NEON AND CNO ABUNDANCES FOR EXTREME HELIUM STARS—A NON-LTE ANALYSIS

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ABSTRACT

A non-LTE (NLTE) abundance analysis was carried out for three extreme helium stars (EHCs): BD+10° 2179, BD—9° 4395, and LS IV+6° 002, from their optical spectra with NLTE model atmospheres. NLTE TLUSTY model atmospheres were computed with H, He, C, N, O, and Ne treated in NLTE. Model atmosphere parameters were chosen from consideration of fits to observed He I line profiles and ionization equilibria of C and N ions. The program SYNSPEC was then used to determine the NLTE abundances for Ne as well as H, He, C, N, and O. LTE neon abundances from Ne I lines in the EHCs: LSE 78, V1920 Cyg, HD 124448, and PV Tel, are derived from published models and an estimate of the NLTE correction applied to obtain the NLTE Ne abundance. We show that the derived abundances of these key elements, including Ne, are well matched with semi-quantitative predictions for the EHe resulting from a cold merger (i.e., no nucleosynthesis during the merger) of an He white dwarf with a C–O white dwarf.

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: evolution – stars: fundamental parameters

1. INTRODUCTION

The principal class of hydrogen-deficient supergiant stars comprises three subclasses which in order of increasing but overlapping temperature intervals from coolest to hottest are the H-deficient carbon stars (HdC), the R Coronae Borealis stars (RCB), and the extreme helium stars (EHe). A common supposition is that the three subclasses are related in terms of origin and evolution. The origin of these very rare stars has long been disputed but it now seems likely that the majority are formed through a merger of an He white dwarf (WD) with a C–O star (Iben & Tutukov 1984; Saio & Jeffery 2002). Others may be the result of a final He-shell flash in a post-asymptotic giant branch (post-AGB) star, the so-called final flash (FF) scenario (Webbink 1984; Iben & Tutukov 1984; Saio & Jeffery 2002). Others may be the result of a final He-shell flash in a post-asymptotic giant branch (post-AGB) star, the so-called final flash (FF) scenario (Iben et al. 1983, 1996; Herwig 2001; Blöcker 2001).

Much of the evidence for deciding whether HdC, RCB, or EHe stars come from the DD or FF scenario (or neither) depends on comparison of the observed chemical composition with predictions by the two scenarios. It is in this context that we present in this paper a non-LTE (NLTE) analysis of the neon abundance of a sample of EHe stars where Ne I lines are prominent in optical spectra; neon is detectable in EHe stars, the warmer RCBs but not the HdCs. (The NLTE analyses are extended here to He, C, N, and O lines.)

If reliable Ne abundances can be provided for EHCs and RCBs, neon will join other abundances as clues to the origins and evolution of the H-deficient supergiants. In addition to the obvious importance of C, N, and O elemental abundances, one may now note a variety of other abundance anomalies peculiar to these supergiants including, for example, the presence of lithium in a subset of RCBs and one HdC (Asplund et al. 2000; Rao & Lambert 1996), the large overabundance of fluorine in EHCs and RCBs (Pandey 2006; Pandey et al. 2008), high concentrations of 18O (relative to 16O) in HdCs and cool RCBs (Clayton et al. 2005, 2007; García-Hernández et al. 2009, 2010), extraordinary high Si/Fe and S/Fe ratios in the “minority” RCBs (Rao & Lambert 1996).

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If neon is to provide an effective addition to the list of abundance anomalies, its abundance must be determined reliably and, in this regard, the primary consideration would appear to be an adequate treatment of NLTE effects in the formation of the observable neon lines. Realization that NLTE effects are considerable for optical Ne I lines arose from pioneering calculations by Auer & Mihalas (1973) for normal B-type stars with effective temperatures of around 20,000 K. These authors showed that the Ne abundance derived by accounting for NLTE effects was about a factor of five less than that given by LTE. Not only was this the first result showing major NLTE effects on abundances for hot stars but the NLTE Ne abundance was shown to be in good agreement with that for H I regions as derived from emission lines. The origin of the marked NLTE effects is discussed by Auer & Mihalas. A key ingredient is that the ultraviolet Ne I resonance lines are optically thick—see a concise discussion by Cunha et al. (2006) who report on modern calculations of Ne NLTE effects as applied to B stars in the Orion Association. Given that the ultraviolet resonance lines may be similarly optically thick in atmospheres of EHe stars, it became apparent that addition of neon to the list of referes between DD and FF scenarios would require evaluation of the NLTE effects on the observable neon lines.

In the following sections, we successively describe our optical spectra, the NLTE calculations including a sanity check involving our analysis of normal B stars previously discussed by Cunha et al. (2006) and Morel & Butler (2008), our abundance analyses of seven EHCs, a discussion of the DD scenario with a comparison of semi-quantitative predictions with the observationally based abundances of He, C, O, and Ne as well as remarks on abundances not determinable for EHCs (e.g., Li, 18O, and F). This comparison is followed by remarks on the FF scenario and a few concluding remarks.

2. OBSERVATIONS

High-resolution optical spectra of BD+10° 2179, BD—9° 4395, and V1920 Cyg were obtained on 1998 January 24, 2000 June 16, and 1996 July 25, respectively, at the coudé focus of the
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Figure 1. Spectral region from 6380 to 6405 Å is shown for five EHes with the hottest star at the top and the coolest star at the bottom. The Ne i lines at 6382.99 Å and at 6402.25 Å are marked.

W.J. McDonald Observatory’s Harlan J. Smith 2.7-m telescope with the Robert G. Tull cross-dispersed echelle spectrograph (Tull et al. 1995) at a resolving power of $R = 60,000$ except for BD−9° 4395’s spectrum acquired at $R = 40,000$. These spectra with $R = 60,000$ were previously described by Pandey et al. (2006). Additional spectra of BD−9° 4395 were obtained on 2002 July 18, 22, and 25 at the W. J. McDonald Observatory’s Otto Struve 2.1-m telescope with the Sandiford Cassegrain echelle spectrograph (McCarthy et al. 1993) at a resolving power of $R = 40,000$. The spectrum of LSE 78 was acquired with the Cassegrain echelle spectrograph at CTIO, and the observations are described in Pandey & Reddy (2006). Finally, spectra at $R = 30,000$ of the two southern EHes—PV Tel and HD 124448—are from the Vainu Bappu Observatory and the fiber-fed cross-dispersed echelle spectrometer (Rao et al. 2004, 2005) at the 2.34-m telescope. The Image Reduction and Analysis Facility (IRAF) software package was used to reduce all spectra.

