Final Report: Temperature and Gravity Dependence of Trace Element Abundances in Hot DA White Dwarfs (94–EUVE–094)

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EUV spectroscopy has shown that DA white dwarfs hotter than about 45,000 K may contain trace heavy elements, while those hotter than about 50,000 K almost always have significant abundances of trace heavy elements. One of our continuing challenges is to identify and determine the abundances of these trace constituents, and then to relate the observed abundance patterns to the present conditions and previous evolutionary histories of the hot DA white dwarfs. The latter is an important factor, given how little we know about the final stages of stellar evolution, in which stars lose from 50% to 90% of their initial mass in the process of forming white dwarf remnants.

Analyses of EUV spectra of extremely metal-rich DA such as G191–B2B and Feige 24 has been difficult due to the very heavy blanketing of the spectra. With few discrete features present, ascribing any given portion of the observed excess opacity to a particular element is difficult. Also, the EUVE short wavelength spectrometer (SW) region of the spectrum, from about 75 to 175 Å, where many absorption features that could be used for abundance diagnostics are found, is essentially unusable in metal-rich DA spectra, given the low flux levels due to the extremely high opacity in this region. However, we had identified a number of hot DA of intermediate metallicity, in which the blanketing was much less severe, and which also had sufficient short wavelength flux to obtain reasonable S/N in the SW spectrometer with modest binning. Accordingly, the aim of this project was to obtain good-quality dithered spectra of some of the intermediate-metallicity hot DA white dwarfs, and to determine their photospheric metal abundances. Comparisons within the intermediate metallicity class and also with metal-rich DA should then give some idea of how abundance patterns vary with basic stellar properties.

New EUV spectra were obtained for WD 0131–163 (GD 984), WD 0718–316 (RE 0720–314), WD 1029+537 (RE 1032+532), PG 1123+189, and WD 2321–549 (RE 2324–544). The images, produced with the final version of the processing software, were obtained from the HEASARC archives. The spectra were extracted from the images using IDL routines adapted from the optimal extraction software that I have been using for optical CCD spectroscopy (Finley, Koester, & Basri 1997). The routines use profile weighting to optimize the S/N while collecting all the source events. The spectra are thus more spectrophotometrically accurate and less noisy than spectra obtained using standard narrow-slit extraction techniques that lose the fraction of events that lie in the scattering wings and have significantly higher noise in the vicinity of the strong geocoronal lines at 304 Å and 584 Å.

The spectra were then analyzed using Koester's line-blanketed LTE model atmospheres that include bound-free opacities for heavy elements from the Opacity Project, and absorption line data from the Kurucz line lists. The analysis procedure consists of calculating a spectra with a given set of heavy element abundances, scaling the spectra using optical photometry or spectrophotometry or ultraviolet spectrophotometry, converting flux units to photon units, including interstellar absorption, multiplying the model spectra by the effective areas to get count spectra for each order, convolving the spectra with the instrument resolution function, and summing the different order contributions to get synthetic count spectra to compare with the observed count spectra. The results for our analyses of the individual targets are given below.

GD 984. GD 984 (WD 0131–163), with T_{eff} = 50,050 K, $\log g$ = 7.76 (Finley, Koester, & Basri 1997), lies at the temperature/gravity threshold where trace heavy elements begin to appear in hot DA white dwarfs, and is evidently one that definitely has trace heavy elements present. A pure H model with ISM opacity added to match the observed spectrum around 250 Å is 10× brighter than the observed flux shortward of 100 Å and 4× too bright between 130 and 170 Å. Furthermore, an absorption edge is quite visible around 102 Å, that I have not seen in any other EUV

spectrum of a hot DA. The edge is quite strong, with a flux contrast of nearly a factor of 2. The $\sim$ 102 Å edge is a unique signature of Al; no other common element with $Z \leq 28$ has an absorption edge at that wavelength. The Al edge lies at 102.32 Å, and is due to absorption from the ground state of Al IV.

