The Metallicity of Hot DA White Dwarfs as Inferred from EUV Photometry

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Photometric EUV observations have shown that the hotter DA white dwarfs tend to show significant excess opacity relative to hydrogen. EUV and high-resolution FUV spectroscopy have conclusively demonstrated that the excess opacity is due to the presence of trace heavy elements in the white dwarf photospheres. In the past, the general abundance distribution in hot DA has been studied as a function of temperature, assuming that He was the trace absorber. We present here the first determination of the variation of relative total heavy element abundances in DA as a function of both temperature and gravity using realistic models that include metals. We compare the observational results with theoretical calculations of equilibrium abundances due to radiative acceleration.

1. Introduction

The DA spectral class is defined by the lack of any observable spectral features in the optical due to elements other than hydrogen. However, FUV, EUV and soft X-ray observations have now made it abundantly clear that the hotter DA can have significant amounts of trace heavy elements in their photospheres. (See Koester (1995), Jordan et al. (1995), and Vennes (1995) and citations therein for more details regarding trace element abundances in DA white dwarfs). Detailed studies of the abundances of individual trace elements in hot DA white dwarfs are currently being pursued using EUV and FUV spectroscopy. Suitable data, though, are available for only a modest number of stars. Therefore, the overall distribution of trace element abundances in DA can best be determined using the full set of EUV photometric observations, which includes over 100 white dwarfs.

2. Analysis Method

EUV fluxes of white dwarfs are determined by the effective temperatures, abundances, and ISM columns. In order to derive abundances and columns from the photometric EUV data, it is therefore necessary to constrain effective temperatures by other means. This has been accomplished for nearly all the DA white dwarfs that have been detected in the EUV via detailed fitting of the Balmer line profiles obtained as part of a recent optical spectroscopic survey of hot DA white dwarfs (Finley, Koester, & Basri (1995)). The model spectra used in this analysis were calculated using D. Koester's model atmosphere code (Koester, Schulz, & Weidemann (1979), Koester (1995)), including only bound-free opacities of C through Ni. (The additional complexity involved in including millions of lines was not justifiable for the analysis of photometric data). Cross sections were taken from the Opacity Project database where available (Seaton et al. 1992), otherwise hydrogenic cross sections were calculated. He abundances were set at a negligible value given the non-detection of photospheric He in any EUV spectra of DA other than the extremely massive white dwarf GD 50 (Vennes 1995), which appears to have only H and He in its photosphere. The other hot DA that are not pure H that have been observed spectroscopically in the EUV (11 of which are known to the author) are clearly dominated

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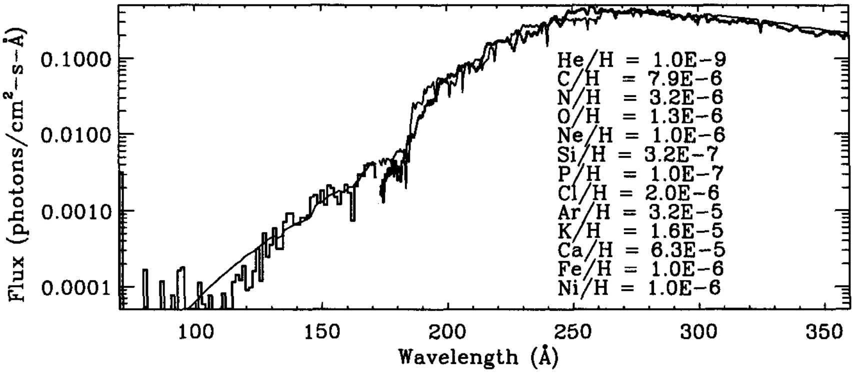

FIGURE 1. Model fit to the observed EUV spectrum of G191-B2B, including only bound-free heavy element opacities, for $T_{\rm eff}$ = 55,000 K, $\log g$ = 7.5, with abundances as listed. Model is thin curve, observed spectrum is thick histogram.

by metal opacity. The only other DA that are likely to be dominated by He opacity in the EUV are the two EUV-detected DAO, RE1016-052 and RE2013+400, and they have been excluded from this analysis.

