THE ORIGIN AND EVOLUTION OF HELIUM-RICH WHITE DWARFS

James Liebert
Steward Observatory
University of Arizona
Tucson, Arizona 85721
USA

ABSTRACT. White dwarfs with helium-rich atmospheres constitute about one fifth of the white dwarfs hotter than 12,000 K. They appear to have a mass distribution similar to the hydrogen atmosphere (DA) stars, and are similar in other properties. However, the temperature distribution exhibits a deficiency of DB/DO stars in the interval 25,000-45,000 K, which implies evolution in the dominant surface composition as the stars cool. The hottest group of transition DO white dwarfs are the pulsating objects of the PG1159 class. The central star of K1-16 is a related object, as may be the newly discovered very hot star H1504+65, which shows no detected surface features of either hydrogen or helium.

1. INTRODUCTION: THE HELIUM WHITE DWARF SEQUENCE

The stellar parameters of the helium rich degenerates may be important in specifying the final boundary conditions for the prior post main sequence evolution of at least some of the hydrogen poor stars discussed at this meeting. The mass distribution of these remnants specifies how much envelope mass loss must have occurred; the rotation rates specify the angular momentum loss. Definite determination of the interior compositions, along with the mass distribution, would fix the extent of post main sequence nuclear evolution quite concretely. The stellar kinematics are a valuable clue to the progenitor population and mass range, especially for the hotter stars which have only recently become degenerate.

White dwarfs offer some diversity in the distribution of the atmospheric chemical compositions. The most basic division is that about four fifths of the hot white dwarfs retain hydrogen-rich surfaces, while one fifth have helium-dominated, and very hydrogen-poor, surfaces. There are no cases known in which the atmosphere is dominated by heavier species. Unfortunately, the usefulness of the atmospheric compositions of white dwarfs in the study of prior evolutionary states is much less clear than for the other stellar properties: Surface compositions can be quickly and completely changed due to the effects of gravitational and thermal diffusion,

K. Hunger et al. (eds.), Hydrogen Deficient Stars and Related Objects, 367–381.

selective radiative acceleration processes, convective mixing, and accretion from the interstellar medium. Quite strong but undetected magnetic fields could play an important role; fields are detected at strengths above 10^6 gauss in only about 1% of the known white dwarfs. It is even possible that none of the helium rich degenerates bear a particular relationship to any of the higher luminosity stars with hydrogen-poor atmospheres! I shall, however, explore some evidence for more optimistic possibilities, suggesting that there is some relationship.

Over most of the observed range in temperature, the white dwarfs divide into the two sequences of hydrogen and helium-rich atmospheres. Over at least the temperature span of 5,000 K to 80,000 K, the hydrogen lines appear in the former, and they are classified DA. The helium-rich cases display much more diverse subgroups of spectra: These include DO stars above 45,000 K showing He II lines, cooler DB stars showing only He I lines, and still cooler objects below 10,000 K which are too cool to show any optical lines from their dominant atmospheric constituent. The cool helium atmosphere objects, in particular, have very transparent atmospheres -- i.e. we view to very high gas densities and pressures -- which makes contaminant elements detectable at very low abundances. Thus, the cool objects usually show evidence for carbon, dredged up in small amounts from the bottoms of their convective envelopes, and often detectable only in the ultraviolet (DQ or DC stars). A minority of the cool helium stars show traces of accreted metals sometimes accompanied by hydrogen (the DZ stars). The stars below 5,000 K have surfaces too cool to reveal the dominant atmospheric constituent, be it hydrogen or helium, and most of these stars are classified DC (featureless). A temperature map for these basic sequences is provided in Figure 1, which will be discussed more fully in Section 3.

In Section 2, the known parameters of this multi-faceted helium atmosphere sequence are compared with those for the dominant DA stars. Then, the possible evolutionary scenarios for cooling degenerates which form part of the sequence are outlined (Section 3). Some very hot, pulsating, precursor stars are discussed in Section 4, as well as possible origins of the helium-rich degenerate sequence.

2. PARAMETERS OF THE HELIUM ATMOSPHERE WHITE DWARFS

2.1. The Mass Distribution and Interior Composition

The physics describing a helium dominated atmosphere--particularly the line broadening theory and the opacities--are less accurately known than for corresponding stars with hydrogen rich compositions. In particular, the helium atmospheres are generally more transparent at a given temperature, so that gas pressures are much higher, convection in the outer envelope more prevalent, and the abundances of trace elements more important. These problems are most severe for the DC/DQ/DZ stars below about 10,000 K. Conversely, the hot DO stars must be observed primarily longward of the peak of the energy distributions, and of the strongest absorption edges and lines. The numerous DB white dwarfs constitute the best sample for determining surface gravities and masses using stellar atmospheres techniques. Several of the He I lines exhibit considerable sensitivity to surface gravity; the optical colors, though covering only weak bound-free continua, exhibit some sensitivity. Little gravity sensitivity is offered by observations at IUE ultraviolet wavelengths.

Early atmospheric analyses suggested that DB white dwarfs might have significantly lower surface gravities and smaller masses than do the DA stars, a result which was attractive to those concerned about how the chemical purity of a DB atmosphere is maintained (Wesemael 1979; Alcock 1979). The masses derived for DBs ($< 0.4M_{\odot}$) were so much smaller as to imply a separate origin for these stars, as might be possible only from close binary evolution (Nather, Robinson and Stover 1979).

The most recent model grids include improved helium line profiles, blanketing and envelope convection. Some attention has been focussed on the effects of trace (and perhaps undetected) abundances of hydrogen and heavier elements. Shipman (1979) has consistently argued that the mean surface gravities and masses for DB stars were similar to the DA stars. The synthetic spectra from the new model grid of Wickramasinghe and Reid (1983) is also consistent with the stars having surface gravities near $\log g = 8.0$. Certainly the most comprehensive analysis is that of Oke, Weidemann and Koester (1984), who find that both the optical colors and the He I line profiles are consistent with the following result: The DB white dwarfs are distributed in a narrow mass range comparable with the DA stars, at $M \sim 0.55 +/- 0.10\ M_{\odot}$. These authors therefore argue that the progenitors for the DB and DA white dwarfs may be the same. There is every reason, then, to expect that most helium atmospheres surround carbon-oxygen cores, the natural end for the asymptotic giant branch evolution of stars with original masses up to approximately eight solar masses.