We achieved a satisfactory fit to the observed spectrum using a fairly simple model with $T_{\rm eff} = 47,000$ K, $\log g = 7.8$, $\log({\rm He/H}) = -5$, $\log({\rm Al/H}) = -6.7$, and $\log({\rm Fe/H}) = -6.4$. While the optically determined effective temperature was 50,000 K, based on fits with pure H models, the addition of trace heavy elements causes backwarming that weakens the Balmer lines. Hence, a lower $T_{\rm eff}$ for the model including Al and Fe was necessary to maintain consistency with the observed Balmer line profiles. The adopted model has Balmer line profiles that are actually consistent with pure H models with $T_{\rm eff} \simeq 51,000$ K.
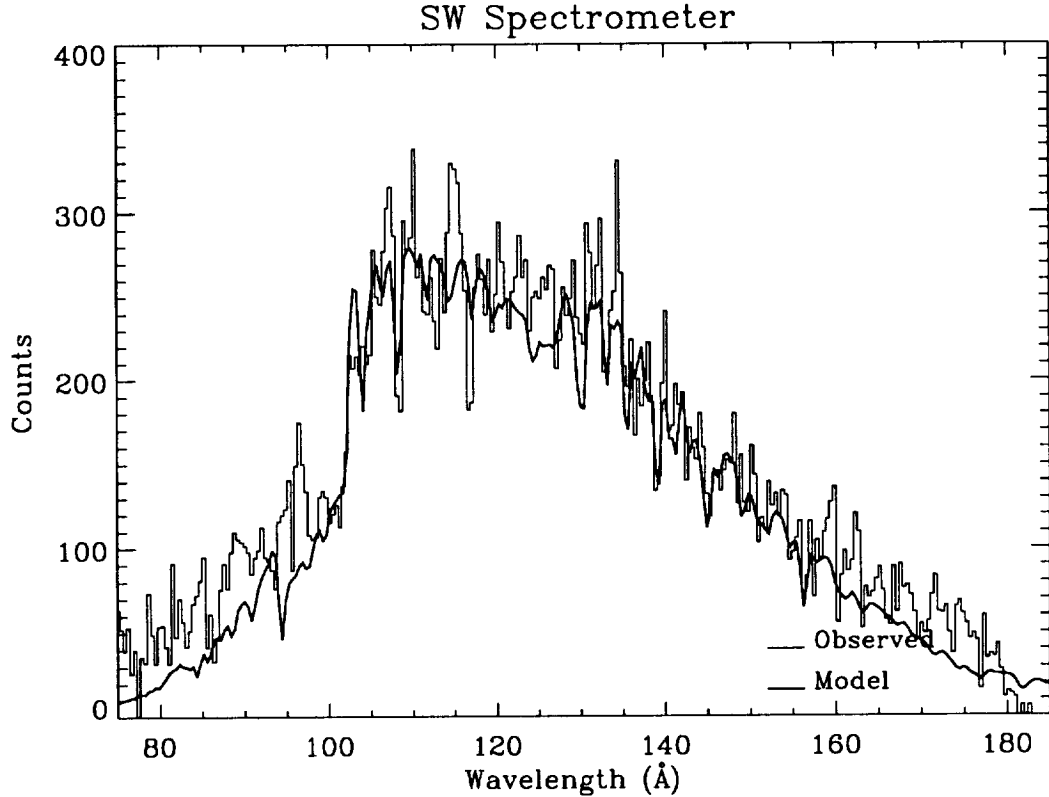

Fig. 1.— Observed SW count spectrum (6-pixel binning) and fit for GD 984. Model parameters are $T_{\rm eff} = 47,000$ K, $\log g = 7.8$. Abundances are $\log({\rm X/H}) = -5.0, -6.7,$ and -6.4 for He, Al, and Fe, respectively.

