ABUNDANCE PATTERNS IN WHITE DWARFS

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ABSTRACT. Various evidence indicates that the atmospheric compositions of white dwarfs may switch from hydrogen– to helium– dominated, and vice versa, over wide ranges of surface temperature (luminosity). This envelope evolution may be understood only by assuming that the hydrogen (DA) sequence retains only a tiny residual mass of hydrogen, many orders of magnitude less than that predicted by stellar evolution theory. A corresponding problem may exist for the helium envelopes of some hot stars with helium-rich atmospheres.

1. Introduction

The atmospheric abundances of white dwarfs convey quite different implications than those for stars in earlier phases. Their explanation generally requires any of several physical processes to operate in white dwarf envelopes – the most important of these being gravitational and thermal diffusion, selective radiative acceleration and even mass loss, convective mixing and dredge-up of core material, and accretion from the interstellar medium. The observed operation of some of these processes carries important constraints on the envelope composition above the degenerate core – in particular the masses of the residual helium and hydrogen layers. The fossilized structure of the dying star in turn constrains late phases of stellar evolution, in particular the nature of the mass loss on the asymptotic giant branch (AGB), and during the planetary nebula ejection and post-AGB phases.

If the white dwarfs had hydrogen and helium layer masses in accordance with the predictions of standard stellar evolution theory, the abundance patterns would be so simple that this talk and the two that follow would probably be too boring to be included in this Symposium. In the standard theory the post-AGB star's hydrogen and helium-burning shells are not sustainable after the layer masses of hydrogen and helium are reduced below a few times 10^{-4} $M_\odot$ for hydrogen and the order 10^{-2} to 10^{-3} $M_\odot$ for helium (cf. Schönberner 1979, 1983; Wood and Faulkner 1986). It is possible for the former to be lost from the star entirely, especially in the form of a late helium shell flash (Iben *et al.* 1983). Thus, the standard theory predicts the star to finish its evolution with a hydrogen layer mass either of the order 10^{-4} $M_\odot$ or zero.

The atmospheric compositions of white dwarfs divide unambiguously into just

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the two classes expected from the stellar evolution codes. These are the DA stars showing hydrogen lines, and the various types of non-DA stars (DB, DO, etc.) whose dominant atmospheric constituent is helium. Schatzman (1958) showed long ago that gravitational settling should operate very quickly in the quiescent envelopes of evolved stars of high gravity. Thus, the DA stars should have essentially pure hydrogen atmospheres – since this lightest element floats quickly to the top. The DB and DO stars exist because virtually all of the hydrogen has been lost, and helium is the lightest remaining element. Moreover, the remaining layer mass of hydrogen is thick enough that the DA stars would retain pure hydrogen surfaces throughout their cooling evolution, unless significant accretion from the interstellar medium is occurring. Likewise, the non-DA stars with their massive outer layers of helium would cool through a spectral sequence of DO to DB, eventually becoming featureless DC stars when their temperatures drop too low to excite even the He I.

The two sequences of hydrogen and helium–atmosphere white dwarfs are now beset with far too many complications to be explainable in terms of the simple predictions of stellar evolution cited above. As observational data has greatly improved in wavelength range and in quality, numerous objects showing many types of "hybrid" spectra have been discovered – atmospheres with more than one chemical element detected. In the last few years in particular, overwhelming evidence has accumulated that some DA and non-DA white dwarfs must change their dominant atmospheric constituent during the cooling evolution. I will devote most of this paper to discussing several previously–unexpected and puzzling observational "facts" which appear to rule out a simple evolution of separate helium and hydrogen white dwarf sequences in the manner predicted by the standard stellar evolution theory. This discussion is limited to the abundance patterns of hydrogen and helium which relate most directly to the evolution of its cooling envelope and constrain the earlier evolution of the star. Trace elements of heavier elements appear in both hot and cool white dwarfs due to such physical effects as radiative acceleration and accretion. Due to lack of time (space), I must also omit discussion of the appearance of carbon in cool DQ white dwarfs with helium–dominated atmospheres.

2. A List of Observational Facts

The discoveries which now cause us to reject the hypothesis that white dwarfs evolve through separate, parallel hydrogen–rich and helium–rich sequences are listed in each of the following headings and discussed subsequently. We begin with the properties of the hottest white dwarfs, and then discuss evolution of the surface compositions as the stars cool. Shown schematically in Figure 1 are the various spectral types of the hydrogen and helium–rich sequences along parallel, horizontal lines as a function of decreasing $T_{\rm eff}$. The points at which the atmospheres may switch from one sequence to the other are indicated with dashed lines and arrows.