2.2 Rotation

There is little evidence for rapid rotation among DB and DO white dwarfs, although little quantitative analysis comparable to that done for the DA stars is currently available. Wickramasinghe and Reid (1983) derive projected rotation velocities of < 135 km s^{-1} for several DB stars showing sharp line cores. Unpublished MMT echelle spectra covering the He I 5876A line obtained by the author and R. Green show that several more cool DB stars exhibit sharp cores not unlike the H-alpha cores found by Greenstein et al. (1977) and Pilachowski and Milkey (1984) for DA stars. The implication is that these DB stars rotate even more slowly than the Wickramsinghe and Reid (1983) limits. Likewise, two hot DO stars observed at high dispersion with the IUE Observatory--PG1034+001 (Sion, Liebert and Wesemael 1985) and KPD0005+5106 (Downes, Liebert and Margon 1985, and work in preparation)-- show sharp ultraviolet features attributed to their photospheric velocities. On balance, there is little evidence that the hot helium rich white dwarfs retained much angular momentum from earlier evolutionary states. Like the mass determinations of Oke, Weidemann and Koester (1984), these results are inconsistent with an origin for most DB stars involving close binary evolution of the type proposed by Nather, Robinson and Stover (1979).

2.3. Population Type

There is little evidence that the DO/DB/DQ/DZ white dwarfs are part of a different kinematical population (Sion and Liebert 1977), although total space motions (which require radial velocities) are available only for a few dozen stars. There is little evidence that the fractions of helium atmosphere white dwarfs found in young galactic clusters or having halo space motions are drastically different. These findings provide further support for an origin of these stars primarily from the old disk population.

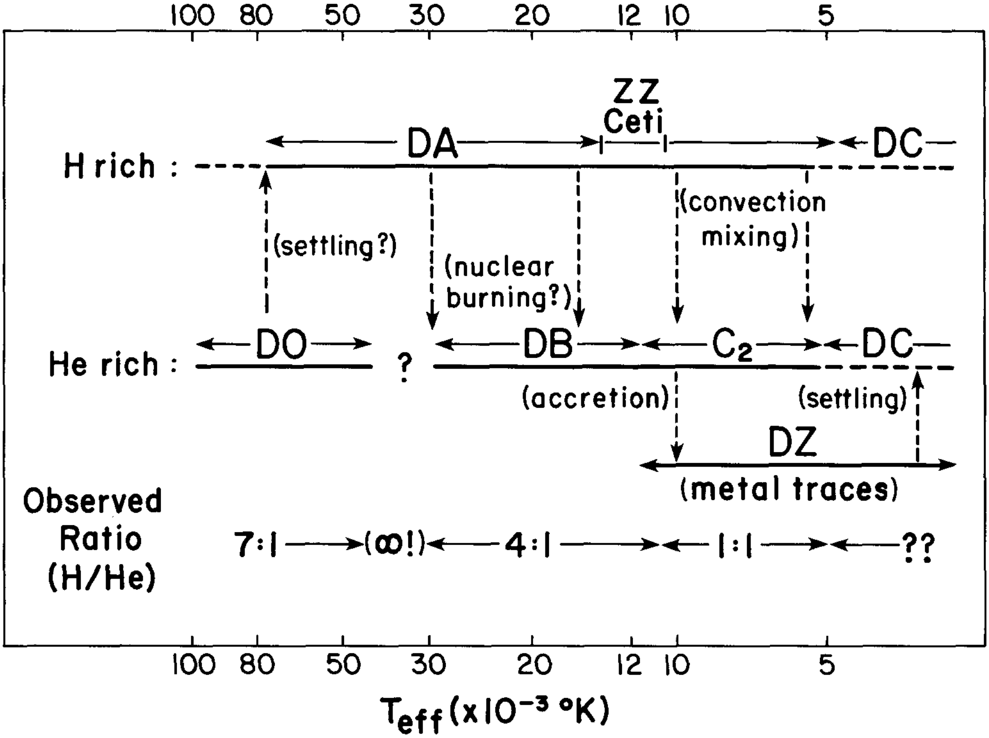

Figure 1. Spectral types of white dwarfs in the hydrogen and helium atmosphere sequences, as a function of temperature. Evolution in observed ratios is indicated at the bottom. Vertical arrows indicate processes (labelled) which might change atmospheric compositions.

2.4. Pulsations

Two groups of helium-rich degenerate stars (or pre-degenerate stars) constitute separate classes of pulsating variables. These are the DBV stars, whose prototype is GD358, with temperatures near 25,000 K and the "PG1159" or DOV variables. The latter are discussed in Section 4. The likely origin of the DB pulsational instability strip is linked to He II ionization (Winget et al. 1982). The temperature range is appropriately higher than that for the pulsating DA (ZZ Ceti) variables, although the exact temperature appropriate to the best analyzed case, GD358, is controversial (Koester et al. 1984; Liebert et al. 1986, and these proceedings). Indeed, the temperature scale for hot DB stars is important in establishing the extent of a deficiency of DB stars above about 25,000 K, as discussed in Section 3. Conceivably, the pulsation strip may be a clue in unravelling the evolutionary scenario.

3. EVOLUTION OF HELIUM ATMOSPHERE DEGENERATES

3.1. The Peculiar Temperature Distribution

The temperature or luminosity distributions of the helium rich white dwarfs differ significantly from those predicted from cooling theory and the assumptions of (1) a constant white dwarf formation rate for the last 10^9 years and (2) no change in the dominant atmospheric species as the white dwarfs cool. There is little evidence that these assumptions are invalid from the analysis of the luminosity function of DA white dwarfs (Greenstein 1979; Fleming, Liebert and Green 1986). For the helium-rich stars, the situation is quite different.