The choice of photospheric He abundance is rather arbitrary. With an interstellar H I column density of 1.5×10^{19} (assuming He I/H I = 1/12), the MW spectrometer count spectrum drops to below 10% of the peak value just longward of 250 Å. Hence there is insufficient S/N at a resolution suitable for discriminating between the photospheric and interstellar contributions to the observed He II 228 Å edge. A firm upper limit may be placed on the photospheric He abundance of $\log({\rm He/H}) < -4.5$. A higher abundance results in a too-strong He II edge even with no interstellar He II included. However, that high an abundance can probably be ruled out, because the modeled edge lies longward of the observed edge, due to the merger of the higher He II absorption lines. Below that abundance, though, there is no way to discriminate between $\log({\rm He/H}) = -6$ (i.e., negligible abundance), requiring interstellar (He II/H I) = 1/18,

or log(He/H) = -5, which requires an interstellar He II/H I ratio of 1/25 (He II/He I $\simeq$ 1/2). In the latter case, the photospheric He is higher than expected, given theoretical expectations of $< 10^{-5.5}$ for this $T_{\rm eff}$ (Vennes et al. 1988), and given that He is not seen in DA except for GD 50 (a very massive DA, perhaps a merger product), and a few DA that are accreting from a companion. GD 984 is a spectroscopic binary, with a dMe companion, but radial velocity measurements do not show it to be a close binary (Schultz et al. 1996), reducing the possibility that the late star is donating material to the white dwarf.

The heavy element abundance determinations are very interesting. Fe is most likely the primary absorber, given the detection of its presence in nearly all hot DA that include trace elements. Fe provides the necessary distribution of opacity with wavelength to match the overall shape of the observed spectrum. Positive identification of Fe is not possible based on any one feature, but is realizable given the number of discrete features that are present at these relatively low abundances. Between about 130 and 157 Å the Kurucz line lists include almost 1600 Fe VI absorption lines involving absorptions from levels lying within 0.25 eV of the ground state. These lines are concentrated in clumps of up to hundreds of lines, that would appear as discrete lines at much better resolution that that of the EUVE spectrometer. The possible line locations are 130, 132, 133, 136, 139, 141, 145, 152, and 156 Å. All except the 132 Å line are apparent in the synthetic spectrum, with 6-pixel binning, with central depths of from 10 to 30%. Some features in the observed spectrum clearly coincide with the model features, but others are less clear. This is expected, given that the signal-to-noise ratio per 6-pixel bin in this range varies from about 12 to about 6, as determined from counting statistics. The observed and synthetic spectra were normalized and the regions from 125 to 165 Å were cross-correlated, giving a peak correlation coefficient of 0.5 at a shift of 0 bins. As a check, an artificial "observed" spectrum was constructed from the synthetic count spectrum by adding noise equal to that in the observed spectrum, and the artificial spectrum was then cross-correlated with the synthetic spectrum, giving a peak correlation coefficient of 0.6, consistent with residual fixed-pattern noise increasing the observed S/N by a modest amount relative to the error derived from counting statistics. Performing the same exercise using the heavily smoothed observed spectrum with random noise added yielded peak correlation coefficients of only 0.2. We conclude that the Fe features are present at near the strengths seen in the calculated model spectrum.

Identifying Al in the spectrum was far more straightforward. The extremely strong Al 102 Å edge is not reproducible by any other element, and the model edge is exactly coincident with the location of the observed edge. Furthermore, the observed strength of the Al V resonance line at 108 Å ($\sim$ 275 mÅ) is within 20% of that predicted by the model ($\sim$ 220 mÅ). We conclude that the identification of Al from the EUV spectrum is incontrovertible. If additional corroboration is desired though, the model (assuming a uniform abundance distribution) predicts equivalent widths of the Al III resonance lines at 1854.79 and 1862.79 of 30 and 20 mÅ, respectively, which would be easily measurable with STIS.