2.1. THE HOTTEST WHITE DWARFS ARE MOSTLY HELIUM AND EVEN CNO-RICH

The study by Wesemael, Green and Liebert (1985,WGL) of the known DO white dwarfs established that these include stars near log $g = 7.0$ with temperatures of 80,000 K and above in which hydrogen was usually not detected. Depending on $T_{\rm eff}$, however, rather generous trace abundances of H could be present since the Balmer lines would be weak in such hot objects, and their detection is also complicated by the presence of the nearly-coincident Pickering series of He II.

It is the hottest group of these hydrogen–poor white dwarf or pre–white dwarf stars that has generated the most excitement. These are the "PG 1159" stars for which PG 1159–039 is the spectroscopic prototype. Many of these have been found to show complicated, non– radial pulsations; GW Virginis is the variable star designation for PG 1159–035 and the class. While much has been learned from

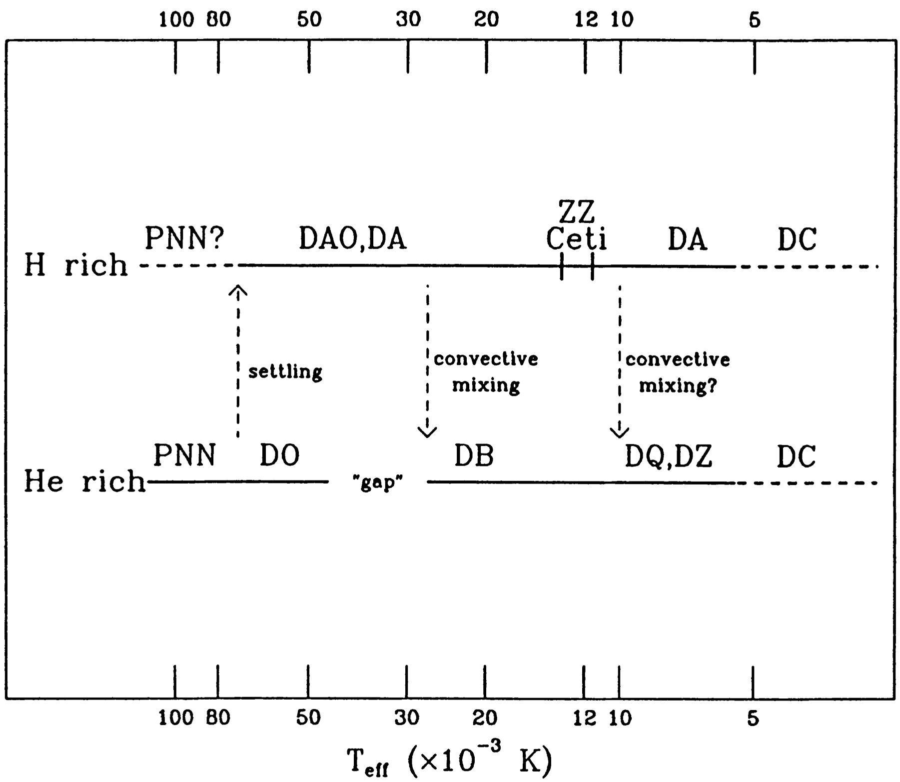

Figure 1. Schematic plot of the two sequences of helium– and hydrogen–rich white dwarf atmospheres as a function of $T_{\rm eff}$, with the principal spectral types labelled. "PNN" refers to planetary nebula nuclei of high log g which may be entering the white dwarf sequences. "ZZ" locates the pulsational instability strip of the ZZ Ceti stars. The dashed lines indicate points at which the stars may switch to the other sequence, due to the labelled process.

the analysis of the pulsations by Winget, Kawaler and associates, we concentrate here on their atmospheric properties. WGL had fit the spectra with LTE models consisting of mixtures of H and He. They estimated $T_{\rm eff}$ near 100,000 K and log g near 7. It was clear that H had to be significantly less abundant than He, but the constraint was weak. Moreover, lines of CNO elements – especially C IV and O VI – were clearly detected along with He II in the spectrum.