The temperature distributions of white dwarfs having hydrogen and helium-rich atmospheres, drawn from the complete sample of the Palomar Green Survey (Green, Schmidt and Liebert 1986) are shown as Figure 2. Only stars with temperatures at or above 12,000 K are shown. Temperatures for the DO stars are taken from Wesemael, Green and Liebert (1985), for the hot DBs from Liebert et al. (1986) and for the cooler DB stars from Shipman, Liebert and Green (1986). The data are not corrected for volume completeness. However, the shape of the discovery function may be estimated by comparing the distribution of DA stars with the luminosity function of Fleming et al. (1986). Moreover, the additional DB/DO stars analyzed in Oke, Weideman and Koester (1984) and one star from Koester, Liebert and Hege (1979) have been added to the helium star distribution. The PG1159-035 objects, borderline white dwarfs at log g ~ 7 and $T_{eff} \sim 10^5$ K, are plotted in the figure. These have few or no counterparts among the DA white dwarfs at the hot end, presumably because the latter have thick hydrogen envelopes and reach the white dwarf radii at somewhat lower temperatures.

The principal peculiarity in comparing the two histograms is the deficiency of helium stars in the interval log $T_e \approx 4.40$-4.65, which corresponds to about 26,000-45,000 K. Admittedly, the temperature scale for DB stars is uncertain for $T_{eff} > 20,000$ K (Liebert et al. 1986, and this conference); had we adopted the optical scale, even fewer stars would have been assigned temperatures as high as 25,000 K. It is curious that the DA distribution shows a marginal bulge centered near log $T_e \sim 4.5$, but an assessment of the statistical significance of this is beyond the scope of this summary paper. Such an effect did not show up in the luminosity function with its coarser magnitude binning (Fleming et al. 1986).

In general, the ratio of DA to non-DA white dwarfs decreases from the higher temperatures to lower temperatures (Sion 1984). In the well defined Palomar Green sample, the ratio is 7.1 +/- 2.9 in the 40-80,000 K interval, may be even higher in the 20-40,000 K range (because of the deficiency of DB stars), but is only 3.4 +/- 0.7 over the 12-20,000 K interval (Fleming et al. 1986). At temperatures below ~ 10,000 K, there is now overwhelming evidence that the fraction of helium-rich white dwarfs increases towards something like a 1:1 ratio (Sion 1979, Wehrse and Liebert 1980, Sion 1984, Greenstein 1986).

3.2. The Evolution in Surface Abundances of Hot White Dwarfs

How can one account for the strange behavior in the DB-DO histogram and in the changes of the volume-corrected ratios of DA/non-DA white dwarfs with temperature? If most white dwarfs belong to the old disk population, with total ages generally >> 10^9 years, it is unlikely that the local white dwarf birthrate would show drastic fluctuations in the last billion years or so. It is therefore very likely that the observed distributions with temperature require changes in the dominant surface abundances of hot white dwarfs, due to effects such as those listed in the Introduction. Since the helium sequence is modest in number compared with the hydrogen sequence (at the higher temperatures), the need for such evolution would not be readily apparent in analyses of the latter alone.

A number of recent theoretical investigations indicate possible ways in which the required surface abundance evolution may proceed. In Figure 1, a working hypothesis is outlined. The ratio of DA to DO stars in the 40-80,000 K range is about 7. However, some of the DO stars show substantial trace abundances of hydrogen (e.g. the prototype HZ21), and could become DA stars with outer hydrogen layers of quite small mass. This would result in an initial increase in the DA/non-DA ratio.

In the 20-30,000 K range, the idea proposed by Michaud, Fontaine and Charland (1984) just might work: If diffusion tails of the carbon core and hydrogen envelope are able to cross in a sufficiently thin helium layer at high enough temperature, stable hydrogen burning via the CNO cycle (whose rate depends only linearly on the trace hydrogen abundance) might eat away the hydrogen surface layer. Indeed, for this mechanism to work efficiently enough requires a rather optimistic treatment of the known physics. Moreover, evolutionary models which also include a treatment of element diffusion (Iben and MacDonald 1985) do not predict enough burning for the outer hydrogen layer to disappear. Note, however, that the numbers require only a modest fraction of the DA stars to be converted to DB stars in this high temperature range.