Sample wavelength intervals in Figures 1 and 2 include one or two of the Ne i lines with the EHes ordered from top to bottom in order of decreasing effective temperature. All spectra are aligned to the rest wavelengths of well-known lines. Inspection of the figures shows that the line profiles are not always symmetric. Asymmetries obviously present in the case of LSE 78 and V1920 Cyg are most probably due to atmospheric pulsations. In the case of V1920 Cyg, another observation on 1996 July 26, one day following the spectrum illustrated in Figures 1 and 2, showed symmetric line profiles with no appreciable change in the equivalent widths of lines. The equivalent width change translates to an abundance change of less than 0.1 dex. In the case of BD−9° 4395, emission components may appear and disappear. Variable photospheric spectra for EHes are common (Jeffery 2008) with V1920 Cyg representative of the variability and BD−9° 4395 as an extreme example. Nonetheless, we assume that models constructed with classical assumptions (plane parallel layers in hydrostatic equilibrium) are adequate for our purpose.

3. NLTE ATMOSPHERES AND ABUNDANCES

Our calculations use codes developed by Hubeny and colleagues: the program TLUSTY for calculating LTE and NLTE model atmospheres (Hubeny 1988; Hubeny & Lanz 1995) and the spectrum synthesis code SYNSPEC (Hubeny et al. 1994). In exercising these codes, we adopt the atomic data and model atoms provided on the TLUSTY homepage4 (Lanz & Hubeny 2007, 2003).

The suite of codes was imported to Bangalore and run by one of us (GP) on a local computer. Before proceeding to construct and apply H-deficient model atmospheres, our imported codes were tested for normal B-type stars. In particular, we computed an NLTE model atmosphere for HD 35299, a normal B star in the Orion sample for which Cunha et al. (2006) derived NLTE Ne abundances. The NLTE TLUSTY model was computed for the stellar parameters adopted by Cunha et al.: $T_{\text{eff}} = 24,000$ K, $\log g = 4.25$ cgs, and a microturbulence of 2 km s$^{-1}$ and solar abundances. The $gf$-values for the Ne i lines are taken from Seaton (1998) who showed that Opacity Project theoretical $gf$-values are in very good agreement not only with theoretical calculations of comparable sophistication but also with experimental determinations. Then, the NLTE Ne abundances were computed using the TLUSTY model by matching the observed equivalent width of Ne i lines with NLTE predictions from running the SYNSPEC code. Observed equivalent widths were kindly provided by Dr. Katia Cunha (2010, private communication) for the eight lines measured by them. Our NLTE Ne abundance for the eight lines is log(Ne) = 8.20 ± 0.08 in good agreement with the value of 8.18 given by Cunha et al. (2006). This agreement over NLTE Ne abundances is taken as evidence that our implementation of the TLUSTY-related codes was successful.

3 The IRAF software is distributed by the National Optical Astronomy Observatories under contract with the National Science Foundation.

4 http://nova.astro.umd.edu/index.html
As a second check, we analyzed Ne i and Ne ii lines in β CMa. Morel & Butler (2008) analyzed seven Ne i and four Ne ii lines in this star. Morel & Butler compute the NLTE Ne abundances for an LTE Kurucz model with the parameters $T_{\text{eff}} = 24,000$ K, log $g = 3.5$ cgs and a microturbulence of 14 km s$^{-1}$. We computed an NLTE TLUSTY model for these stellar parameters. The $g'f$-values and the measured equivalent widths of the Ne i and the Ne ii lines were taken from Morel & Butler. NLTE Ne abundances were computed using the TLUSTY atmosphere and model atoms by matching the measured width of Ne i and Ne ii lines with NLTE predictions from the SYNSPEC code. Our NLTE Ne abundance for the seven Ne i lines is log(Ne) = 7.89 ± 0.09 in agreement with the value of 7.89 ± 0.04 given by Morel & Butler. For the three Ne ii lines, our NLTE Ne abundance is log(Ne) = 8.16 ± 0.16, where the value of 7.89 ± 0.06 is given by Morel & Butler. Note that one of the four Ne ii lines returns a higher abundance and was not included in calculating our mean abundance. The different Ne abundances from Ne i lines are noted and may arise from the use of different models (TLUSTY NLTE versus Kurucz LTE) and the use of different model Ne atoms. These checks on published NLTE Ne abundances are taken as evidence that our implementation of the TLUSTY-related codes was successful.

A small grid of NLTE TLUSTY model atmospheres for EHe stars was computed for $T_{\text{eff}}$ from 15,000 K to 31,000 K and surface gravities log $g = 2.35$ to 4.3. The abundances adopted for the grid were representative of the LTE abundances given by Pandey et al. (2006). In particular, the C/He ratio was assumed to be 1%. Sample models for H/He = 0.1 and 0.0001 showed that the derived abundances of neon and other elements are insensitive to the H abundance in this range.

4. NLTE ABUNDANCE ANALYSES

4.1. BD+10° 2179

An extensive LTE abundance analysis of BD+10° 2179 was reported by Pandey et al. (2006) from optical and ultraviolet spectra. Abundances were obtained for 18 elements from H to Zn but neon was not included. Here, we present an NLTE model atmosphere redetermination of the He, C, N, and O abundances and the first determination of the Ne abundance. The star’s atmospheric parameters are reassessed using NLTE atmospheres and NLTE line formation for He, C, N, O, and Ne lines.

Optical lines of He i, C i-iii, N ii, O ii, and Ne i are used. Details about these lines except for Ne i are taken from Table 2 of Pandey et al. (2006). Details include a line’s $g'f$-value and the reference to the source of that value, its lower excitation potential ($\chi$), and information on the line’s Stark and radiative damping constants. Values from 2006 are adopted here in full. For Ne, which is not in the 2006 table, we adopt the $g'f$-values from Seaton (1998), as noted above. Table 1 of this paper lists the chosen lines of C, N, O, and Ne where the equivalent widths of Ne i lines were measured off the spectrum used for the 2006 analysis.

Atmospheric parameters are obtained by the procedures used for the 2006 LTE analysis but using NLTE TLUSTY model atmospheres and NLTE line formation using the TLUSTY model atoms. The microturbulence is provided from the usual requirement that the abundance from lines of a given species be independent of a line’s equivalent width: we use the C ii lines. The effective temperature and surface gravity are found from intersecting loci in the ($T_{\text{eff}}$, log g) plane with loci provided by
fits to He I line profiles, and the ionization equilibria among C\textsuperscript{+}, C\textsuperscript{2+}, and C\textsuperscript{3+}. The LTE analysis is repeated but this time with TLUSTY LTE model atmospheres instead of models from the code STERNE (Jeffery et al. 2001).

Figure 3 illustrates the determination of the microturbulence from C\text{n} lines. A value of 7.5 km s\textsuperscript{-1} is adopted. Although this value is for a particular model (T\text{eff} = 17,000 K, log g = 2.5), the result is insensitive to the model choice.

