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ON THE SURFACE COMPOSITION OF COOL, HYDROGEN-LINE WHITE DWARFS: DISCOVERY OF HELIUM IN THE ATMOSPHERES OF COOL DA STARS AND EVIDENCE FOR CONVECTIVE MIXING

P. BERGERON,[1,2] F. WESEMAEL,[1] G. FONTAINE,[1] AND JAMES LIEBERT[2]

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ABSTRACT

A determination of the helium abundance in 37 cool DA white dwarfs is presented. A spectroscopic analysis of the high Balmer lines reveals that the atmospheres of most objects below $T_e \sim 11,500$ K are contaminated by significant amounts of helium, with abundances sometimes as high as $N(\mathrm{He})/N(\mathrm{H}) \sim 20$. This result is interpreted as the result of convective mixing between the thin superficial hydrogen layer with the more massive underlying helium envelope. The lack of hydrogen-rich objects in our sample in the range $7500 < T_e < 11,500$ K indicates that most DA white dwarfs mix near $T_e \sim 11,500$ K, a result which is consistent with the location of the red edge of the ZZ Ceti instability strip. A definite trend for cooler objects to have lower helium abundances is also observed. These results are briefly discussed in terms of current models of convective mixing.

Subject headings: convection — stars: abundances — stars: white dwarfs

I. INTRODUCTION

Statistical studies of large samples of white dwarfs show that the relative number of white dwarfs with hydrogen lines (DA stars) to that without (non–DA stars) varies considerably as a function of effective temperature (see, e.g., Fig. 3 of Fontaine and Wesemael 1987). This result suggests that a variety of physical processes may be competing with gravitational settling and altering the atmospheric composition of DA and non–DA white dwarfs as they evolve along their cooling sequence.

One such process is convective mixing. Koester (1976), Vauclair and Reisse (1977), and D'Antona and Mazzitelli (1979) have shown independently that below $T_e \sim 12,000$ K, mixing between the thin superficial hydrogen layer and the more massive underlying helium layer can turn a hydrogen-rich star into a helium-rich star, provided the mass of the hydrogen layer is small enough ($M_{\mathrm{H}} < 10^{-8}\ M_{\odot}$). Their results show that the mixing temperature is a function of the mass of the hydrogen layer: for thicker hydrogen layers, the mixing occurs at lower effective temperatures. It has also been suggested that, for ZZ Ceti stars, the interplay between convective mixing and the pulsation-driving mechanism could return these stars to stability and account for the well-defined red edge of the ZZ Ceti instability strip (Winget and Fontaine 1982). Since essentially all DA white dwarfs in the temperature range of the ZZ Ceti instability strip are observed to pulsate (Fontaine *et al.* 1982, 1985), convective mixing should occur for these stars at a temperature close to that characteristic of the red edge of the instability strip, around $\sim 11,500$ K.

On the observational front, Sion (1979, 1984) has emphasized the presence of a drop in the observed DA/non–DA number ratio in both motion- and color-selected white dwarf samples. His latest statistics (Sion 1984), and those of Greenstein (1986; Figs. 1 and 2), show this ratio dropping from ~ 6 at $M_V \sim 11$ to a nearly constant value of ~ 2 in the absolute magnitude range 12–13.5 (or $7500 \lesssim T_e \lesssim 12,000$ K), a decrease interpreted as the signature of the dilution of the overlying hydrogen layer into the massive helium convection zone. Were this the case, however, the mixing temperature could be as high as 20,000 K (i.e., near $M_V \sim 11$), a temperature much in excess of the theoretically predicted value.

Clearly, the evidence based on the relative frequency of the various spectral types remains an ambiguous test of the mixing hypothesis, and our current picture of the situation below 12,000 K is, at best, sketchy. For example, it is generally assumed that convective mixing turns DA stars into non–DA stars, since the helium convection zone is so much more massive than its hydrogen counterpart; however, the efficiency of the convective mixing process may be sufficiently poorly understood that the atmospheric composition expected once mixing occurs remains uncertain. Also, because of the intrinsic difficulty of detecting any hydrogen lines at very cool temperatures (Greenstein 1986) and because the presence of hydrogen lines is not necessarily an indication of a hydrogen-rich composition, it is not even clear to what extent the DA and non–DA classes can be used to verify the occurrence of convective mixing. A further problem arises if one also considers that some fraction of the cool, non–DA white dwarfs must come from the cooling of hotter DB stars.