Given the goal of obtaining the variation of overall metal abundances as a function of $T_{\rm eff}$ and $\log g$, absolute abundances of individual elements are unimportant if the models used in the analysis accurately reproduce the observed EUV fluxes. The latter criterion was explicitly satisfied by determining an initial set of trace element abundances that matched the *EUVE* spectrum of G191-B2B (see Fig. 1). Models of different "metallicity" were calculated by varying all heavy element abundances relative to H by the same factor. As seen in Fig. 1, the match at high metallicities was quite good. At sufficiently low abundances (between −2.5 and −3 dex relative to the G191-B2B values) the models became indistinguishable from pure H. The models also worked well for the intermediate metallicity DA GD 246. Independent fits were made to the EUV photometry and to the *EUVE* spectra for that object. Identical abundances were obtained, requiring a difference in $T_{\rm eff}$ of only 2,000 K and a difference in the HI column of only 0.2 dex.

Relative abundances and ISM columns were obtained by comparing the observed count rates with theoretical count rates for those DA for which optical temperatures and gravities were available from the Finley, Koester, & Basri (1995) sample. ($T_{\rm eff}$ and $\log g$ for WD 2331-375 (MCT2331-4731) were kindly provided by S. Vennes). Theoretical fluxes were scaled using published V magnitudes or V magnitudes derived from the optical spectra; the latter were generally accurate to about 0.1 magnitude. Interstellar absorption was calculated assuming an HI/HeI ratio of 10:1, using the cross-sections of Rumph, Bowyer, & Vennes (1994). Observed count rates were taken from the *EUVE* catalogs (Bowyer et al. (1994), Malina et al. (1994)), the *ROSAT* Wide Field Camera catalog (Pounds et al. (1993)), and pointed *EUVE* observations. The error determinations included the addition of an assumed 15% calibration error in quadrature with the counting statistics errors.

Some typical confidence contours obtained for representative objects are shown in Fig. 2. WD 2111+498 (GD394) and WD 2211-495 (RE2214-491) were detected in multiple EUV bandpasses. ISM opacity reduces the flux more strongly toward longer wave-

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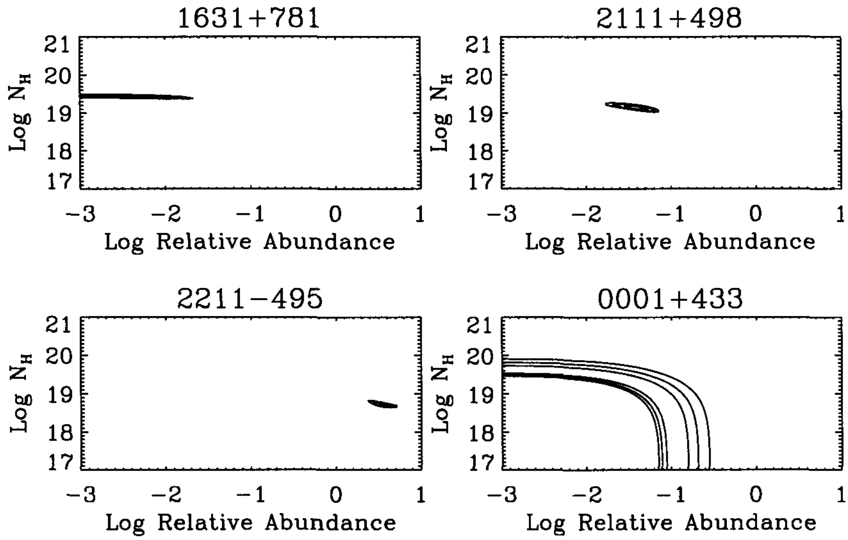

FIGURE 2. Fits for some representative objects, labeled at top with WD numbers. Contours plotted are 90%, 99%, and 99.9% confidence intervals.

lengths, while trace metals preferentially attenuate the flux toward shorter wavelengths; hence unique solutions requiring significant trace element abundances were obtainable in both these cases. WD 1631+781 (RE1629+780) also has well-determined fluxes in multiple EUV bandpasses, but is consistent with a pure H atmosphere. WD 0001+433 (RE0003+433) was detected in only one EUV bandpass, thereby precluding a unique solution for both the trace element abundances and the ISM column.

3. Results

The abundance determinations for the DA hotter than 33,000 K and with $\log g < 8.3$ are displayed in Fig. 3 as a function of temperature and gravity. Both the measurements and the 90% confidence upper limits such as that obtained for 1631+781 are included. However, limits for objects similar to WD 0001+433, for which both the columns and abundances were effectively unconstrained, were excluded. The figure shows that abundances increase strongly as gravity decreases and increase less strongly with T_{eff}, as is expected for radiatively supported heavy elements. The absence of detectable trace elements at lower temperatures and higher gravities is strengthened by additional EUV spectroscopic results presented in this volume by Dupuis & Vennes (1995). In addition to the DA shown in Fig. 3 as being spectroscopically pure H (GD 153, (PG)1057+719, HZ43, GD 2, WD 1029+537 (RE1032+532)) based on our analyses of *EUVE* spectra, Dupuis and Vennes present spectroscopic confirmation of the photometric determination that trace metals are also absent in GD 659, WD 0715-703 (RE0715-702), and WD 2152-548 (RE2156-543).