The presence of Al is very interesting. I have not seen a noticeable 102 Å Al edge in any of the other EUVE spectra of hot DA. Additionally, a comprehensive survey of IUE spectra of hot DA found Al in only two stars: the unusual DA GD 394, and G191$-$B2B (Holberg et al. 1998). Chayer et al. (1995) predicted equilibrium abundances for a number of elements in otherwise pure H atmospheres as a function of the depth, expressed as the fractional mass m/M_* at a given depth. The continuum at 1850 Å is formed at a fractional mass depth M/M_* of about 2×10^{-16}, with $T = 53,000$ K, while the continuum at 100 Å is formed at 5×10^{-15}, with $T = 95,000$ K. From Figure 15 in Chayer et al. (1995), the abundance predicted by diffusion theory would be less than 10^{-10} at the EUV photosphere, and orders of magnitude lower in the FUV photosphere. Hence Al is present at an abundance that is more than three orders of magnitude greater than theoretical calculations would predict.

Heavy elements can be present in a white dwarf either through accretion, or through diffusion to the surface of material that was present in the white dwarf envelope at its formation. We have not calculated accretion rates that would be necessary to produce the observed abundances. However, some recent work leads to the possibility that

high Al abundances could be intrinsic to the white dwarf. Much recent attention has been devoted to observational evidence of Al enhancements among globular-cluster stars on the first giant branch (RGB) (Kraft et al. 1997). The observations led to revised evolutionary calculations that showed that proton capture in the vicinity of the H-burning shell on ^{24}Mg, ^{25}Mg, and ^{26}Mg results in the production of high abundances of ^{27}Al, which can then be mixed to the surface (Cavallo et al. 1998). Evolutionary abundance calculations for stars on the second giant branch (AGB) have concentrated on ^{26}Al production, following the detection of ^{26}Al decay products in meteorites (Wasserburg 1985) and the discovery 1809 keV γ-ray line due to β-decay of ^{26}Al in the interstellar medium (Schönfelder & Varendorff 1991). However, a search of the literature did not reveal any calculations devoted to possible ^{27}Al enhancements in AGB stars. The possibility thus remains to be investigated whether proton capture near the H-burning shell in AGB stars could also enhance Al abundances near the base of the outer envelope, which in turn could be greatly increased as most of the envelope is lost during the terminal phases of the AGB and afterwards.

WD 0718−316 (RE 0720−314). This star is also a binary, as I discovered in 1993, based on the presence of significant Balmer line emission by a cool companion, similar to that seen in the close binary Feige 24. Followup observations by Vennes & Thorstensen (1994) confirmed the close binary nature of this system, showing that the emission came largely from the face of the cool companion that is heated by the white dwarf. The most significant factor related to analysis of the EUV spectrum is that the helium abundance in the white dwarf varies on a timescale of months by as much as two orders of magnitude, as discussed extensively in Finley, Koester, & Basri (1997). The abundance variations are likely to be caused by a variable rate of accretion from the cool companion.

The pure H-derived T_{eff} was 55,120 K, with a modestly high gravity of 7.92 (Finley, Koester, & Basri 1997). Given the significant trace element abundances, the model T_{eff} had to be lowered to 50,000 K in order to maintain consistency with the observed Balmer line profiles. The ISM H I column density was determined to be 1.9×10^{18} by fitting the flux longward of the He I edge at 504 A. The He I edge is so strong, though, that the LW spectrum below the 504 Å edge is almost entirely due to second order flux. The He I ISM column density of 1.15×10^{18} was therefore determined by matching the MW flux between 250 and 300 Å. The spectrum has a prominent rolloff between 250 Å and the ISM He II edge at 228 Å, due to the fact that photospheric He, with blended higher lines, is responsible for most of the observed He II absorption. Observed features are also present at the locations of the He II 256 and 304 Å lines. The resulting photospheric He abundance was log(He/H) = −4.6, requiring an ISM column density for He II of 5.9×10^{17} to match the observed flux shortward of 228 Å.