Progress in solving some of these complex issues may well come from detailed atmospheric abundance analyses of cool DA and non–DA white dwarfs. We report, in this *Letter*, the first results of such an analysis for a sample of DA stars below 13,000 K. Because this is roughly the temperature below which helium becomes spectroscopically invisible, it is then no longer possible to use helium lines to determine the helium abundance, and one has to rely on more subtle indices. In particular, Liebert and Wehrse (1983; also Wehrse 1977) have shown that the atmospheric helium abundance can be determined from a detailed examination of the high Balmer lines, since the presence of helium increases the photospheric pressure and thus produces a quenching of the upper levels of the hydrogen atom which, in turn, affects the line profiles. This is a potentially powerful method which requires an accurate knowledge of the way high-lying levels of the hydrogen atom are perturbed. To model this effect accurately we use a new formalism

[1] Département de Physique, Université de Montréal.
[2] Steward Observatory, University of Arizona.

to compute atomic level populations which will allow us—as we discuss below—to determine the helium abundance in cool DA white dwarfs. Preliminary results of this work were presented in Bergeron, Wesemael, and Fontaine (1987, 1989).

II. THEORETICAL FRAMEWORK

We briefly summarize here the procedure used in our model atmosphere and line profile calculations. Details will be given in Bergeron, Wesemael, and Fontaine (1990). The model atmospheres are calculated using a version of Grenfell's (1972) code, modified to take into account the blanketing of the hydrogen lines. The models are in LTE and include only hydrogen and helium. Convection is treated within the mixing-length theory parameterized with the so-called ML1 version (Fontaine, Villeneuve, and Wilson 1981). The computed grid covers the range $T_e = 5000$ (500) 12,000 K, $\log g = 7.5$ (0.5) 8.5, and $N(\mathrm{He})/N(\mathrm{H}) = 0$, 0.01, 0.1, 1, 5, 10, and 25. The thermodynamical stratification of these models is used to calculate synthetic spectra which include thermal broadening as well as an improved treatment of Stark, resonance, and van der Waals broadening.

The population of the individual levels of the hydrogen atom is calculated within the Hummer-Mihalas formalism (Hummer and Mihalas 1988; Däppen, Anderson, and Mihalas 1987). Examples of spectra calculated with this improved treatment are presented elsewhere (Bergeron, Wesemael, and Fontaine 1987, 1989). These spectra also illustrate the influence, on the high Balmer lines, of the increased pressure caused by the inclusion of helium in the atmosphere. However, a similar effect can be obtained by simply increasing the surface gravity of the star. Liebert and Wehrse (1983) have suggested, from theoretical considerations, that both effects could be separated; a detailed study of our synthetic spectra suggests that, in practice, *it is not possible to separate the pressure effects originating from increased helium abundance from those stemming from an increased surface gravity*, even from a careful examination of the Balmer lines and photometric colors (Bergeron, Wesemael, and Fontaine 1990). At a given effective temperature, a white dwarf with a pure hydrogen atmosphere and a given surface gravity will have the same line profiles and photometric colors as a helium-enriched DA star at a lower surface gravity. Thus, for a given object, no single solution for the atmospheric parameters [T_e, $\log g$, and $N(\mathrm{He})/N(\mathrm{H})$] can be obtained unless the surface gravity (or helium abundance) is known *a priori* from independent analyses. Because of the narrowness of the mass distribution of DA white dwarfs obtained by Koester, Schulz, and Weidemann (1979) and Weidemann and Koester (1984), we feel justified to use for this sizable sample of objects the average gravity determined from large samples of those stars, namely $\log g \sim 8$. With this assumption, the analysis yields individual helium abundances for each star. By studying a fairly large sample of cool DA white dwarfs, these helium abundances can be interpreted statistically.

