE PARAMETERS FOR RE 2214–492 AND G191-B2B

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and $-4.1 \text{ mÅ}$, respectively. The sample variance for all 16 wavelength differences in Table 2 is 16 mÅ, well within what is observed for stellar and interstellar features in IUE echelle spectra of other white dwarfs. We estimate the uncertainty in the observed equivalent widths of the Ni vi features in Table 2 to be $\pm 10\%$. The predicted equivalent widths in Table 2 are obtained from the model atmosphere spectra whose parameters are described in Table 1. As can be seen, the general agreement between observed and predicted equivalent widths for the individual features in Table 2 is very good.

In addition to the features evident in Figure 1 and discussed in Table 2, the co-added spectra contain a large number of additional features. In particular, in the region between 1230 and 1600 Å, where the S/N of the spectra generally exceed 15 or 20, respectively, for RE 2214 − 492 and G191-B2, our procedures identified 211 and 76 possible narrow features exceeding 12 mÅ in equivalent width. Of these, the vast majority can be identified with either Fe v, Fe iv, Ni v, or Ni iv on the basis that they lie within 0.1 Å of the predicted wavelengths of these ions. This and other important aspects of these spectra will be discussed elsewhere.

3. DISCUSSION

In Figure 1 we show the 1320–1340 Å regions of both RE 2214 − 492 and G191-B2. Also shown in Figure 1 are the locations of those Ni vi lines (long arrows) and Fe v lines (short arrows) that have predicted equivalent widths larger than 12 mÅ. As can be seen, numerous features of Ni vi and Fe v are evident in RE 2214 − 492, while several of the stronger lines of each element are also seen in G191-B2. Consistently, however, the Ni and Fe features are significantly weaker in G191-B2 than in RE 2214 − 492. We can use the equivalent widths of the stronger unblended features of Ni vi and Fe v to estimate the abundances of these elements in both stars. A simple comparison of predicted and observed equivalent widths reveals a considerable amount of scatter. The primary reasons for this are the relative weakness of the lines (10–40 mÅ) and the resulting measurement uncertainties of 50%–25% for individual lines. Added to this is the theoretical uncertainty regarding the oscillator strengths of individual features. To reduce both sources of uncertainty, we selected 10 of the stronger and more isolated Fe v and Ni vi features which are common to both stars. We then estimate the metal abundance by comparing the observed and synthetic spectra calculated for various abundance values. For RE 2214 − 492 we find abundances of log [Ni/H] = $-5.5 \pm 0.3$ and log [Fe/H] = $-4.0 \pm 0.3$. This latter value is slightly higher than, but entirely consistent with, the Fe abundances found by Holberg et al. (1993) using an independent set of NLTE models.

![Figure 1](image_url)

**Fig. 1.** A comparison of the co-added echelle spectra of RE 2214 − 492 (top) and G191-B2 (bottom). Relative fluxes for both stars are plotted over the wavelength range 1320–1340 Å; both spectra have been Doppler-shifted to the rest frame. The arrows at the top of the plot indicate the expected locations of Ni vi (long arrows) and Fe v (short arrows) features. These features are derived from the model atmospheres specified in Table 1. All Ni vi and Fe v lines with expected equivalent widths exceeding 12 mÅ in the RE 2214 − 492 model are plotted. Synthetic model spectra (dotted lines) are overplotted on each spectrum.
For G191-B2B we find [Ni/H] = −6.0 ± 0.3 and log [Fe/H] = −4.5 ± 0.3. The Fe abundance of G191-B2B determined here is somewhat higher than the range of −5.5 to −4.8 estimated by Vennes et al. (1992) for G191-B2B. It is interesting to note that the Fe and Ni abundances in RE 2214−492 and G191-B2B are observed to be not far from the respective solar values of −4.6 and −5.7. Because these two stars are among the most metal-rich of the known DA stars, the general agreement with solar abundances is likely coincidental. The Ni/Fe abundance ratio is perhaps more significant in view of the expectation that the radiative forces on Ni and Fe are quite similar.

The detection of Ni v in RE 2214−492 and G191-B2B, while not unexpected in light of the presence of Fe v, is nevertheless the second Fe group element found in the photosphere of a hot white dwarf. We have also searched for evidence of other Fe group ions in RE 2214−492 and find tentative evidence for the presence of Fe iv and Ni iv but much less convincing evidence for Cr v. We used the models to select the six strongest unblended features for the Ni v, Ni iv, Fe v, Fe iv, and Cr v and co-added each in velocity space. As expected, the Fe v and Ni v lines yield strong features centered on 0 km s⁻¹ in the laboratory frame. There are also weak features at the same velocity corresponding to the six strongest features of Fe iv and Ni iv.

We have presented the first evidence of the presence of Ni in the spectra of two hot DA white dwarfs, RE 2214−492 and G191-B2B. Nickel, along with other metal ions seen in both stars, helps to explain the large number of weak features seen in the IUE echelle spectra of both stars. The derived abundances of these metals can ultimately help to constrain modeling of the EUV spectra of these and other white dwarfs. Finally we have not attempted here to optimize the atmospheric parameters for RE 2214−492 or G191-B2B; in particular we have not simultaneously adjusted abundance levels, $T_{\text{eff}}$, and log $g$. Additionally, we have not directly tested the consequences of our metal abundances on the EUV energy distributions of these stars. Such investigations will be carried out on these and other hot DA stars for which high-quality co-added spectra are available.

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