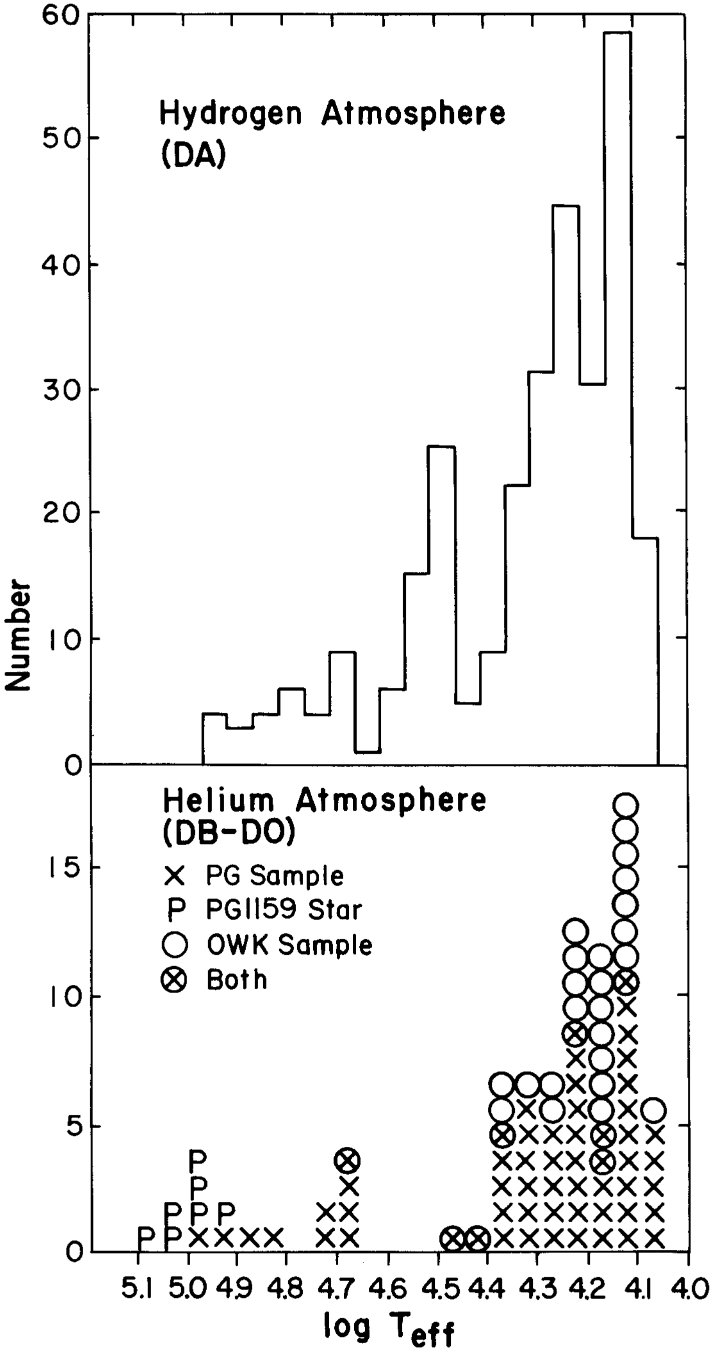

Figure 2. Histogram of temperatures for DA and DB-DO stars, from the Palomar Green Survey (PG) or previously known (OWK).

At lower temperatures -- possibly even as high as the 20-30,000 K range -- the onset of convective mixing can mix a hydrogen surface layer into a more massive helium envelope. Such mixing is believed to be the reason for the ~ 1:1 ratio at T_{eff} < 10,000 K, and implies that something like half of the hotter DA stars suffer this fate. Yet this mechanism is also invoked to cause the red temperature edge of the ZZ Ceti instability strip, which applies to most (or all) DA stars in the 10-13,000 K range (Winget and Fontaine 1982). Moreover, convective mixing should not work if the hydrogen layer mass remains higher than 10^{-7} $M_\odot$ as the stars reach these low temperatures.

Fortunately, the explanations for trace elements in the cooler DQ and DZ stars are on somewhat more solid ground. The traces of carbon appear routinely in helium-rich atmospheres below 10,000 K due to the dredge-up by the deepening outer convective envelope of the diffusion tail of the carbon core (Koester, Weidemann and Zeidler-K.T. 1982; Wegner and Yackovich 1984; Fontaine et al. 1984; Pelletier et al. 1986). For the DZ stars, the mechanism is accretion from the interstellar medium, although the messy interplay of accretion from a clumpy medium and diffusion in a convective envelope remains to be really understood (c.f. Alcock and Illarionov 1980; Wesemael and Truran 1982; Shipman and Greenstein 1983). A large fraction of these objects seem to show traces of hydrogen as well (Liebert, Wehrse and Green 1986), although this is certainly compatible with an accretion hypothesis.

The DBA stars are objects above 12,000 K which show traces of hydrogen. These seem to constitute more than 10% of the DB stars in the 12-18,000 K range (Shipman, Liebert and Green 1986). A survey of the H-alpha region with a precision (CCD) detector would likely increase the fraction further. If accretion were the cause of the DBA phenomenon, one would expect that the more extreme cases might show metals as well. Likewise, the hottest stars showing strong metals -- GD401 and GD40 -- do not show hydrogen features (c.f. Shipman and Greenstein 1983). An alternative explanation for the DBA stars is that these objects have recently mixed their outer hydrogen layers into helium envelopes, possibly evolving from DA to DB below 30,000 K. Perhaps the strange DAB object GD323 -- whose energy distribution and line spectrum have not been reconciled to any atmospheric model with a mixed H, He composition -- may provide a clue to an evolutionary answer (see Liebert et al. 1984). However, modest hydrogen pollution of helium-rich atmospheres is a characteristic of stars as hot as HZ21 (~ 50,000 K).

4. THE ORIGIN OF HELIUM RICH WHITE DWARFS

4.1. Precursor Stars: Helium-Rich PNNs and SdOs

Stars which feed the helium white dwarf sequence must include both some helium-rich planetary nebulae nuclei (PNNs) and some subdwarf O stars. Most sdO stars are actually hydrogen-rich, but with detectable helium. Moreover, it is also possible that many extremely He-rich sdOs and

PNNs retain enough envelope hydrogen that gravitational settling could turn them into DA atmospheres. Conversely, gravitational and thermal diffusion might also be overcome by selective radiative acceleration processes, which might preferentially expel hydrogen from such heliumrich envelopes, leaving an essentially pure helium surface as the remnant becomes a white dwarf.

The helium-rich PNNs constitute some 30% of the particular sample of nuclei for which photospheric abundance results are available (Mendez 1986, this conference). This is a somewhat higher fraction of helium enriched objects than for the hot (DO/DA) white dwarfs, but scarcely enough different for serious concern. The PNN selection bias favors analysis of central stars with low surface brightness nebulae; they should also tend to be nearby and low luminosity objects. Since the evolution time scale for the dying stellar core decreases with a high power of the core mass -- while the envelope dispersal time scale presumably is less sensitive to mass -- those PNNs with analyzable photospheres may have preferentially lower masses.

By this kind of reasoning, the subdwarf O stars may simply be cores of modestly lower mass than the PNNs which are observed after dissipation of the nebula (Heber et al. 1984). Of course, many PNNs have sdO spectral types, but the numbers of isolated sdO stars (over 200 in the PG Survey) exceed this type of PNN to comparable limiting stellar magnitudes.

The above ideas imply that most stars entering the helium-rich white dwarf channel may have lower core masses than those entering the DA sequence, but calculations show that the expected difference is small (Schönberner 1983) and is well within the uncertainties of the masses reviewed in Section 2. Moreover, there are other indications that some helium-rich sdOs and PNNs might have higher than average masses: First, Heber (1986, this conference) discusses several very luminous helium-rich sdOs which fit evolutionary tracks at higher than 0.6 $M_\odot$. Secondly, as discussed in Sections 4.2-3, the very hottest prewhite dwarf stars (at least those outside of high surface brightness PNs) appear to be hydrogen-poor stars like PG1159-035 and H1504+65. At the point where dying stars are descending in the H-R diagram to the white dwarf sequence, the hottest stars at a given luminosity and for a given composition should be the most massive. Finally, it now appears that a large fraction of planetary nebulae in the Magellanic Clouds -- which should logically include a higher fraction of more massive progenitors and more massive PNNs -- have nebulae which are enriched in helium (Boroson and Liebert 1986).