III. RESULTS AND ASTROPHYSICAL IMPLICATIONS

Spectra for 19 cool DA white dwarfs were obtained in 1982 October, and a further sample of 18 objects was observed in 1989 January with the Steward Observatory 2.3 m reflector. Typical DA stars were selected on the basis of their colors, mainly $(b - y)$ and $(G-R)$, in the catalog of McCook and Sion (1987), and cover a range in effective temperature of $6000 \leq T_e \leq 13{,}000$ K. Two ZZ Ceti stars (GD 66, G238–53), included in the sample, allow a check on the hypothesis that these objects have pure hydrogen atmospheres.

As discussed above, a surface gravity of $\log g = 8.0$ is assumed for all objects. The Hγ and Hδ line profiles are first fitted at various helium abundances in an interpolated grid [$\log N(\mathrm{He})/N(\mathrm{H}) = -2.0(0.1)1.4$] in order to obtain a helium-dependent estimate of the effective temperature. This locus of acceptable $T_e - N(\mathrm{He})/N(\mathrm{H})$ combinations is then searched in order to fit satisfactorily the Hϵ and H8 lines, which are sensitive to the helium abundance. H9 is also checked but only for internal consistency of the adopted solution. Typical internal errors of ± 60 K in effective temperature and ± 0.2 dex in $N(\mathrm{He})/N(\mathrm{H})$ are achieved. A sample fit is shown in Bergeron, Wesemael, and Fontaine (1989). The results of our fits to the complete sample is displayed in Figure 1. Details will be given in Bergeron *et al.* (1990). Our analysis demonstrates that the atmospheres of most DA white dwarfs below $T_e = 11{,}500$ K are contaminated by large amounts of helium. In some of these objects, the latter is even the dominant constituent. Two stars (G1–7 and G67–23) have $N(\mathrm{He})/N(\mathrm{H}) > 10$. Clearly, at these temperatures, the DA designation may well bear no relation to the dominant chemical constituent of the atmosphere!

Since it is not possible to separate helium abundance effects from surface gravity effects, the helium abundance of *individual* objects depends on the adopted surface gravity. Accordingly, it might still be possible to fit all these DA white dwarfs with pure hydrogen models but at a surface gravity different from our assumed mean value of $\log g = 8.0$. However, we find that to fit

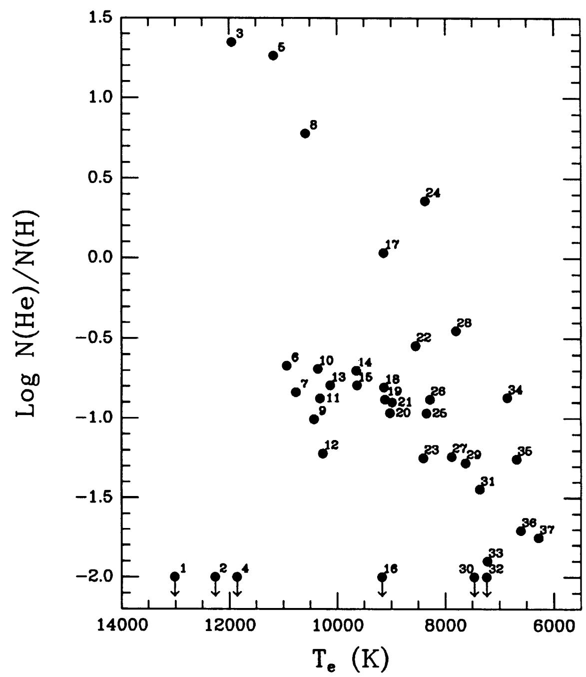

FIG. 1.—Helium abundances determined in cool DA white dwarfs as a function of effective temperature. The upper limits of $N(\mathrm{He})/N(\mathrm{H}) = 0.01$ are completely equivalent, from a spectroscopic point of view, with pure hydrogen atmospheres and represent the detection limit of our technique. The various stars are (1) GD 165, (2) G238–53, (3) G1–7, (4) GD 66, (5) G67–23, (6) GD 275, (7) PG 1149+057, (8) PG 1237−028, (9) G61–17, (10) GD 340, (11) G172–4, (12) GD 83, (13) G121–22, (14) GD 290, (15) L710-30, (16) L587-77A, (17) GD 25, (18), G115–9, (19) PG 0901+140, (20) G28–13, (21) G93–53, (22) G49–33, (23) G175–46, (24) G117–25, (25) G187–32, (26) G1–45, (27) G90–28, (28) G92–40, (29) GD 69, (30) GD 96, (31) R627, (32) G259–21, (33) G74–7, (34) G108–26, (35) G156–64, (36) G144–51, and (37) G217–37.