The flux level in the SW spectrometer could be entirely accounted for by including Fe at an abundance of log(Fe/H) = −6.0. Despite the 2.5× higher abundance than was found for GD 984, the 130–160 Å model Fe features did not correlate significantly with the observed spectrum, due to the fact that the S/N in that range varied from 9 to 4, even with 18-pixel binning. Therefore, we cannot rule out the possibility that the Fe abundance is actually lower, and other trace absorbers are partially responsible for the observed opacity.

The ISM column densities are quite unusual. The photospheric He abundance at the time of the EUVE observation is far greater than can be supported by radiative acceleration alone, and optical spectra taken at different times have required abundances as high as log(He/H) = −2.35 based on fitting the He II 4686 Å line (Vennes & Thorstensen (1994). These factors point to the most likely explanation being that the photospheric absorbers are accreted from the companion, and much of the intervening material consists of highly ionized gas within the system.

WD 1029+537 (RE 1032+532). Previous investigators have concluded that this is a pure H DA. In actuality, it is possible that it has small amounts of trace heavy elements present. Published values for T_{eff} include 46,900 ± 460 K (Finley, Koester, & Basri 1997), 47,000 ± 500 K (Vennes et al. 1997), and 44,980 ± 550 K (Marsh et al. 1997). The average of those three is 46,300 K, and the average of log g is 7.78. A precise determination of V is available from Marsh et al. (1997): V = 14.455 ± 0.02. Fitting the EUV spectrum with a pure H model with those values, and

choosing ISM column densities such that the observed MW flux is matched at 300 Å, the predicted MW flux around 180 Å was high by about 40%, and the predicted SW flux was uniformly high by at least 25%, based on differential comparisons with the well-studied pure H DA white dwarfs GD 71, GD 153, and HZ 43.

Matching the SW spectrum with a pure H model required reducing the effective temperature to 44,600 K, about a 4 σ difference relative to the optical results, using the quoted internal errors in the $T_{\rm eff}$ determinations. An additional problem with the cooler model fit is that if lowered ISM column densities (relative to those required for hotter models) are chosen such that the MW spectrum is matched at 300 Å, the predicted LW spectrum, which includes the residual flux longward of 300 Å coadded with the second, third, and fourth order response to the 170–300 Å flux, is 20% high across the board, while the MW flux at 200 Å was high by 13%, and is therefore inconsistent with the pure H DA, for which the SW, MW, and LW could be fit self-consistently to within several percent.

The MW spectrum includes a significant edge around 228 Å. Given the non-detection of a He II 256 Å line, with an uncertainty of $\sim$ 100 mÅ, the 2-σ upper limit for the strength of the observed line is $\sim$ 200 mÅ, which corresponds to an abundance of log(He/H) $\leq$ −5.9. Therefore, we adopt the value log(He/H) = −6.0. Such a low He abundance requires that all the absorption that is observed at 228 Å be due to interstellar He II. Fitting the observation with a model with $T_{\rm eff}$ = 46,000 K, log g = 7.8, log(He/H) = −6, and log(Fe/H) = −7.4, and choosing ISM columns again so that the MW flux was matched at 300 Å, the predicted SW flux about 3% higher than observed near the count rate peak around 120 Å, while the MW flux was high by 15% around 200 Å, and the LW flux remained high by 20%. This is a significant inconsistency, the source of which is unclear. Given the low abundances, the model $T_{\rm eff}$ was set just below the pure-H result. The trace element opacity does weaken the Balmer lines slightly, by an amount such that the model Balmer lines match those of pure H models with $T_{\rm eff}$ = 47,350 K, which remains consistent with two of the three pure H fit results. The derived ISM H I column density was 5.4×10^{18}, while the H I/He I and H I/He II ratios were 12/1 and 25/1, respectively.