4.2. The Pulsating Stars: PG1159-035 and K1-16

Immediate precursors, which overlap in the H-R diagram both the hottest PNNs and sdOs, are the pulsating variable stars whose prototype is PG1159-035. We have previously described these (Wesemael, Green and Liebert 1985) as defining the high temperature end of the DO degenerate sequence; their surface gravities (log g ~ 7) suggest that they are borderline white dwarfs using the definition of Greenstein and Sargent (1974). Indeed, I would not quarrel with calling them high gravity sdO stars. However, they are considerably hotter than nearly all previousl analyzed sdO stars. At $T_{eff} \sim 10^5$ K, they are among the hottest fiel stars known, comparable to the very hottest PNNs whose photosphere have been analyzed. Their spectra show broad absorption lines (ofte with narrow emission cores) of He II, C IV and O VI, wit no trace of hydrogen and indications that the corresponding N transitions are weak or absent. At such high temperatures, however, i is difficult to establish to what degree that hydrogen is absent.

Some of the stars defining this spectroscopic class are pulsating variables (McGraw et al. 1979; Bond et al. 1984); the variations are complicated, non-radial pulsation modes, believed to be driven in ionization zones of the CNO species (Starrfield et al. 1984). The pulsation behavior is of interest to stellar pulsation theorists, and is of great potential value in measuring the rate of interior evolution in stars which should be evolving rapidly (Winget, Hansen and Van Horn 1983). Indeed, a period change in the prototype (PG1159-035) has recently been reported (Winget et al. 1985), though its interpretation is complicated by the possibility of rotation (Kawaler et al. 1985).

The planetary nebula K1-16 has a central star which is also (1) pulsating with complicated modes, (2) very hot, and (3) shows absorption lines with emission reversals of the same He II, C IV and O VI ions seen in the PG1159 stars (Grauer and Bond 1984; Sion, Liebert and Starrfield 1985; Grauer et al. 1986). Possible differences may be noted, however. K1-16 has somewhat sharper absorption lines, i.e. may be more luminous; and its typical periodicities are longer, which may be a consequence of higher luminosity. This behavior is of course exactly what is expected for a roughly vertical instability strip at the left edge of the H-R diagram. K1-16 also supports a link between the isolated PG1159 variables and that somewhat heterogeneous class of PNNs called the O VI stars (Sion, Liebert, and Starrfield 1985). The latter may exhibit strong Wolf-Rayet-like winds, which may drive the remaining hydrogen from the stars. K1-16, in particular, shows evidence for a subtle but high velocity wind (Kaler and Feibelman 1985). Moreover, there are even several "field" stars -- not associated with PNs but likely to be evolved, low mass objects -- which show very strong C IV and O VI emission (Sanduleak 1971, Barlow and Hummer 1982, Downes 1984).

4.3. H1504+65

An extremely hot, hydrogen-poor star has recently been discovered by the HEAO-1 X-ray satellite; H1504+65 shows some similarities to the PG1159 stars (Nousek et al. 1986). The ratio of its soft (EXOSAT) X-ray to optical fluxes is over 600 times that for PG1159-035. The energy distribution from 1000-6000Å is also steeper. The spectrum shows O VI and C IV features, but no trace of He II! The widths of the O VI absorption suggests a high surface gravity. There is as yet no conclusive evidence as to whether or not H1504+65 pulsates.

The absence of He II lines indicates that, if the atmosphere were helium dominated, the temperature must substantially exceed 150,000 K, the highest value for which Wesemael (1981) pure helium models are