the two most helium-rich objects in Figure 1 with pure hydrogen models, the surface gravity of these objects must be increased to an unlikely value of $\log g \sim 8.8$, a result which is nevertheless consistent with previous analyses of those objects under the assumption that these stars have *pure hydrogen atmospheres:* Shipman (1979) found $\log g = 8.6$ for G1–7 and G67–23; Koester, Schulz, and Weidemann (1979) found $\log g = 8.57$ for G1–7 and $\log g = 8.43$ for G67–23; McMahan (1989) found $\log g = 8.88$ for G67–23.

If we ignore these extreme cases, the mean surface gravity of the subsample must be increased to $\log g \sim 8.2$ to fit the bulk of our objects found in the range $-1.5 < \log [N(\mathrm{He})/N(\mathrm{H})] > -0.5$ with pure hydrogen models. It could be argued that this mean value simply reflects a systematic tendency of our models to produce high surface gravities in individual fits, and thus that most of our objects do indeed have a pure hydrogen atmosphere. However, our technique of fitting the high Balmer lines with synthetic spectra calculated with the Hummer-Mihalas formalism has also been applied to a sample of 10 ZZ Ceti stars (Daou *et al.* 1990), as well as to 16 hotter DA white dwarfs (Bergeron, Saffer, and Liebert 1990). The mean surface gravity obtained for these 26 additional objects, where helium abundance effects do not come into play, is $\log g = 7.87$ with a standard deviation of $\sigma = 0.21$, an indication that our models do not produce fits at systematically high surface gravities (note that were this lower value for the mean $\log g$ used instead of 8.0 in our analysis, the helium abundances of individual objects would be even higher than those shown in Fig. 1).

It can also be argued that a mean surface gravity of $\log g = 8.2$ for a subsample of objects is not statistically implausible and that this somewhat higher value is not inconsistent with $\log g = 8.0$ for the total population of white dwarfs. However, the probability of our subsample having a mean surface gravity of $\log g = 8.2$ and still being drawn from a population of white dwarfs with a mean surface gravity of $\log g = 8.0$ and a standard deviation of $\sigma = 0.25$ (Shipman and Sass 1980), is less than 0.01% (Bergeron *et al.* 1990). We thus believe that the inability of pure hydrogen models at $\log g = 8.0$ to yield satisfactory fits to the observations does not reflect an improper choice of mean surface gravity for our sample of objects but rather is the signature of *the presence of helium in the atmospheres of most cool DA stars.*

Because the gravitational settling time scale for helium at effective temperatures representative of this sample is of the order of 10^2–10^4 yr (Paquette *et al.* 1986), the observed helium cannot be of primordial origin. One must also abandon the idea that the observed helium has been accreted from the interstellar medium, as implausibly large steady state accretion rates of the order of $10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$ are required to maintain an abundance of $N(\mathrm{He})/N(\mathrm{H}) \sim 0.1$ in these stars. Undoubtedly, the presence of helium in the atmosphere of cool DA white dwarfs indicates that *mixing between the hydrogen convection zone and the more massive underlying helium layer has indeed occurred.*

Figure 1 also shows that three of the hottest objects in our sample, beyond 11,500 K, are hydrogen-rich: two of these objects (G238–53 and GD 66) are well-known ZZ Ceti stars, while the third (GD 165) has recently been identified as a new variable DA white dwarf (Bergeron and McGraw 1990). These results confirm the hypothesis that the ZZ Ceti stars have pure hydrogen atmospheres and represent an evolutionary phase prior to the onset of convective mixing.