The S/N in the 125–160 Å range varied from 25 to 16 per 6-pixel bin. Even so, at this effective temperature and with such a low Fe abundance, the central depths of the Fe features in the SW were only of the order of 10%, resulting in only a weak correlation between the observed EUV spectrum and the model in that wavelength range. Binning into 12-pixel bins yielded a S/N of from 36 to 22, giving a sharply-peaked, unshifted correlation coefficient of 0.4 for the $\sim$ 5%-depth features,while the maximum of the correlation coefficient outside the peak was only about 0.2.

I conclude that while it may be possible to stretch the optically-determined effective temperature such that pure H models can fit the EUV spectrum, there is a significant likelihood that a finite amount of Fe or an equivalent absorber is present.

PG 1123+189. While this star has trace heavy element abundances much lower than in the canonical high-metallicity objects such as G191−B2B and Feige 24, it has perhaps the highest abundances of the intermediate-metallicity DA, and significant opacity is provided by elements other than Fe. While many of the 125–160 Å Fe features are clearly present in the observed spectrum, if sufficient Fe is added to reduce the SW flux to the observed overall level, the Fe VI edge at 127 Å becomes far too strong. Hence other absorbers are needed to reproduce the spectrum < 160 Å. Additionally, a sharp absorption edge is present at 190 Å, and perhaps a weaker edge is seen at 185 Å. A possible candidate for producing those features would be C, but the photoionization threshold from the ground state of C IV lies at 192.43 A. The resulting edge in the model is clearly not coincident with the observed edge, and other elements that might reproduce this portion of the spectrum have not been found. The difficulties experienced to date in modeling the EUV spectrum of PG 1123+189 suggest that it is likely that an abundance analysis for this star may do no better than producing a somewhat arbitrary set of abundances that may partially match the observes spectral shape, but fail to be unique. In order to make better progress in unraveling the abundances for this object, it will be included in an HST proposal for observations using STIS to determine abundances based on FUV line strengths. After the

FUV-detected trace elements are included at the indicated abundances, finding the other elements required to match the EUV spectrum should become more tractable.

WD 2321−549 (RE 2324−544). WD 2321−549 turns out to be a very interesting object. Whereas other DA cooler than about 50,000 K generally show no evidence of trace heavy elements, this star, at T_{eff} = 44,960 K, $\log g$ = 7.94 (Finley, Koester, & Basri 1997), definitely has trace heavy elements present. Normalization of model spectra is unambiguous, given the accurate V magnitude determination of 15.197 ± 0.017 (Marsh et al. 1997), corroborated by a value of 15.21 obtained by fitting the IUE spectrum (SWP 44779) in the 1300–1900 Å range with a 45,000 K, $\log g$ = 8.0 pure H model. A pure H model with the optically determined temperature and gravity, with interstellar column densities that match the longer wavelength flux, and scaled per the observed FUV and optical flux levels, has 1.5 times the observed EUV flux around 120 Å. A good fit to the SW spectrum is obtainable with a pure H model only by lowering T_{eff} to 42,000 K. Such a low T_{eff} may be ruled out, however, given the published Balmer line profile temperature determinations, one cited above, and another of 45,860 ± 1,420 K (Marsh et al. 1997).

A very good fit to the SW spectrum is obtained with log(Fe/H) = −6.8. At that abundance, and at EUVE resolution, with 12-pixel binning for good S/N, Fe reduces the continuum flux shortward of 250 Å, with uniformly increasing attenuation toward shorter wavelengths, but does not produce features strong enough to obtain a significant cross-correlation between the model and the observed spectrum. Furthermore, a reduction of the flux between 228 and 237 Å can be matched by the inclusion of photospheric He at an abundance log(H/He) = −5.6. While a higher abundance can be ruled out based on the absence of a definite He II 256 Å absorption line, the relative contributions of photospheric and non-photospheric He II to the observed edge near 228 Å cannot be determined with any precision due to the fact that the 180 ksec observation resulted in S/N < 5 per 12-pixel bin in the 200–260 Å region