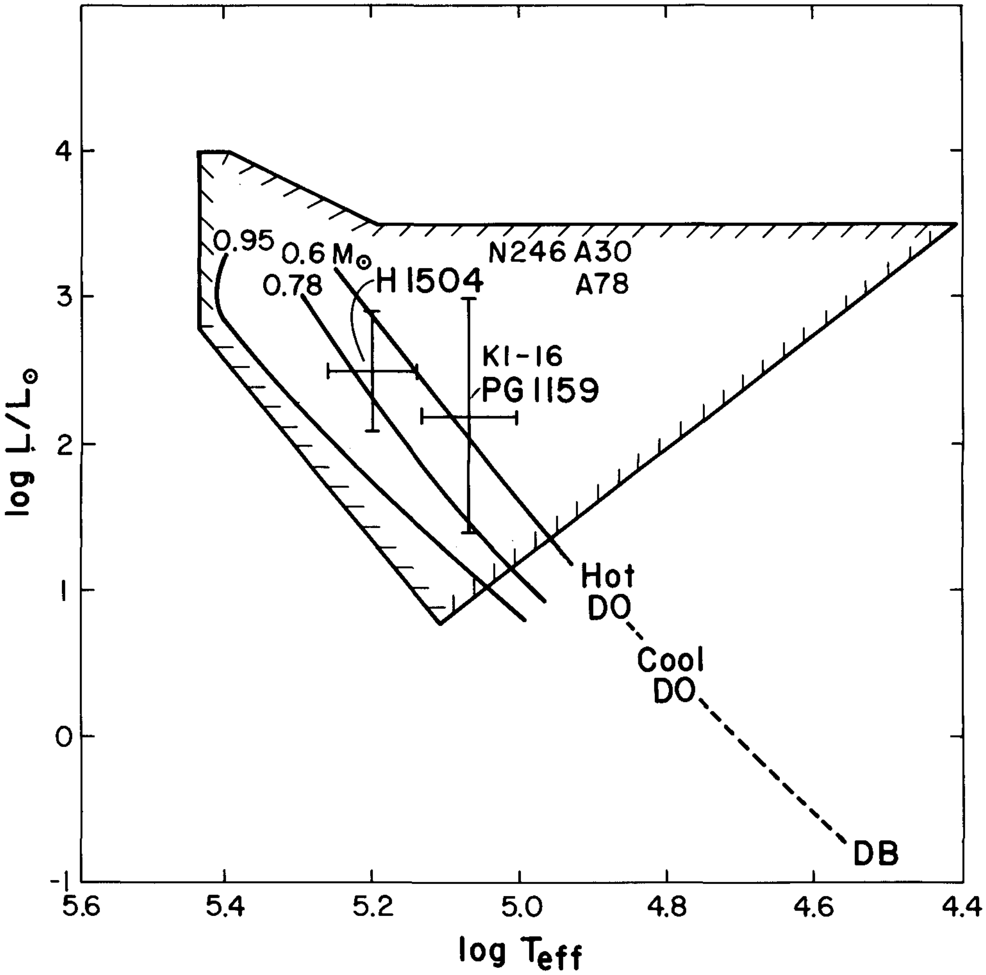

Figure 3. H-R Diagram for the hot helium white dwarfs, and some of their likely progenitors, as discussed in Section 4. Also shown are a cross-hatched region occupied by PNNs and evolutionary models (curves).

available. An alternative and still untested hypothesis is that the surface of H1504+65 is also helium poor, and presumably dominated by carbon and oxygen. This seems incompatible with stellar evolution models of the AGB and post-AGB phases, which predict that a helium layer of thickness $M > 10^{-3} M_\odot$ will be retained. Moreover, there are no known carbon/oxygen dominated surfaces among the > 1,000 known white dwarfs of cooler temperature. One might at least presume that the outer envelope retains enough helium for settling to later result in a helium-rich (DO) surface. On balance, Nousek et al. estimate the surface temperature as 160,000 +/- 30,000 K.

In Figure 3, adapted from Nousek et al., the stars H1504+65 and PG1159-035 are plotted with best current estimates of their error bars, and with theoretical evolution tracks taken from Kawaler et al. (1985). The hot, helium-rich white dwarf spectral groups (DO,DB), into which these stars presumably evolve, are also shown. Several O VI PNNs are indicated, although temperature/luminosity determinations of the photospheres are lacking. K1-16 is shown as more luminous than PG1159. It appears from the nebular analyses that the nuclei of NGC 246, Abell 30 and Abell 78 -- which do not pulsate (Grauer et al. 1986) -- may be higher in luminosity and/or lower in temperature than the instability strip. The large hatched region in the figure is approximately that occupied by the known PNNs with reasonably determined values given by Pottasch (1984).

It appears to be a reasonable conclusion that objects like PG1159 and H1504 have higher masses than those for most helium-rich sdO stars. Given the large uncertainties in the derived parameters, however, it is not clear that H1504+65 and the stars of the PG1159 class necessarily fit stellar evolution tracks of higher mass than the mean ($\sim 0.6 M_\odot$) for DA white dwarfs. The point was made earlier (see also Fleming et al. 1986) that their temperatures do appear to be hotter than those for the hottest DA stars or exposed PNNs near log g ~ 7. However, if the DA stars retain thick ($> 10^{-4} M_\odot$) hydrogen envelopes, their radii would be significantly larger (and surface temperatures cooler) for quite similar masses. Likewise, the more massive and hotter of the DA progenitors may remain buried in PN envelopes at lower luminosities. Certainly, a few of these -- see Pottasch (1984, Fig. XI-1) -- probably harbor PNNs well in excess of 100,000 K.

4.4. A Word about Origins

Three partly-overlapping groups of progenitor stars to the helium white dwarf sequence have been identified in the preceding discussion -- the helium-rich sdO stars, the helium-rich PNNs and the hotter, high gravity field stars like PG1159-035 and H1504+65. It is beyond the scope of this presentation to explore in detail how these stars lost their hydrogen surfaces in prior evolution. The cooler subdwarf progenitors could actually include both sdOs having had similar AGB evolution to the PNNS and also objects (sdBs, sdOBs) which evolved from an extended horizontal branch directly towards the white dwarf state (Groth, Kudritzki and Heber 1986). Both groups could become DO/DB white dwarfs with masses modestly lower than typical DA values.

For the apparently more massive progenitors, the appearance of oxygen and carbon features suggests a common origin for the PG1159 field stars and at least some PNNs of the O VI group. For these, it is tempting to consider an origin involving a late helium shell flash (c.f. Schönberner 1979, Iben and Renzini 1983, Iben et al. 1983). Such a hypothesis offers an explanation as to how a relatively massive star might have already shed its principal (hydrogen-rich) PN in an earlier episode. The problem is that the likelihood of a late shell flash should normally be higher for lower mass cores which take considerably longer to cool in the post-AGB phase. A remaining wildcard is the possible link between the helium shell flash timing and the mechanism which controls the final (superwind?) PN ejection. Thus, it remains to be worked out what fraction of helium-rich white dwarfs might owe their origin to a late helium shell flash, and what their mass distribution is.

I wish to thank Al Grauer, Harry Shipman, Francois Wesemael, John Nousek, Richard Green and other colleagues for some collaborative results presented at the meeting in advance of publication dates. In addition to discussions with numerous colleagues at this conference, I wish to acknowledge the preprints and valuable discussions with Rolf Kudritzki, Dirk Husfeld and Detlev Koester. This work was supported by the National Science Foundation grant AST 85-14778.

REFERENCES

Alcock, C. 1979, in White Dwarfs and Variable Degenerate Stars, Proc. IAU Coll. No. 53, eds. H. M. Van Horn and V. Weidemann, Univ. of Rochester Press, New York, p. 202.

Alcock, C., and Illarionov, A. 1980, Ap. J., **235**, 541.

Barlow, M. J., and Hummer, D. G. 1982, in Wolf Rayet Stars: Observations, Physics, Evolution, Proc. IAU Symp. No. 99, eds. C. W. H. de Loore, and A. J. Willis, D. Reidel Publishing Co., Dordrecht, p. 387.

Bond, H. E., Grauer, A. D., Green, R. F., and Liebert, J. 1984, Ap. J., **279**, 751.