Sample theoretical NLTE line profiles and the observed profile of the He I 4471Å line are shown in Figure 4 for a...
model with an effective temperature of 16,375 K and a surface gravity of 2.45 g cm$^{-2}$ and with microturbulence and rotational broadening included (see Pandey et al. 2006). The best-fitting theoretical profile (log $g = 2.45$) provides one point on the $T_{\text{eff}} - \log g$ locus. The He I lines at 4009, 4026, and 4387 Å lines were similarly analyzed. The helium model atoms and line broadening coefficients are from TLUSTY. Using the TLUSTY grid of model atmospheres, the loci were mapped out. The four loci are shown in Figure 5 and are almost coincident.

Loci representing ionization equilibria are provided from the requirements that (C i, C ii), (C ii, C iii), and (C i, C iii) provide the same C abundance.

Figure 5 shows the several loci. Their intersection suggests that the best NLTE model has $T_{\text{eff}} = 16,375 \pm 250$ K and $\log g = 2.45 \pm 0.2$. The best LTE TLUSTY model with the LTE line analysis gives a best model with $T_{\text{eff}} = 17,000$ K and $\log g = 2.60$. This LTE model differs a little from that adopted in the 2006 LTE analysis of the optical lines where loci representing ionization equilibria for (Si ii, Si iii), (S ii, S iii), and (Fe ii, Fe iii) were also considered. The 2006 LTE analysis gave a model with $T_{\text{eff}} = 16,400 \pm 500$ K and $\log g = 2.35 \pm 0.2$ cgs.

Abundances for C, N, O, and Ne are given in Table 1. Mean abundances and their standard deviations are listed for both the NLTE and LTE TLUSTY analyses. Abundances are given as log $\epsilon(X)$ and normalized to log $\Sigma_{\mu X} \epsilon(X) = 12.15$, where $\mu X$ is the atomic weight of element X. The NLTE abundance errors arising from uncertainties in the atmospheric parameters are estimated by considering changes of $\Delta T = \pm 250$ K, $\Delta \log g = \pm 0.2$ cgs, and $\Delta \xi = \pm 1$ km s$^{-1}$. The rms errors in the abundances from C i, C ii, C iii, N ii, O ii, and Ne i are 0.22, 0.03, 0.18, 0.08, 0.12, and 0.10, respectively, with a negligible contribution from the microturbulence. The C/He ratio is 0.6% but a ratio of 1% was assumed in construction of the NLTE model. Recomputation of the model for C/He = 0.6% results in negligible changes to the abundances in Table 1. Abundance uncertainties are similar for the LTE analysis.

With the exception of H I, C III, and Ne i lines, the introduction of NLTE for the model atmosphere and line analysis has a minor effect on the derived abundances. The mean abundance differences in dex in the sense (LTE–NLTE) are 0.07 (C i), 0.04 (C ii), 0.07 (N ii), −0.26 (O ii), and 0.81 (Ne i).

The H I lines show similar NLTE effects (LTE–NLTE) across the lines. The difference in abundance (LTE–NLTE) is about 0.33 dex. Note that the NLTE/LTE abundance from H $\beta$ down the sequence decreases by about 0.3 dex.

The C iii lines represent a fascinating issue in line formation. In the LTE analysis, the 4186.9 Å 40 eV line gives an abundance that is 0.6 dex greater than that from the 4650 Å triplet which provides a more plausible abundance. In NLTE, however, the abundance discrepancy is reversed: the 4186 Å line gives a plausible abundance that is 0.7 dex less than that from the triplet. Nieva & Przybilla (2008) state that the sense of this reversal is plausible abundance that is 0.7 dex less than that from the 4471 Å triplet.

In the LTE analysis, the 4186.9 Å 40 eV line gives an abundance that is 0.6 dex greater than that from the 4650 Å triplet which provides a more plausible abundance. In NLTE, however, the abundance discrepancy is reversed: the 4186 Å line gives a plausible abundance that is 0.7 dex less than that from the triplet. Nieva & Przybilla (2008) state that the sense of this reversal is expected according to their calculations for normal B stars. The magnitude of the NLTE effects and the failure of our calculations to provide consistent NLTE abundances suggest that the C iii be given lower weight in the analysis.

There are small and unimportant differences between the 2006 LTE abundances and those in Table 1. Such differences arise from a combination of factors: the model atmosphere codes are different, and the derived atmospheric parameters are different. The differences in dex in the sense (TLUSTY–STERNE) are 0.12 (C i), 0.04 (C ii), 0.14 (N ii), 0.18 (O ii), and 0.04 (Ne i).

4.2. BD$−9^\circ$ 4395

This star’s spectrum contains absorption lines with variable profiles and variable emission lines mainly from He i, C ii, and Si ii transitions. These emission lines have been attributed to a shell or extended atmosphere. An extensive library of optical and ultraviolet spectra of BD$−9^\circ$ 4395 was discussed by Jeffery & Heber (1992) who undertook an abundance analysis using absorption lines drawn from a mean optical spectrum. Their LTE analysis led to the atmospheric parameters: $T_{\text{eff}} = 22,700 \pm$
1200 K, log $g = 2.55 \pm 0.10$, and $\xi = 20 \pm 5$ km s$^{-1}$. In addition to the line broadening from the high microturbulence and line profile variations, the line profiles suggested that the star may be rotating at about 40 km s$^{-1}$.

Our high-resolution optical spectra confirm the characteristics described by Jeffery & Heber. We measure equivalent widths off our spectra. Most of the measured equivalent widths are from the 2000 June 16 spectrum. These measured equivalent widths are in fair agreement with those measured off the spectra obtained on other dates.

Our abundance analysis follows the method discussed in the previous section. Details about the majority of the lines are taken from Pandey et al. (2006) with information on other lines of C $\text{ii}$-$\text{iii}$, N $\text{ii}$-$\text{iii}$, O $\text{ii}$, and Ne $\text{i}$ from the NIST database (http://physics.nist.gov/PhysRefData/ASD/lines_form.html).

The source of $gf$-values for Ne $\text{i}$ lines is as given in Section 4.1. The O $\text{ii}$ lines confirm the high microturbulence with our NLTE analyses giving $\xi = 17.5 \pm 5$ km s$^{-1}$. This value is not sensibly different from the 20 km s$^{-1}$ obtained by Jeffery & Heber. The microturbulence is somewhat higher than that found for most other EHe stars and indicates supersonic atmospheric motions.

The He $\text{i}$ lines are moderately sensitive to gravity. As clearly noted by Jeffery & Heber, emission affects the He $\text{i}$ profiles to differing degrees. For example, the 5876 Å line is in emission. Observed profiles of the 4143 Å and 4387 Å lines are shown in Figure 6 with predicted NLTE profiles for an NLTE atmosphere of $T_{\text{eff}} = 24,300$ K and three different surface gravities. The chosen lines have been convolved with a (Gaussian) profile with an FWHM of 40 km s$^{-1}$ to represent the projected rotational velocity suggested by Jeffery & Heber. The chosen lines are those least affected by emission (Jeffery & Heber 1992). There may be indications that weak emission contaminates the red wing and, perhaps, the line core. LTE profiles shown by Jeffery & Heber predict less deep cores than the observed profiles; the NLTE profiles reproduce the line cores more closely than LTE profiles.