Also remarkable is the nature of the interstellar absorption. Our inferred column densities for H I, He I, and He II are 4.68×10^{18}, 9.35×10^{17}, and 5.85×10^{17}, respectively. The He I column density was determined from the strong 206 Å resonance feature, given that the H I column is high enough that the 504 Å feature is strongly diluted by the second and third order contributions to the total count rate spectrum. In most lines of sight, the He I/H I ratio is usually ∼ 1/12. In this very unusual case, however, He I/H I = 1/5. This abundance ratio suggests that a significant portion of the interstellar matter providing the observed absorption is actually circumstellar, and highly ionized by the intense radiation field of the white dwarf. That abundance ratio also implies relatively low column densities for non-circumstellar material in the line of sight to the object. Low column densities are possible, despite the photometric distance of about 175 pc, given that the galactic latitude of the star is −58°. I investigated imaging data at other wavelengths (X-ray through radio) that are available for this location, and saw no evidence for any diffuse emission sources in the vicinity of the star, although no H-alpha images that might show a compact nebula are available yet.

Photospheric heavy elements are not expected to be present at 45,000 K, $\log g$ = 8, and the observed interstellar column densities are certainly unusual. Both the photospheric and non-photospheric absorption can be explained if the white dwarf has a close companion from which it is accreting material. Already accreted material could explain the observed photospheric opacity, while material either streaming in to the WD or accumulating in its immediate vicinity could provide the observed H I, He I, and He II columns. Problems with this picture, though, include the lack of apparent red excess in the optical spectrum (3500–5500 Å), or of detectable emission in the optical or the IUE spectrum (SWP 44779) in He I 4471 Å or He II 1640 or 4686 Å, that might be expected from highly ionized material. There was a not-very-convincing hint of emission in the core of Hβ, that would require observation at higher resolution and S/N to confirm, while Hα unfortunately was not observed. Clearly, photometry or spectroscopy in the red is needed, as well as a sequence of observations to look for radial velocity variations, in order to confirm the companion hypothesis.

An alternative possibility is that WD 2321−549 is undergoing a chance encounter with a relatively dense

interstellar cloudlet. High spatial resolution Hα imaging would be desirable for checking for the presence of diffuse material near the star.

Summary. The results of the abundance determinations are tabulated below. This sample, by itself, is too small to make a rigorous determination of the dependency of abundances on effective temperature and gravity. Also, as noted in the text, the photospheric He determinations are not very precise, and can be regarded merely as upper limits. Another complication is the fact that WD 0718-316 is likely to be accreting material from its companion, while WD 2321-549 is suspected to be in an unusual environment, perhaps due to the presence of an as yet undetected companion. Regarding Fe, for which the expected increase of abundances with T_{eff} is demonstrated here, there is a strong differential effect present between WD 1029+537 and WD 2321−549, with the higher Fe abundance in WD 2321−549 perhaps being due to accretion from a companion. The occurrence of Al, seen rather spectacularly in WD 0131-163, is quite rare in hot DA, and probably depends not so much on temperature and gravity as on the particular conditions the progenitor star experienced near the end of the AGB.

TABLE 1

ABUNDANCE DETERMINATIONS

WD Name	Optical T_{eff}	$\log g$	EUV T_{eff}	log(He/H)	log(Al/H)	log(Fe/H)
0131−163	50,000	7.76	47,000	−5.0	−6.7	−6.4
0718−316	55,120	7.92	50,000	−4.6	−	−6.0
1029+537	46,300	7.78	46,000	−6.0	−	−7.4
2321−549	44,960	7.94	45,000	−5.6	−	−6.8

Status. Except for WD 0718-316, which requires further observations for effecting the EUV spectral fits, the analyses are complete, and the results are now being prepared for publication.

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