Boroson, T. A., and Liebert, J. 1986, preprint.

Downes, R. A. 1984, Publ. A.S.P., **96**, 807.

Downes, R. A., Liebert, J., and Margon, B. 1985, Ap. J., **290**, 321.

Fleming, T., Liebert, J., and Green, R. F. 1986, Ap. J., in press.

Fontaine, G., Villeneuve, B., Wesemael, F. and Wegner, G. 1984, Ap. J., Letters, **277**, L51.

Grauer, A. D., and Bond, H. E. 1984, Ap. J., **277**, 211.

Grauer, A. D., Liebert, J., Fleming, T., Green, R. F., and Bond, H. E. 1986, preprint.

Green, R. F., Schmidt, M., and Liebert, J. 1986, Ap. J. Suppl., in press.

Greenstein, J. L. 1979, Ap. J., **233**, 239.

Greenstein, J. L. 1986, Ap. J., in press.

Greenstein, J. L., Boksenberg, A., Carswell, R., and Shortridge, K. 1977, Ap. J., **212**, 186.

Greenstein, J. L., and Sargent, A. 1984, Ap. J. Suppl., **28**, 157.

Groth,H. G., Kudritzki, R. P., and Heber, U. 1986, Astr. Ap., in press.

Heber, U., Hunger, K., Jonas, G., and Kudritzki, R. P. 1984, Astr. Ap., **130**, 119.

Iben, I., and Renzini, A. 1983, Ann. Rev. Ast. Ap., **21**, 271.

Iben, I., Kaler, J. B., Truran, J. W. and Renzini, A. 1983, Ap. J., **264**, 605.

Iben, I., and MacDonald, J. 1985, Ap. J., **296**, 540.

Kaler, J. B., and Feibelman, W. A. 1985, Ap. J., **297**, 724.

Kawaler, S. D., Hansen, C. J., and Winget, D. E. 1985, Ap. J., **295**, 547.

Koester, D., Liebert, J., and Hege, E. K. 1979, Astr. Ap., **71**, 163.

Koester, D., Vauclair, G., Dolez, N., Oke, J. B., Greenstein, J. L., and Weidemann, V. 1985, Astr. Ap., **149**, 423.

Koester, D., Weidemann, V., and Zeitler-K.T., E. M. 1982, Astr. Ap., **116**, 147.

Liebert, J., Wehrse, R., and Green, R. F. 1986, preprint.

Liebert, J., Wesemael, F., Sion, E. M., and Wegner, G. 1984, Ap. J., **277**, 692.

Liebert, J., Wesemael, F., Hansen, C. J., Fontaine, G., Shipman, H. L., Sion, E. M., Winget, D. E., and Green, R. F. 1986, Ap. J., in press.

McGraw, J. T., Starrfield, S. G., Liebert, J., and Green, R. F. 1979, in IAU Coll. No. 53, White Dwarfs and Variable Degenerate Stars, eds. H. M. Van Horn and V. Weidemann, Univ. of Rochester Press, Rochester, N.Y., p. 377.

Michaud, G., Fontaine, G. and Charland, Y. 1984, Ap. J., **280**, 247.

Nather, R. E., Robinson, E. L., and Stover, R. J. 1979, in IAU Coll. No. 53, White Dwarfs and Variable Degenerate Stars, eds. H. M. Van Horn and V. Weidemann, Univ. of Rochester Press, Rochester, N.Y., p. 453.

Nousek, J. A., Shipman, H. L., Holberg, J. B., Liebert, J., Pravdo, S. H., White, N. E., and Giommi, P. 1986, Ap. J., in press.

Oke, J. B., Weidemann, V., and Koester, D. 1984, Ap. J., **281**, 276.

Pelletier, C., Fontaine, G., Wesemael, F., and Michaud, G. 1986, Ap. J., in press.

Pilachowski, C. A., and Milkey, R. W. 1984, Publ.A.S.P., **96**, 821.

Pottasch, S. R. 1984, in Planetary Nebulae, Vol. 107, Astrophysics and Space Science Library, D. Reidel Publishing Co., Dordrecht, Figure IX-1, p. 218.

Sanduleak, N. 1971, Ap. J. Letters, **164**, L71.

Schönberner, D. 1979, Astr. Ap., **79**, 108.

Schönberner, D. 1983, Ap. J., **272**, 708.

Shipman, H. L. 1979, Ap. J., **228**, 240.

Shipman, H. L., and Greenstein, J. L. 1983, Ap. J., **266**, 761.

Shipman, H. L., Liebert, J., and Green, R. F. 1986, in preparation.

Sion, E. M. 1979, in White Dwarfs and Variable Degenerate Stars, Proc. IAU Coll. No. 53, eds. V. Weidemann and H.M. Van Horn, Univ. of Rochester Press, New York, p. 245.

Sion, E. M. 1984, Ap. J., **282**, 612.

Sion, E. M., and Liebert, J. 1977, Ap. J., **213**, 468.

Sion, E. M., Liebert, J., and Starrfield, S. G. 1985, Ap. J., **292**, 471

Sion, E. M., Liebert, J., and Wesemael, F. 1985, Ap. J., **292**, 477.
Starrfield, S., Cox, A., Kidman, R. B., and Pesnell, W. D. 1984, Ap. J., **281**, 800.
Wegner, G., and Yackovich, F. H. 1984, Ap. J., **284**, 257.
Wehrse, R., and Liebert, J. 1980, Astr. Ap., **83**, 184.
Wesemael, F. 1979, Astr. Ap., **72**, 104.
Wesemael, F. 1981, Ap. J. Suppl., **45**, 177.
Wesemael, F., Green, R. F., and Liebert, J. 1985, Ap. J. Suppl., **58**, 379.
Wesemael, F., and Truran, J. 1982, Ap. J., **260**, 807.
Wickramasinghe, D. T., and Reid, N. 1983, M.N.R.A.S., **203**, 887.
Winget, D. E. and Fontaine, G. 1982, in Pulsations in Classical and Cataclysmic Variables, eds. J.P. Cox and C.J. Hansen, Boulder: JILA, p. 46.
Winget, D. E., Hansen, C. J., and Van Horn, H. 1983, Nature, **303**, 781.
Winget, D. E., Kepler, S. O., Robinson, E. L., Nather, R. E., and O'Donoghue, D. 1985, Ap. J., **292**, 606.
Winget, D. E., Robinson, E. L., Nather, R. E., and Fontaine, G. 1982, Ap. J. Letters, **262**, L11.