Ionization equilibria C $\text{ii}$/$\text{iii}$ and N $\text{ii}$/$\text{iii}$ provide two loci in the ($T_{\text{eff}}$, log $g$) plane (Figure 7). Inspection of this figure suggests a solution with $T_{\text{eff}} = 24,300 \pm 700$ K and log $g = 2.65 \pm 0.20$ cgs, where we give equal weight to the C and N ionization equilibria. This effective temperature is 1600 K hotter than that estimated by Jeffery & Heber. The difference is partly accounted for by the fact that the earlier (LTE) analysis included loci representing ionization equilibrium for Si $\text{ii}$/$\text{si}$ and S $\text{ii}$/$\text{si}$ and these loci of similar slope to the C and N loci fell about 1000 K to lower temperatures. Final abundances for our adopted model are given in Table 2. Mean abundances and their standard deviations are given. The rms uncertainties arising from the estimated uncertainties of the atmospheric parameters are 0.05 (C $\text{ii}$), 0.16 (C $\text{iii}$), 0.08 (N $\text{ii}$), 0.20 (N $\text{iii}$), 0.02 (O $\text{ii}$), 0.08 (Ne $\text{i}$), and 0.16 (Ne $\text{ii}$).

The LTE abundances in Table 2 were computed from a TLUSTY LTE model atmosphere with model parameters ($T_{\text{eff}}$, log $g$, $\xi$) = (24,800, 2.85, 23.0). Line-by-line LTE abundances including the mean abundance and the line-to-line scatter are given in Table 2. These LTE abundances are quite similar to those reported by Jeffery & Heber from a different line list with different atomic data, a different model chosen from a different grid of LTE atmospheres: the differences in dex in the sense (TLUSTY–JH) are 0.22 (C $\text{ii}$), $-0.35$ (C $\text{iii}$), 0.03 (N $\text{ii}$), $-0.01$ (N $\text{iii}$), 0.05 (O $\text{ii}$), 0.02 (Ne $\text{i}$), and $-0.13$ (Ne $\text{ii}$).

Corrections for NLTE effects in the sense (LTE–NLTE) are $-0.34$ (H $\text{i}$), 0.11 (C $\text{ii}$), $-0.07$ (C $\text{iii}$), 0.32 (N $\text{ii}$), 0.37 N $\text{iii}$, $-0.09$ (O $\text{ii}$), 0.60 (Ne $\text{i}$), and $-0.01$ (Ne $\text{ii}$) in dex. In the case of Ne, the two stages of ionization treated in NLTE give consistent abundances but do not in LTE. Also noteworthy is that the C $\text{iii}$ lines treated in NLTE give fairly consistent results but this was not the case for BD+10$^\circ$ 2179.

The NLTE correction (LTE–NLTE) for H $\text{i}$ is about $-0.34$ dex, a reversal in the NLTE correction that was provided by the analysis of BD+10$^\circ$ 2179. It appears that the NLTE
correction (LTE–NLTE) is mainly a function of effective temperature as these stars are of similar surface gravity.

4.3. LSE 78, V1920 Cyg, HD 124448, and PV Tel

Neon abundances for this quartet are estimated by applying corrections to the LTE Ne abundances from Ne I lines based on the NLTE calculations computed for model atmosphere grids computed for BD+10° 2179 and BD−9° 4395. NLTE Ne abundances for LSE 78 and V1920 Cyg are estimated by interpolation in the grids of computed NLTE corrections but for HD 124448 and PV Tel an extrapolation is required. Neon LTE abundances are computed with the LTE models and the Armagh LTE code SPECTRUM (Jeffery & Heber 1992; Jeffery et al. 2001). In Tables 3–6, we give line-by-line LTE neon abundances including the mean abundance, and the line-to-line scatter. The estimated NLTE corrections to the LTE neon abundances of LSE 78, V1920 Cyg, HD 124448, and PV Tel are 0.73, 0.8, 0.8, and 0.88, respectively.

For LSE 78 and V1920 Cyg, the LTE Ne abundance is independent of an Ne I’s line equivalent width when the microturbulence from the 2006 paper is adopted. For HD 124448, two weak Ne I lines provide the abundance and the adopted value of the microturbulence is unimportant. In the case of PV Tel, the only Ne I lines available from our spectra are strong and the microturbulence from the 2006 paper gives an Ne abundance that is a function of a line’s equivalent width, a trend that may be removed by increasing the adopted value of the microturbulence from the 15 ± 4 km s$^{-1}$ found in 2006 from optical N II and S II lines to 25 km s$^{-1}$ and then the LTE Ne abundance is 8.53 ± 0.08 (Table 6). An estimated NLTE correction of 0.9 dex gives the NLTE Ne abundance of 7.6.

4.4. LS IV +6° 002

Abundance analysis of LS IV +6° 002 was done by Jeffery (1998) using absorption line equivalent widths drawn from the optical spectrum. This LTE analysis led to the atmospheric parameters: $T_{\text{eff}} = 31,800 ± 800$ K, log $g = 4.05 ± 0.10$, and $\xi = 9 ± 1$ km s$^{-1}$. This is the hottest star in our sample with Ne II but not Ne I lines in its spectrum. Here the Jeffery (1998) equivalent widths have been reanalyzed using our gf-values from Pandey et al. (2006) and the NIST database. Two sets of model atmospheres are considered: NLTE/TLUSTY and LTE/TLUSTY. Analyses of the C II, N II, and O II lines confirm the microturbulence obtained by Jeffery.
with our NLTE and LTE analyses giving $\xi$ about 9 km s$^{-1}$. Ionization equilibria C II/C III, and N II/N III provide two loci in the ($T_{\text{eff}}$, $\log g$) plane (Figure 8). The He I 4471 Å line that is moderately insensitive to gravity provides another locus.

Inspection of Figure 8, produced by adopting NLTE/TLUSTY models, suggests a solution with $T_{\text{eff}} = 30,000 \pm 800$ K and $\log g = 4.10 \pm 0.15$ cgs. The He I 4686 Å line suggests an effective temperature about 1000–2000 K hotter. Here we give more weight to the C and N ionization equilibria, and the locus provided by the He I 4471 Å line. This effective temperature is 2000 K cooler than that estimated by Jeffery. Final abundances for our adopted model are given in Table 7. Mean abundances and their standard deviations are given. Corrections for NLTE effects in the sense (LTE–NLTE) in dex are as follows: $-0.33$ (H i), $0.13$ (C ii), $-0.36$ (C iii), $-0.30$ (N ii), $0.25$ N iii, $0.14$ (O ii), and $-0.02$ (Ne ii).