Now Werner, Heber and Hunger (1991) have a greatly improved analysis using non–LTE models including detected transitions of carbon, oxygen and nitrogen. They fitted improved observations taken with a CCD detector. These authors found that the stars had very high $T_{\rm eff}$ – 100,000 to 140,000 K, *logg* near 7 and hydrogen less than 8% of the surface abundance by mass. Their startling conclusion is that the three elements which dominate the line spectrum have comparable atmospheric abundances: carbon (48%, by mass), helium (32%), and oxygen (15%). There was no significant difference in abundances between the two stars in their analysis which pulsate and the two that appear to be nonvariable, nor between those with the higher or lower temperatures.

These abundances of C and O are orders of magnitude larger than those predicted for diffusive equilibrium including selective radiative acceleration mechanisms in a helium envelope (Vauclair 1989). The abundances of C and O suggests instead that the residual helium layer mass is less – perhaps far less – than that predicted by standard stellar evolution theory. These authors point out that most of the residual helium layer could be lost in the Wolf–Rayet phase of those planetary nebula central stars showing strong O VI, C IV and helium emission lines. They argue that this sequence is linked to the post–AGB stars undergoing at late helium shell flash, as argued earlier by Iben *et al.* (1983) and Sion, Liebert and Starrfield (1985).

In contrast, the hottest field DA white dwarfs subjected to careful analysis include objects no hotter than about 72,000 K (Holberg et al. 1989; Kidder, Holberg and Wesemael 1990, in preparation). There may be a few planetary nebula nuclei such as that of NGC 7293 which are hydrogen-rich and have $T_{\rm eff}$ near 100,000 K with log $g = 6.5$–7, but these appear to have a lower space density than those of the hot DO and PG1159 objects. Thus, while some DA stars may be progeny of H–rich planetary nebula nuclei and hot subdwarfs, it appears that some of the very hot, hydrogen–poor white dwarfs must evolve into hot DA stars. The latter are many times more numerous than DO stars at 50–70,000 K. In fact, we shall see in §2.3 that the helium sequence is completely absent below 47,000 K.

2.2. THE HOTTEST DA STARS SHOW GENEROUS TRACES OF HELIUM

This evidence has unfolded in two ways: First, lines of He II and He I having been detected in optical and ultraviolet spectra of several of the hottest known DA stars. (These stars are thus classified DAO.) Secondly, X–ray observations generally show a deficiency of soft X–ray and extreme ultraviolet fluxes relative to predictions of models assuming a pure hydrogen composition. Matching of the helium lines of the DAO objects to predictions of model atmospheres permits a direct determination of the trace helium abundance, assuming a fully mixed atmosphere. In the highest cases, the derived helium abundances exceed 0.01 by number. If the extra opacity required at high frequencies in the second group is attributed also to helium, high trace abundances of this element are also inferred in several examples (cf. Paerels 1987).

Such high trace abundances of helium in homogeneous, hydrogen–rich atmospheres would appear to require a source of mixing not predicted by theory. Vennes *et al.* (1988) showed that radiative forces fail to support the derived abundances of helium in the observed cases by at least one and usually several orders of magnitude. Convective instability of the surface layers is precluded by the high degree of ionization of the dominant element hydrogen.

An alternative possibility has been developed by several authors (Jordan and Koester 1986, Jordan *et al.* 1987, Paerels 1987, Vennes *et al.* 1988, and Paerels and Heise 1989). They proposed that the atmospheres have extremely small outer hydrogen layer masses. If the envelope is in steady–state, diffusive equilibrium, then the observed helium is the "tail" of the underlying helium layer reaching up to the surface. If this interpretation is correct, the observed hot DA white dwarfs are required to have hydrogen layer masses between $10^{-13.3}$ and approximately 10^{-15} $M_{\odot}$ (Vennes *et al.* 1988), values which at face value seem astonishingly small!

One important observational test should be able to distinguish whether the atmospheres are mixed or layered: the detailed profiles of the helium lines in the DAO stars ought to differ for the two explanations. Koester (1991, these proceedings) has made preliminary comparisons of a few observed spectra with line profiles calculated using both kinds of model atmospheres.

2.3. THERE ARE NO KNOWN DO-DB WHITE DWARFS BETWEEN 28,000 K AND 47,000 K

This "gap" in the distribution of helium–rich atmospheres was discovered as a biproduct of the WGL analysis of the DO stars and that of Liebert et al. (1986) of the hotter DB stars in the Palomar Green Survey – see also Liebert (1986). However, the temperature boundaries quoted above incorporate a new and improved model atmospheres analysis of the IUE spectra of the hotter DB stars by Thejll, Vennes and Shipman (1990); this study concludes that the temperatures for most of the hottest DB stars are generally some 2000 K lower than those determined in the earlier study, resulting in an increased temperature interval for the "gap."