DISCUSSION

MENDEZ: I would like to make two comments: First one about Iben and Renzini's idea of explaining H-deficient stars as "born again" AGB stars. As discussed by Schönberner (1983, Ap.J. 272, 708), while the "fading times" of post-AGB objects increase with decrasing stellar mass, the interpulse times go through a maximum at about 0.57 M_o and then start decrasing with decreasing mass. Therefore, the chance for a given post-AGB star to suffer a suitable He shell flash increases substantially for smaller masses, and we would expect non-DA white dwarfs to have smaller masses than DA white dwarfs. The fact that the mean masses of DA and non-DA white dwarfs are turning out to be quite similar, might then be used to argue that the "born again" mechanism is not the dominant one for the production of H-deficient white dwarfs.

LIEBERT: Quite right.

MENDEZ: I would like to point out that the gap you find in the temperatur distribution on non-dA white dwarfs appears to happen at the same temperature as the gap in the distribution of H-deficient CSPN. I do not know what this could possibly mean, but there it is.

T.M.K. MARAR: According to you there are more than half a dozen DO white dwarfs. The temperature range from 50,000° to 100,000°. Simply from the thermal emission they should all have been seen as soft X-ray sources.

LIEBERT: No. Hot helium white dwarfs should be heavily blanketed at soft X-ray wavelengths. One 12th mag star, PG 1034+001, at T_e = 80,000°K (Wesemael, Green and Liebert, 1985, Ap.J. Suppl.) was not detected in a pointed Einstein observation. The rest of the DO white dwarfs were not targeted (except for PG 1159).

T.M.K. MARAR: Is the survey complete with respect to all these DO white dwarfs and their regions of observations by Einstein?

LIEBERT: No... Two answers... The PG survey covered one quarter of the sky at galactic latitude above 30° and it is complete to B = 16 for stars bluer than U-B of -0.3 which is a blue color criterion. The Einstein satellite in survey mode covered only about 1% of the sky. In a field of 30 arcmin or so that is accessible we can find serendipitous X-ray sources. It is worth remarking that only about 2 hot white dwarfs that were genuinely new were found in this way, but in the Einstein survey mode which I actually worked to fair extent, I expected to find more white dwarfs, but did not.

T.M.K. MARAR: The mass distribution you mentioned applies only to single white dwarfs, I suppose (not to the ones in interacting binaries).

LIEBERT: Yes. It applies only to non interacting binary and single white dwarfs.

HUNGER: In cool degenerates, pulsation depends not only on g and T_{eff}, but sensitively on the composition. Do you think that pulsations in the hot pulsators are also influenced by the chemistry?

LIEBERT: Certainly. DA stars pulsate in the 10-13,000° K range, DB stars near 25,000° K. The indications are that the hydrogen envelope contains the driving for the former, and the He II ionization drives the latter. So we have actually looked at a few H rich stars such as the central stars. They are as dead as a door nail. They do not show propensity for pulsations. The exact chemical composition of the PG 1159 atmospheres is not yet determined, but it appears that they are helium rich, and carbon and oxygen rich. Starfield, Cox and collaborators attribute the driving by the ionization of oxygen and possibly carbon.

N.K. RAO: Regarding the born again red giant scenario there is some evidence that R CrB stars might be undergoing or passing through such a stage. In such a case one would expect to see the remnants of the first giant stage to be visible like the presence of planetary nebulae and cool dust shell at large distance. Both these are seen around R CrB.

LIEBERT: Some concern about the Iben et al scenario is also the optical depth effects. Whether the photosphere is something really big remains to be seen. So this sort of star looks like a red giant.

HILL: How many DB stars in the ragne 20-30 x 10^3 K are pulsating and, what is the type of pulsation?

LIEBERT: Our paper (Liebert et al; this proceedings) lists all of them, as we made an attempt to determine the temperature from IUE. Liebert, Winget and collaborators have discovered four such DB white dwarfs, including the prototype GD 358. The pulsations are non-radial overtones and may be caused by the helium ionization. There is a controversy about the temperature between the Kiel group and us, as to where the high temperature end really is, we would say around 28,000 K down to about 24,000 K being the cool end. According to the Kiel group it goes from 24,000 K to may be only 23,000 or 22,000 K. They have not analysed cooler pulsating stars. Hence it is possible that all the stars which are within the temperatur range are unstable like the pulsators, without proving that's the case. It is approximately the case with DA stars as they come through the instability strip of 10,000 to 12,000 K.

KILAMBI: You said that some of these white dwarfs are accreting matter. What kind of accretion rate are you expecting?

LIEBERT: The main problem has been how little they accrete, particularly the DB stars with nearly hydrogen-free atmospheres. There is also evidence that hydrogen is selectively excluded in the only cases where there is direct, observational evidence that accretion occurs, namely in the DZ white dwarfs with metallic features (in a He-dominated atmospheres). In the normal ISM the rates appear to be negligibly low; the DZ stars are the result (apparently) of chance encounters with interstellar clouds. As the metals diffuse downwards, the spectral type reverts to DC.

KILAMBI: You said between 30,000 K to 50,000 K some of these DB stars could be pulsating. Can you give a rough estimate of the pulsation period for these stars?

DISCUSSION

LIEBERT: The pulsating DB stars show complicated, non-radial pulsations with periods of several to tens of minutes. I believe they will be discussed further by Dr. Saio.

FEAST: What is the emission line you are measuring to give you the luminosity scale of the Planetary Nebulae in the Clouds.

LIEBERT: The luminosities are derived from λ5007. The only line effectively to be used is H . Jacoby used [OIII] ; however, using only [OIII] means that one would miss the lower excitation nebulae.