The results presented in Figure 1 indicate that the highest mixing temperature falls near $T_e \sim 11{,}500$ K, where the hottest, helium-rich objects are found. Such a high mixing temperature implies that *the mass of the hydrogen layer in some of these DA white dwarfs is very small.* Although the exact value depends on the adopted convective efficiency, the hydrogen layer mass can be estimated to be in the range 10^{-14} to $10^{-11} M_*$ (Forestini 1990). In addition, the near-absence of hydrogen-rich white dwarfs in the range $7500 < T_e < 11{,}500$ K implies that few DA white dwarfs have survived the helium enrichment. Because white dwarfs with thicker hydrogen layers mix at lower effective temperatures, the paucity of hydrogen-rich survivors in that temperature range suggests that *the mixing temperature of most DA white dwarfs is near* $T_e = 11{,}500$ K. This implies that *the mass of the hydrogen layer must be of the order of* 10^{-14} to $10^{-11} M_*$ *for most DA stars.* These values are consistent with the results obtained from pulsation studies of ZZ Ceti star models (e.g., Winget and Fontaine 1982) and also with other values quoted in the context of the spectral evolution of white dwarfs (see Fontaine and Wesemael 1987 for a review) but remain inconsistent with current models of pre–white dwarf evolution (Iben 1984; Iben and Tutukov 1984; Iben and MacDonald 1985, 1986; Koester and Schönberner 1986).

The existence of a unique mixing temperature for all DA white dwarfs also reinforces the suggestion (Winget and Fontaine 1982) that the interplay between nonradial pulsations and convective mixing could be responsible for the observed red edge of the ZZ Ceti instability strip near $T_e \sim 11{,}500$ K. Furthermore, since the statistics of Sion (1984) and Greenstein (1986) show little evidence for a significant decrease of the number of DA relative to the number of non–DA white dwarfs at that temperature, our results suggest that convective mixing usually does not produce non–DA white dwarfs but instead produces hydrogen-line (DA) objects of moderate helium content $[N(\mathrm{He})/N(\mathrm{H}) < 100]$. If this interpretation is correct, most cool non–DA white dwarfs would originate from the cooling of DB stars.

Also observed in Figure 1 is a trend for lower helium abundances at lower effective temperatures which is not predicted by evolutionary mixing calculations (Forestini 1990). Instead, the expected helium abundance after convective mixing is governed by the ratio of the mass of the hydrogen convection zone to that of the helium convection zone, as long as hydrogen remains a trace element. Since the mass of the helium convection zone is almost constant below $T_e \sim 12{,}000$ K ($M_{\mathrm{He\text{-}conv}} \sim 10^{-6} M_*$), the predicted $N(\mathrm{He})/N(\mathrm{H})$ ratio is in the range 10^4–10^7 for a mixing temperature of $T_e \sim 11{,}500$ K and would remain essentially constant along the cooling sequence. White dwarfs with such abundances would presumably be classified non–DA stars; thus an interpretation in terms of pure convective mixing cannot account for the existence of the objects of less-extreme helium content which we discovered. For the latter, provided the efficiency of convective mixing is well enough understood, additional sources of hydrogen may have to be considered.

One such potential source of hydrogen is interstellar accretion. Because of their cooling time scales of several Gyr below $T_e = 12{,}000$ K, cool white dwarfs may accrete important quantities of hydrogen from the interstellar medium, mostly through frequent encounters with interstellar clouds (Wesemael 1979). The accreted hydrogen will be thoroughly diluted in the mixed hydrogen-helium convection zone. The cumulative effect of the accreted material could, perhaps, explain the trend observed in Figure 1. It is not an easy task to estimate the accretion rate required to account for the observed trend, since hydrogen at the observed level is no longer a trace element in the convection zone, and detailed simulations are therefore required. We hope to report on such calculations in the near future. If this interpretation is correct, however, our results indicate that accretion is a common phenomenon in all cool DA white dwarfs. This conclusion emphasizes the challenging problem of explaining—in that context—the persistent existence of stars with no hydrogen lines at very cool effective temperatures (Greenstein 1986). Clearly, we have only begun to sort things out at the low-temperature end of the white dwarf sequence.

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P. BERGERON and J. LIEBERT: Steward Observatory, University of Arizona, Tucson, AZ 85721

G. FONTAINE and F. WESEMAEL: Département de Physique, Université de Montréal, C.P. 6128, Succ. A, Montréal, Québec, Canada H3C 3J7