The disappearance of helium–rich atmospheres would seem to require that the remaining DO stars retain a sufficient though modest mass of hydrogen spread over some depth in their envelopes as they begin their cooling evolution as white dwarfs. The time scale for this hydrogen to float to the surface must be shorter than that for the stars to cool to 47,000 K. That is, all of the DO stars must turn into DA atmospheres by the time they reach this temperature. The greatest difficulty with this picture is explaining why such a diffusion process takes so long! A star with a temperature near 50,000 K already has a cooling age of over 10^6 years, while it has been known since the early work of Schatzman (1958) that the gravitational settling time scale should be shorter than this by orders of magnitude. This difficulty is discussed in a recent paper by MacDonald and Vennes (1990).

2.4. THE HELIUM SEQUENCE REAPPEARS AS THE DB STARS BELOW 28,000 K

About 25% of the stars in the 11–27,000 K temperature range are DBs, and in these atmospheres the number densities of helium are higher than hydrogen by at least a few thousand times and hydrogen is not detected at all in the majority of DB stars. Three quarters of the white dwarfs in this temperature range remain of DA type. Fontaine and Wesemael (1987) – see also Liebert, Fontaine and Wesemael (1987) – proposed that the reappearance of the helium-rich atmospheres is due to convective

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mixing of the thin, outer hydrogen layer of some DA stars when the large convection zone of the underlying helium layer penetrates to the surface. Quantitative studies have been made by Pelletier (1986) and MacDonald and Vennes (1990). For the mixing to occur at all requires (1) that the outer hydrogen layer mass be only of the order 10^{-15} $M_{\odot}$ or less and (2) that the convective overshooting be quite efficient. The required layer mass is more than ten orders of magnitude less than the stellar evolution value quoted in the Introduction!

2.5. MOST OR ALL DA STARS AT 11–13,500 K PULSATE

Moreover, this ZZ Ceti pulsational instability strip appears to have well-defined blue and red edges. While Pesnell (1987) and Cox et al. (1987) have argued that stars with either thick or thin hydrogen layer masses would be pulsationally unstable in the observed temperature range, their models do not yet explain the observed temperature distribution and pulsational properties of the ZZ Ceti stars. On the other hand, Winget (1981), Dolez and Vauclair (1981), Winget and Fontaine (1982) and their collaborators have succeeded in explaining most of the observed properties with the assumption of outer layer masses which are again several orders of value less than that predicted by stellar evolution models at the end of the AGB. In fact Winget and Fontaine (1982) conclude that the hydrogen layer mass cannot exceed 10^{-8} $M_{\odot}$, but could in fact be orders of magnitude lower than this value.

Winget, Fontaine and their collaborators have found that the complicated, non-radial g-mode pulsation spectra of these stars are best explainable by a mechanism involving the trapping of the observed modes within a thin hydrogen layer. This mode-trapping mechanism accounts for the rather long periodicities observed, and the absense of shorter-period modes, at least in a qualitative sense. More importantly, they find that the use of a low mass H layer is necessary to fit the observed "blue edge" of the temperature range for instability near 13,500 K, and indirectly to account for the "red edge" near 11,500 K.

The argument to explain the observed low temperature boundary to the instability strip stems from the fact that the only viable mechanism suggested up to now for suppressing the pulsations as the stars cool below 11,500 K is to assume the development of a deep convection zone within the hydrogen layer. There must then be some kind of interplay between the two processes in the region of the envelope which normally drives the pulsations, causing the pulsations to be supressed. The most plausible such interplay would be to assume that convective mixing occurs between the hydrogen and helium layers, resulting in dilution of the hydrogen abundance in the driving region of the envelope. Recent calculations indicate that if the hydrogen mass does not exceed 10^{-11} $M_{\odot}$, the entire hydrogen layer can be mixed into the helium convection layer near the observed red edge at $T_{\rm eff} \sim 11{,}500$ K (Tassoul, Fontaine and Winget 1990; Forestini 1990). The helium convection zone (10^{-6} $M_{\odot}$) is predicted to be many orders of magnitude more massive than the hydrogen layer, so that complete mixing would convert the stellar atmosphere into a very helium-dominant composition, with at most a small trace of hydrogen remaining. We will see in the next section that this prediction is not consistent with the observed abundances of cooler DA stars. Thus, the existence of a very thin hydrogen layer may turn out to be a key ingredient to understanding the further cooling of ZZ Ceti stars, but more pieces of the evolutionary puzzle remain to be found.