The LTE abundances in Table 7 were computed from a TLUSTY LTE model atmosphere. The best TLUSTY LTE model parameters are ($T_{\text{eff}}$, $\log g$, $\xi$) = (32,000, 4.20, 9.0). Note that no weight is given to the C ionization equilibrium suspecting departures from LTE. Line by line LTE abundances including the mean abundance and the line-to-line scatter are given in Table 7. These LTE abundances are quite similar to those reported by Jeffery from a different line list with different atomic data, a different model chosen from a different grid of LTE atmospheres.

Our NLTE Ne abundance in Table 7 is based on Kurucz $gf$-values for the Ne II lines. The NLTE corrections for these Ne II lines are small, being typically 0.02 dex in the sense that the NLTE abundance is higher than the LTE value. Jeffery’s 1998 LTE Ne abundance is based on $gf$-values that are systematically smaller than our adopted values with a mean difference of 0.7 dex. Thus, our LTE Ne abundance is 0.7 dex lower than Jeffery’s value of 9.33.

### Table 7

| Line          | $\chi$ (eV) | $\log gf$ | $W_i$ (mA) | NLTE$^b$ | LTE$^b$ |
|---------------|-------------|------------|------------|---------|---------|
| H i 4340.462 | 10.199      | $-0.447$   | 20         | 8.15    | 7.95    |
| H i 4861.323 | 10.199      | $-0.020$   | 11         | 7.80    | 7.34    |
| Mean…        | …           | …          | …          | …       | 7.98 ± 0.25 | 7.65 ± 0.43 |
| C ii 4467.901| 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| C ii 4467.953| 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| Mean…        | …           | …          | …          | …       | 8.78 ± 0.17 | 8.96 ± 0.17 |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| Mean…        | …           | …          | …          | …       | 8.78 ± 0.17 | 8.96 ± 0.17 |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| Mean…        | …           | …          | …          | …       | 8.78 ± 0.17 | 8.96 ± 0.17 |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| N i 4652.194 | 18.046      | +0.563     | 92         | 8.78    | 8.78    |
| Mean…        | …           | …          | …          | …       | 8.78 ± 0.17 | 8.96 ± 0.17 |

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**Figure 8.** $T_{\text{eff}}$ vs. $\log g$ plane for LS IV+6' 002. Loci satisfying ionization equilibria are plotted—see keys on the figure. The locus satisfying the optical He I 4471 Å line profile is shown by the solid line. The cross shows the adopted NLTE model atmosphere parameters.
Knowledge of the chemical composition of EHe stars has become more complete in recent years. Neon adds a new constraint on proposed origins for these H-deficient stars. In order to exploit this probe fully, the Ne abundance must be considered with the reported abundances of other elements in (X) at [Fe/H] = −0.004% (Jeffery et al. 1999) and HD 144941 with [C/Fe] = 0.002% (Harrison & Jeffery 1997). One supposes that the scenario accounting for the stars in Table 8 and others with a similar C/Fe ratio will need major revision to account for V652 Her and HD 144941.

Nitrogen: the N abundance is generally equal to the sum of the initial C, N, and O abundances as inferred from an EHe’s Fe abundance and standard relations for C, N, and O dependences on initial Fe abundance for normal (i.e., H-normal) dwarfs. This is shown in Figure 9.

Oxygen: oxygen abundances show a large spread: for example, [O/H] at [Fe/H] ~ 0 runs from about +1 to −1 and is, therefore, generally at odds with a simple extrapolation from the N abundances that O should be greatly depleted (Figure 10). The spread persists to lower [Fe/H] with EHe stars with [O/H] ≳ 0 found at [Fe/H] ≃ −2.

Neon: our NLTE analysis shows that Ne abundances are approximately independent of a star’s Fe abundance (Figure 11). The spread in Ne abundance at a given Fe/H is about 1 dex. Qualitatively, Ne is similar to O with respect to spread and Fe-independence. Neon is not tightly correlated with the O abundance but the O-richest stars include two of the most Ne-rich and, perhaps significantly, are stars with a strong s-process enrichment (V1920 Cyg and LSE 78). This is shown in Figure 12.

Mg to Ni: abundances of these metals (relative to Fe) follow the relations determined from analyses of Galactic disk and halo stars. In particular, the so-called α-elements (Mg, Si, S, Ca, and Ti) in EHe stars fall quite well on the established [α/Fe] versus [Fe/H] trends.

Iron: EHe stars span the metallicity range [Fe/H] = −0.3 to −2.0.

s-process: several EHe stars appear enriched in s-process products. V1920 Cyg and LSE 78, for example, show 50-fold overabundances of the lighter s-process products Y and Zr.

5. INTERPRETING THE NEON AND CNO ABUNDANCES

5.1. The Context

Knowledge of the chemical composition of EHe stars has become more complete in recent years. Neon adds a new constraint on proposed origins for these H-deficient stars. In order to exploit this probe fully, the Ne abundance must be considered with the reported abundances of other elements in (X) at [Fe/H] = −0.004% (Jeffery et al. 1999) and HD 144941 with [C/Fe] = 0.002% (Harrison & Jeffery 1997). One supposes that the scenario accounting for the stars in Table 8 and others with a similar C/Fe ratio will need major revision to account for V652 Her and HD 144941.

Notes.

\( \alpha(T_{\text{eff}}, \log g, \xi) = (30000, 4.10, 9.0) \)

\( \beta(T_{\text{eff}}, \log g, \xi) = (32000, 4.20, 9.0) \)

Jeffery (1998).

Kennicutt g-f value.

Wiese et al. (1996).
Figure 9. N vs. Fe. Our sample of seven EHe stars is represented by open circles. Five cool EHe stars are represented by open squares (Pandey et al. 2001, 2006; Pandey & Reddy 2006). The results taken from the literature for EHe stars with C/He of about 1% (Drilling et al. 1998; Jeffery et al. 1998) are represented by open triangles. The two EHe stars of much lower C/He—V652 Her and HD 144941—are shown by filled triangles (Jeffery & Harrison 1997; Harrison & Jeffery 1997; Jeffery et al. 1999). DY Cen (Jeffery & Heber 1993) is represented by a filled circle. The circled dot represents the Sun. N = Fe is denoted by the solid line. The dotted line represents conversion of the initial sum of C and N to N. The dashed line represents the locus of the sum of initial C, N, and O converted to N.

Other intriguing abundance anomalies are provided from analyses of RCB and HdB stars which would seem probable relatives of the EHe stars. These anomalies which are undetectable in the EHe stars because the spectroscopic signatures vanish at the higher temperatures include:

$^{18}$O: a spectacular anomaly is the extraordinarily high $^{18}$O abundance seen in cool HdB and RCBs: $^{18}$O/$^{16}$O $\simeq$ 0.5 in extreme cases (Clayton et al. 2005, 2007; García-Hernández et al. 2009, 2010). Of course, the O isotopic abundance ratio requiring detection of the CO molecule is not measurable for either warm RCBs or the EHe stars.