The dependences of the observed abundances on different parameters are shown in Fig. 4. The only correlation with T_{eff} alone was the apparent lower temperature threshold. A much better correlation was obtained with gravity alone. A good correlation was also

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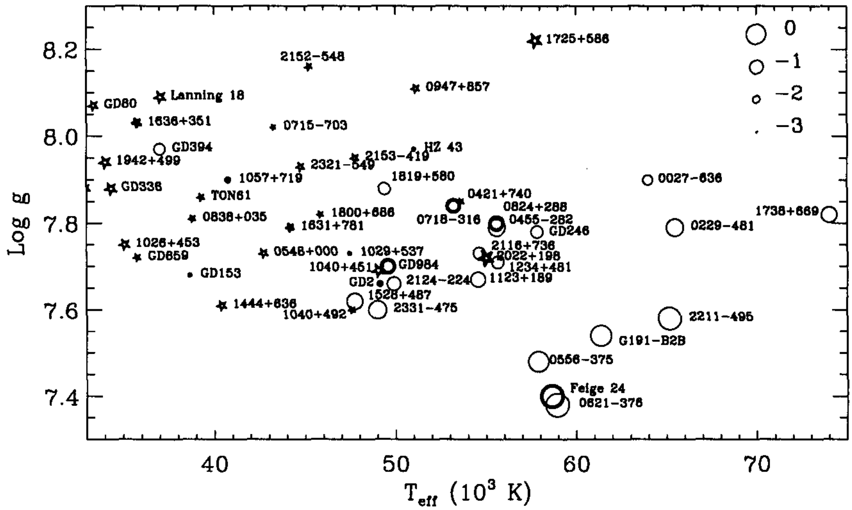

FIGURE 3. Inferred trace element abundances relative to G191-B2B. The sizes of the symbols are proportional to the logs of the relative abundances (see key). Circles are measurements, stars are upper limits, and solid circles are spectroscopic determinations that are consistent with pure H atmospheres. Error bars are omitted for clarity, but typical errors in $T_{\rm eff}$ range from 150 K at the cool end to 1,000 K at the hot end, while the average error in $\log g$ is 0.05 dex. Symbols drawn with thick lines represent WD in binaries. Numerical labels are WD numbers.

obtained with age, but that could due to a fortuitous correlation between the cooling isochrones and the isocontours of observed abundances. The dependence of derived abundances on the interstellar HI column is displayed to show that there is no obvious bias present except for the absence of DA with both very high abundances and HI columns, which were undetected in the EUV or were detected in only one bandpass.

We also compared the relative abundance determinations with recent extensive calculations of radiative support of heavy elements presented in Chayer, Fontaine & Wesemael (1995, hereafter CFW). CFW calculated equilibrium photospheric abundances for individual heavy elements in an otherwise pure H atmosphere as a function of temperature and gravity. Using their results (kindly provided by P. Chayer), we interpolated in $T_{\rm eff}$ and $\log g$ to find predicted abundances (normalized to 60,000 K, $\log g = 7.5$) for each individual object. The comparisons for Fe+H and C+H are presented in Fig. 5. Linear regressions were performed on the logs of the predicted and measured abundances for the 20 DA in which metals were definitely present, resulting in correlation coefficients near 0.9 and residuals of about 0.3 dex for both Fe and C. However, the slopes of the fits were 2.5 for Fe and 3.6 for C, and about 2 for N, O and Ar. A slope near unity was obtained for Ca, but our analysis of the G191-B2B spectrum with models including the Ca lines from Kurucz (1991, 1992) requires Ca/H $< 10^{-8}$, hence Ca cannot contribute significantly to the observed opacities. We conclude that the observed variation of trace element abundances with $T_{\rm eff}$ and $\log g$ is much greater than predicted by current theory.