2.6. THE PRESENCE OF HELIUM MAY BE INFERRED FOR COOLER DA STARS

Since it is now well established that the great majority of DA stars with temperatures in the ZZ Ceti instability strip actually pulsate – and it is possible that they all do – the continuation of a well–populated DA sequence below 11,500 K is difficult to explain according to the ideas discussed in the previous section. The ratio of DA to non–DA stars might be somewhat smaller below 10,000 K relative to those in the 12,000 – 27,000 K range (Sion 1984, Greenstein 1986), but it is clear that the DA sequence accounts for approximately half of these cooler white dwarfs. Envelope models predict the onset of complete mixing which would convert a pulsating DA star into a non–DA atmospheric composition. Otherwise, the mechanism causing the low $T_{\rm eff}$ boundary remains unexplained. Without convective mixing, the models predict that cooler stars with intact hydrogen envelopes would also pulsate.

For the above reasons, it has been important to estimate the helium abundances of cool DA stars, despite the obvious difficulty that this element cannot be detected directly in optical (or IUE ultraviolet) spectra at temperatures below about 12,000 K. However, the presence of significant amounts of helium can dilute the continuum opacity resulting in increasing atmospheric pressures, in a manner similar to that caused by an increase in the surface gravity. Liebert and Wehrse (1983) attempted to fit the more pressure–sensitive high Balmer lines in spectra of a few cool DA stars, in an attempt to discover whether the atmospheres showed evidence of such an additional pressure, i.e. had either high log g or enhanced helium abundances. A much more comprehensive analysis involving a detailed grid of models and extensive spectroscopic observations of cool DA stars has now been published by Bergeron *et al.* (1990); the conclusions are both unexpected and perplexing!

Bergeron *et al.* (1990) find that the set of cooler DA stars with 7,500 $< T_{\rm eff} <$ 11,500 K do show evidence for the additional pressure. That is, they appear either to have a mean surface gravity higher than that obtained for hotter DA white dwarfs, or to have significant but not dominant helium abundances. Since it is implausible that the mean mass of white dwarfs should increase with cooling age (at least not for cooling times less than a few Gyr), these authors argued that the stars are likely to be helium–enriched.

The problem is that the indicated helium abundances (if the gravities are equated to the mean for hotter DA stars) range from only $logN(He/H) =$ -1 to +1. These values are orders of magnitude lower than those predicted by envelope models assuming complete mixing of the hydrogen layer into its more massive helium counterpart. The presence of helium should be evidence that the stars have performed the deed, but one cannot currently understand why complete turnover of the hydrogen layer has not occurred. Until direct detection of the atmospheric helium becomes possible, or some observation which can distinguish between surface gravity and helium abundance is found, we will not be sure that these objects have moderate helium enrichments.

3. Summary and Implications

In Section 2 the evidence was presented which indicates that (1) most DA stars retained residual hydrogen masses in their envelope many orders of magnitude less than that predicted by stellar evolution models of AGB stars, and (2) recent results on PG1159 stars suggest that these hot, hydrogen–poor envelopes may have even lost most of the helium. Are these conclusions plausible?

Standard stellar evolution codes lack the sophistication necessary to compute quantitatively the mass loss, in particular, for the evolution after the star leaves the AGB. As Werner, Heber and Hunger (1991) argue (see §2.1), the precursors of the PG1159 should be helium–rich PNN which could undergo a vigorous period of mass loss in the Wolf–Rayet phase. If their post-AGB evolution lasts a few times 10^4 years (for a mass of 0.6 $M_\odot$), the loss of most of the helium envelope having 10^{-3} to 10^{-2} $M_\odot$ would require a mean mass loss rate of the order 10^{-7} or 10^{-6} $M_\odot$ per year, probably not an implausible value given the appearance of the spectra. Correspondingly smaller rates of the order 10^{-8} $M_\odot$ per year are required for the the sequence of H–rich PNN, again a value which cannot be excluded by observations. Thus, it is possible that both the H– and He–rich sequences leave the AGB with the masses correctly predicted by stellar evolution, but lose most of their hydrogen and/or helium envelopes in the subsequent evolution. However, the post–AGB evolution remains poorly understood in some important respects, although space limitations preclude a discussion here. Thus there remain missing pieces in our understanding of the evolution of the envelopes of post–AGB stars and white dwarfs.

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