Lithium: similarly, measurement of the Li abundance demands a cool atmosphere for detection of the Li i resonance doublet at 6707 Å. Lithium is seen in one of the five HdB and in four of approximately 30 known RCBs.

Fluorine: a remarkable overabundance of F was discovered by Pandey (2006) for the cooler EHe stars and Pandey et al. (2008) for the warmer RCBs. The F i lines vanish at the higher temperatures of the hot EHe stars discussed here. The F abundances extend to 300 times the solar abundance and the maximum value appears to be independent of a star’s C abundance. There is a star-to-star spread in F abundances at a given [Fe/H].

Minority RCBs: a few RCBs show highly anomalous [Si/Fe] and [S/Fe] ratios. Such stars were called minority RCBs by Lambert & Rao (1994) with examples including the RCB V CrA with [Si/Fe] $\simeq$ [S/Fe] $\simeq$ +2 where $\simeq$ +0.3 is expected for normal H-rich stars of the same metallicity (Rao & Lambert 2008). None of the analyzed EHe stars has this minority characteristic but a larger sample may uncover an example. The hot RCB DY Cen, a star known for its reluctance to decline from maximum light, is a minority star and might almost be called an EHe star.
C–O WD’s He shell and again the effects of gravitational settling are negated. Our recipe assumes that the He WD is thoroughly mixed with the thin He shell of the C–O WD. Implications of mergers involving H-rich layers are explored briefly in an attempt to account for the Li-rich RCB stars. To predict the merged star’s composition we need the masses and compositions of the ingredients.

5.2.2. One Ingredient—The He WD

In principle, an He WD is created from low mass main sequence stars but this requires a time exceeding the age of the Galaxy. Thus, the He WD in a DD scenario must be a product of a binary system experiencing mass loss and probably mass transfer. Iben et al. (1997) predict the mass distribution of He and C–O WDs expected to result from evolution of close binaries: \( M(\text{He}) \simeq 0.3 \pm 0.1 \, M_\odot \) and \( M(\text{C–O}) \simeq 0.6 \pm 0.1 \, M_\odot \). Such an He WD’s composition is dominated by He and N: the mass fraction \( \mu(\text{He}) \) of He is essentially unity and, thanks to H-burning by the CNO cycles, the N abundance is the sum of the initial C, N, and O abundances, say \( \mu(\text{CNO})_0 \) where 0 denotes that the initial C, N, and O abundances will be dependent on the initial metallicity (here inferred from the Fe abundance). Mass fractions of C and O in the He WD may be taken to be zero. Heavier elements will have their initial mass fractions. Thus, the masses of helium and nitrogen contributed to the merged star assuming a conservative cold merger are essentially \( M(\text{He}) \) and \( \mu(\text{CNO})_0 M(\text{He}) \), respectively.

5.2.3. Another Ingredient—The He Shell of the C–O WD

For the He shell of the C–O WD, estimates of the mass and composition of the He shell should be obtained from calculations of binary star evolution that result in appropriate He and C–O WD pairs, but understandably such calculations appear not to have been reported. Therefore, we take estimates from calculations for the inner regions of single stars in their AGB phase prior to loss of their H-rich envelopes. In such cases, the mass of the He shell is approximately \( 0.02 \, M_\odot \) for 1–3 \( M_\odot \) stars but decreases to 0.002 \( M_\odot \) for the more massive stars. We denote this mass by \( M(\text{C–O:He}) \).

Early calculations showed that the He shell was primarily comprised of \( ^4\text{He} \) and \( ^{12}\text{C} \) with mass fractions of about 0.75 and 0.20, respectively, with \( ^{16}\text{O} \) having a mass fraction of only about 0.01 (Schönberner 1979). We make use of calculations by Karakas (2010) (and A. I. Karakas 2010, private communication) for stars with masses of 1–6 \( M_\odot \) and with initial compositions \( Z = 0.0001–0.02 \). Adopted compositions are the average of the He shell’s composition just prior to third dredge-up and at the point at which the star leaves the AGB. Mass fractions of \( ^4\text{He} \), \( ^{12}\text{C} \), and \( ^{16}\text{O} \) are consistent with Schönberner’s estimates. In Karakas et al.’s calculations (A. I. Karakas 2010, private communication, and others like Schönberner 1979), the He mass fraction \( \mu(\text{He})_{\text{C–O:He}} \) is about 0.75, almost independent of mass and composition. The \( ^{12}\text{C} \) mass fraction \( \mu(\text{C})_{\text{C–O:He}} \simeq 0.20 \), again with little dependence on mass and composition. \( ^{14}\text{N} \) is effectively cleansed from the region and we take its mass fraction to be zero. The \( ^{16}\text{O} \) mass fraction is \( \mu(\text{O})_{\text{C–O:He}} \simeq 0.005 \).

Of particular interest to attempts to match the EHe composition is that the He shell has enhanced \( ^{22}\text{Ne} \) and \( ^{19}\text{F} \) abundances. Mass fractions of these two nuclides are dependent on the mass of the initial star but are not particularly sensitive to the initial metal mass fraction \( Z \). The \( ^{22}\text{Ne} \) is synthesized from \( ^{14}\text{N} \) by \( \alpha \)-capture, first to \( ^{18}\text{O} \) and then to \( ^{22}\text{Ne} \): its abundance peaks in stars of about 3 \( M_\odot \) reaching a mass fraction of about 0.05,

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5 Here, the He WD has an He-core and is to be distinguished from a DB WD, a star with an He atmosphere but a C–O core.
a value not greatly dependent on the initial metallicity of the star. The $^{22}\text{Ne}$ mass fraction decreases to lower initial stellar masses by a factor that is metallicity dependent: at $Z = 0.008$, the mass fraction for a $1 M_\odot$ star is a factor of six below that for a $3 M_\odot$ star. At higher masses than $3 M_\odot$, $^{22}\text{Ne}$ is destroyed by $\alpha$-particles and converted to $^{25}\text{Mg}$ and $^{26}\text{Mg}$.

Synthesis of $^{19}\text{F}$ occurs from $^{15}\text{N}$ by $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ in competition with $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ with $^{15}\text{N}$ produced by either $^{14}\text{N}(n, p)^{14}\text{C}(\alpha, \gamma)^{18}\text{O}(\alpha, \alpha')^4\text{He}$ or $^{14}\text{N}(\alpha, \gamma)^{18}\text{O}(\beta^+)^8\text{O}(\alpha, \alpha')^{12}\text{C}$ with neutrons from $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and protons from $^{14}\text{N}(n, p)^{14}\text{C}$. The $^{19}\text{F}$ mass fraction is a maximum for $M \simeq 3 M_\odot$ decreasing by about factors of 20–30 for 1 $M_\odot$ and 10 for 6 $M_\odot$. At maximum, the mass fraction $\mu(\text{F})_{\text{C–O:He}} \simeq 1 \times 10^{-4}$.