In the case of the predicted abundances for carbon, applying a linear scale factor of 3.6 to the logs of the predicted abundances (and a shift of 0.2) produced excellent agreement with the measured abundances. All the abundance measurements were consistent with a

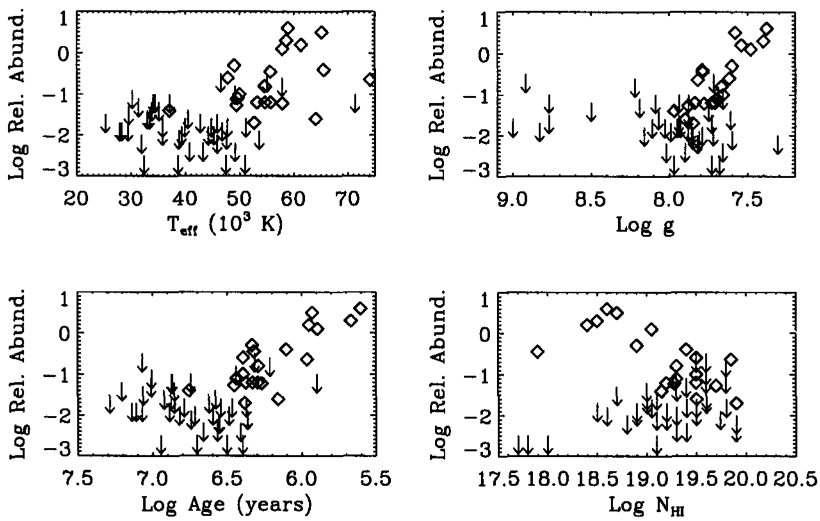

FIGURE 4. Abundance measurements (diamonds) and upper limits (arrows) vs. stellar parameters and ISM columns. Ages are taken from Wood's latest evolutionary models (Wood 1990, 1994).

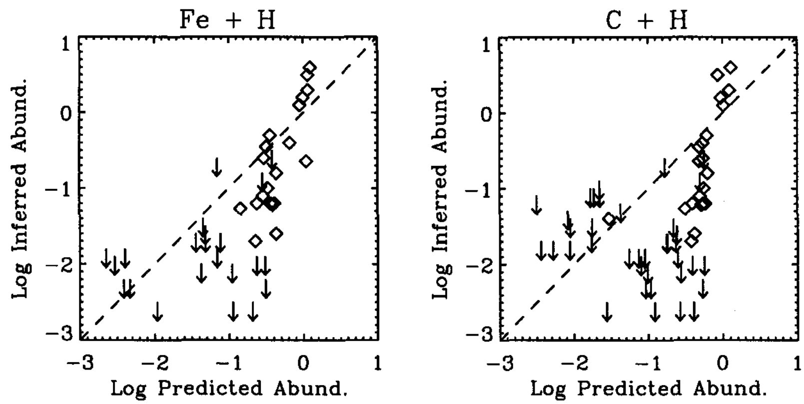

FIGURE 5. Relative abundance measurements (diamonds) and upper limits (arrows) vs. single-element relative abundances predicted by CFW. Dashed line has slope of unity.

linear fit (except GD394) and the 1 σ dispersion was only 0.34 dex. The only significant discrepancies found were for HZ 43, GD 2, WD 1040+492 (RE1043+492), and WD 1029+537 (RE1032+532), all of which had observational upper limits of about an order of magnitude below the adjusted predicted abundances.

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4. Summary

Many previous studies have quoted a 40,000 K lower threshold for the appearance of detectable trace elements in hot DA. This analysis shows that there are no DA cooler than 48,000 K or with $\log g > 7.9$ that *require* the presence of trace heavy elements, with the exception of GD 394. The theoretical abundances calculated by CFW correlate well with the observed abundances, but vary much more slowly with $T_{\rm eff}$ and $\log g$. Further investigations of the joint effects of a mix of trace heavy elements may modify the predicted abundances; some initial results are presented in this volume (Chayer et al. 1995). The current discrepancy between theory and observation may also support the suggestion by CFW that radiatively driven winds may deplete the photospheric trace elements over time. However, if mass loss is occurring, differential effects must be small as long as significant amounts of photospheric trace elements are present, given the tight correlation obtained between the equilibrium abundance predictions and the observed abundances for the DA with definite metal detections. It is notable that the four objects that depart significantly from the adjusted predictions are underabundant by at least 1 dex and lie near the "dividing line" (see Fig. 3) between effectively pure H and metal-rich DA. The challenge to theorists is to find a way to accelerate the reduction in abundances as the DA cool (by factors of 2 to 3.5 in the logarithm relative to current equilibrium calculations) without altering the observed regular dependence on $T_{\rm eff}$ and $\log g$ and yet allow some DA to have effectively eliminated their trace metals when abundances as high as 10% of G191-B2B are expected.

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