Other series of calculations for AGB stars introduce convective overshoot at the base of the He-burning thermal pulse in the He shell.6 Overshoot necessarily brings more $^{16}\text{O}$ and ($^{12}\text{C}$) into the shell from the top of the C–O core. Various implementations of convective overshoot have been reported in the literature: for example, Herwig (2000) (see also Herwig 2006) reports for a star of initial mass $3 M_\odot$ that the He shell at the last thermal pulse has mass fractions of 0.41 and 0.18 for $^{12}\text{C}$ and $^{16}\text{O}$, respectively, showing an order of magnitude increase in the $^{16}\text{O}$ mass fraction from the calculation without this convective overshoot. One may anticipate the possibility that $O$ abundances in EHe stars may offer an indirect test of calculations with and without convective overshoot extending into the C–O core.

5.2.4. Mixing the Ingredients

With estimates of the compositions of the two principal ingredients, we may predict the outcomes of a cold merger. As noted above, we may set $H$ aside because its abundance in the C–O WD is contributed by the He WD which also is the dominant supplier of a reference element such as Fe. These circumstances explain quite naturally why the observed $N$ abundance in stars of different Fe abundance is equal to the sum of the initial C, N, and O abundances.

The oxygen abundance: the O abundance is given by

$$O_{\text{He}} \simeq \frac{A(\text{He})}{A(\text{O})} \frac{\mu(\text{O})_{\text{C–O:He}} M(\text{C–O : He})}{M(\text{He})},$$

where $A(X)$ denotes the atomic weight of $X$.

$$\frac{C}{\text{He}} \simeq \frac{A(\text{He})}{A(\text{C})} \frac{\mu(\text{C})_{\text{C–O:He}} M(\text{C–O : He})}{M(\text{He})},$$

where $\mu(X)$ denotes the atomic mass of $X$. With $\mu(\text{C})_{\text{C–O:He}} \simeq 0.2$, $M(\text{C–O : He}) \simeq 0.02 M_\odot$, and $M(\text{He}) \simeq 0.3 M_\odot$, $C/\text{He} \simeq 0.4%$. Since the observed range of the $C/\text{He}$ ratio is from 0.3% to 1.0%, our prediction accounts well for the lower end of the observed range. It is possible to account for the upper end with not implausibly different choices for the three variables. If additional $^{13}\text{C}$ is needed, it may be provided by the third ingredient, the “surface” layers of the C–O WD where the $^{13}\text{C}$ mass fraction may approach 0.5–0.8. For example, an additional contribution of 0.01 $M_\odot$ with a $^{13}\text{C}$ mass fraction of 0.5 raises the $C/\text{He}$ to 1% after the merger.

Although not present in our sample of EHe stars for which we have derived the Ne abundance, two EHe stars—V652 Her and HD 144941—as noted above have lower C/He ratios by two orders of magnitude: $C/\text{He} \simeq 0.003%$. An interpretation is that these stars result from a DD scenario involving a pair of He WDs. An alternative possibility based on the above equation

6 This episode of convective overshoot is to be distinguished from convective overshoot at the base of the H-rich convective envelope into the top of the He shell of an AGB star. This affects operation of the s-process in the He shell between thermal pulses and also the composition of the surface layers—see Karakas et al. (2010) for a discussion.
The $^{18}$O/$^{16}$O ratio is higher and the $^{18}$O abundance is lower in most of the RCBs where CO lines are detectable; García-Hernández et al. (2010) speculate that a late dredge-up in an Hdc star is responsible for these differences between Hdc and RCB stars. These high $^{18}$O abundances cannot be explained by the two or even the three ingredient recipe describing the DD scenario as a cold merger. One may wonder if the C–O WD’s He shell has a composition that is not a complete replica of an He shell of a single star, the model we have adopted for these calculations. Perhaps the synthesis of $^{22}$Ne from $^{14}$N is incomplete and some $^{18}$O remains. But one wonders if this suspicion may be reconciled with the fact that the maximum $^{18}$O abundances for the Hdc stars ($\log \epsilon(\,^{18}$O$) \approx 8.6$) are greater than the Ne abundances ($\log \epsilon(\,^{22}$Ne$) \approx 8.5$) in the EHe stars. Is such fine tuning possible?

Clayton et al. (2005) considered $^{16}$O synthesis to occur by nuclear processing during accretion of He WD material by the C–O WD. In the processing, $^{14}$N is converted to $^{18}$O by $\alpha$-capture. The observed $^{18}$O abundances are not sufficiently great to have sensibly reduced the $^{14}$N abundances: the $^{18}$O abundances are factors of four to 20 less than the $^{14}$N abundances. However, fine tuning is required in order not to deplete entirely the $^{14}$N supply and also to prevent conversion of significant amounts of $^{18}$O by $\alpha$-capture to $^{22}$Ne.

The $s$-process: enrichment of $s$-process nuclides likely in the C–O WD’s He shell will be diluted by the absence of enrichment in the He WD. Thus, the enrichment will be diluted by about an order or magnitude if $M(\text{He}) \approx 0.3 \, M_{\odot}$ and $M(\text{He})\text{C–O} \approx 0.02 \, M_{\odot}$. Two of the EHe stars are observed enriched in Y and Zr 50-fold and another 10-fold. Other stars have lower enrichment levels. Although a 100- to 500-fold enrichment is within expected levels for isolated AGB stars, the general lack of a large $s$-process enrichment of these EHe stars, as well as the cool EHe stars (Pandey et al. 2001) and the warmer RCBSs (Asplund et al. 2000) implies that the He shell of the C–O WD was not itself greatly $s$-process enriched. This would seem to confirm suspicions that the He shells participating in the DD scenario may not be near-copies of He shells of isolated AGB stars.

Lithium: lithium is, of course, not observable in EHe stars but its presence in several RCBSs and in one of five known Hdc stars suggests that it is probably present in at least some EHe stars. Therefore, the challenge exists to account for the Li abundance in the DD scenario.

An initial supposition is that the Li was present in the H-rich skin around the WDs. Then, the observed Li/H ratio for the RCB star is the mass-weighted mean of the Li/H ratio in the two H-rich skins. For the four RCBSs with Li, log Li/H ranges from $-1.7$ for RZ Nor to $-4.8$ for SU Tau (Asplund et al. 2000) or Li abundances of 10.5 to 7.2 on the usual logarithmic scale where the H abundance is 12.0. Such extraordinarily high Li abundances are observed nowhere else: for example, the Li-rich carbon stars have Li abundances only (!) in the range from three to five (Abia et al. 1999).

In the usual scheme of Li synthesis known as the Cameron–Fowler mechanism (Cameron & Fowler 1971), Li as $^7$Li is synthesized from $^3$He by the chain $^3$He($^3$He,$^7$Be)$^7$Be($^7$Be,$^9$B)$^9$B. The potential reservoir of $^3$He is the star’s original supply of $^3$He and $^3$H (which is burnt to $^3$He in pre-main sequence phase) and additional $^3$He provided by operation of the $pp$-chains in low mass main sequence stars. The original $^3$He/H after $^3$H-burning will have been about $2 \times 10^{-5}$. In low mass stars, a layer of enriched $^3$He exists outside the H-burning core. The abundance can reach $10^{-3}$ of that of H over a shell about 0.2 $M_{\odot}$ in thickness (Iben 1967). Protons are not directly involved in the Cameron–Fowler mechanism but the temperature of the synthesis site may be influenced by the mass exterior to the site.

In the case of the Li-rich normal carbon stars, the site is the high-temperature base of the H-rich convective envelope in an intermediate-mass AGB star. In this environment, the observed range of Li abundances can be achieved. To achieve a higher abundance (i.e., a higher Li/H ratio), it seems necessary to reduce the mass of the H into which products (Be and then $^7$Li) of $^3$He consumption are mixed. Efficiency of $^7$Li production might be maximized were the $^3$He consumed in a layer completely devoid of H; this would remove the loss of $^7$Be and $^7$Li by proton capture but these nuclides would still be prone to destruction by $\alpha$-capture. Further exploration of $^7$Li synthesis will require very detailed calculations of nucleosynthesis in close binary systems.

5.3. The Final-flash Scenario

Several classes of H-deficient hot luminous post-AGB stars are believed to have resulted from an FF scenario. Compositions of these stars offer a direct point of comparison for the EHe (also RCB and Hdc) stars and, therefore, a test of the FF scenario as an origin for some EHe stars.

A valuable review of the observed compositions and theoretical origins of hot H-deficient post-AGB stars was provided by Werner & Herwig (2006). Their Table 1 clearly shows that the several families ([WCL], [WCE], [WC]-PG1159, and PG1159) of such post-AGB stars have compositions differing in several distinctive ways from the compositions of EHe and RCB stars. In particular, the relative C/He ratio is quite different. The (He,C) mass fractions are roughly in the range (0.30,0.60) to (0.85,0.15) whereas the EHees are close to (0.98,0.02) (Werner et al. 2008). This contrast is, of course, very largely attributable to the He contribution by the He WD to the DD scenario. Several of the post-AGB stars show a residue of their original H with a mass fraction of as much as 0.35, but a lower value is more common. (These are hot stars and, therefore, detection of H lines is difficult.) In other respects, the compositions of the post-AGB and EHe stars are more similar: the O mass fractions show a star-to-star spread but the highest value for a post-AGB star (0.20, Werner et al. 2008) is several times higher than the maximum value for an EHe. The F and Ne abundances are similar for the two groups of stars.

Theoretical FF models are discussed by Werner & Herwig (2006). These models differ as to when the He-shell flash (thermal pulse) occurs that restores the star to the post-AGB track as an EHe-like star. If the thermal pulse occurs when the star is on the AGB, it is termed an AFTP and may account for the relatively H-rich stars known as hybrid-PG1159 stars. If the thermal pulse occurs in the post-AGB period of approximately constant luminosity, it is an LTP (L = Late) and is predicted to create an H-deficient star with some H, say a mass fraction of about 0.02. FG Sge may have experienced an LTP—recently! Finally, if the thermal pulse is delayed until the star is on the WD cooling track, it is a VLTP (V = very). Sakurai’s object is considered to have undergone a VLTP—very recently! Although these post-AGB FF scenarios fail to account for the EHees, one may note some similarities with the ideas behind the DD scenario. In particular, convective extramixing into the “surface” layers of the C–O core is invoked in both cases to account for the spread in the O abundances, and high F and Ne abundances in the He shell around the C–O core of the AGB star to explain the F and Ne overabundances in both kinds of H-deficient stars.
6. CONCLUDING REMARKS

Understanding the origins of peculiar stars often awaits recognition of predecessors and descendants along the evolutionary sequence. The sequence may provide clues not always provided by even detailed observational studies of a single class of peculiar star in the sequence. Even more important than expanded observational studies is the development of theoretical understanding of relevant stellar models and associated nucleosynthesis. The EHe stars well illustrate these remarks.

The first EHe HD 124448 was discovered by Popper (1942) at the McDonald Observatory and this was followed ten years later by discovery of PV Tel, alias HD 168476, by Thackeray & Wesselink (1952) at the Radcliffe Observatory. Today, the register of EHe stars totals about 30 (Jeffery 1996).7 Today, the chemical compositions of EHe stars are quite well determined with our estimates of Ne abundances adding one more data point. Similarities in composition argue for an evolutionary link between EHe and RCB stars and less convincingly between these stars and the Hdc stars of which only five are known and their spectra blessed with a rich array of molecular lines render accurate abundance analysis difficult. Theoretical ideas have centered on two possibilities: the DD and the FF scenarios.

While the FF scenario may account for H-deficient stars like FG Sge and Sakurai’s object (as noted above), the argument eliminating it as the origin of EHe stars is a fusion of two principal points. First, the compositions of H-deficient central stars of planetary nebulae differ in critical aspects from those of EHe stars. As noted in Section 5.3, the He and C mass fractions of the central stars differ greatly from these quantities as found for EHe (and RCB) stars. Second, the observed compositions of the central stars are reasonably well accounted for by models of final He shell flashes in post-AGB stars. Thus, a safe conclusion would appear to be that the FF scenario cannot account for the EHe stars.

Identification of the EHe (and RCB) stars with the DD scenario depends on the correspondence between the measured chemical compositions and semi-quantitative theoretical estimates resulting from the merger of an He WD with a C–O WD. Predictions for a cold merger seem especially sensitive to the adopted composition of the He shell around the C–O WD before the merger and the extent to which mixing during the merger may incorporate material from the surface layers of the C–O WD. An additional uncertainty concerns the extent of nucleosynthesis occurring during the merger; the proposal that the 16O seen in cool Hdc and RCB stars is synthesized from 14N during the merger was noted (Clayton et al. 2007).

Although work remains for quantitative spectroscopists to do, we close with the thought that the larger challenges remain in the area of theoretical modeling of single stars in order to refine prediction for the several forms of the FF scenario and of double stars that through common envelope stages and mass loss provide the necessary stage for the DD scenario of a close binary of an He and a C–O WD that merge with possibly a concluding episode of nucleosynthesis to provide an EHe, RCB, or an Hdc.

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