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A Comprehensive Spectroscopic Analysis of DB White Dwarfs

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Abstract. We summarize salient results from a comprehensive analysis of the optical spectra of a large sample of helium-line DB and DBA white dwarf stars.

Keywords: White dwarfs, atmospheres, abundances
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INTRODUCTION

It has been 15 years since we last reviewed the work carried out in Montreal on the optical spectra of DB and DBA white dwarfs [7]. Parts of this work have been published over the years [6, 4, 2, 3, 5, 10, 14], and full and definitive results from this long-term project will be available shortly.

The DB are characterized by the extreme purity of their helium-dominated atmospheres with, occasionally, only minute traces of hydrogen and heavy elements seen in their optical spectra. Progress on several fronts relevant to the study of DB stars has been significant since our review [7]: the discovery of stars in the DB gap through the Sloan Digital Sky Survey (SDSS), the discovery of a new class of carbon-rich stars− the so-called hot DQ stars, the analysis of the DB stars in the ESO Supernova Ia Progenitor Survey (SPY), the far-ultraviolet observations of DB stars with FUSE, the likelihood of atmospheric contamination of the photospheres of DB stars through disk-fed accretion, etc. Yet, our knowledge of some of the fundamental properties of DB stars, embodied in a set of questions posed by Beauchamp et al. [7], remains sketchy. These questions referred to the respective mass distributions for the DA and DB stars and to the possible existence of a bimodal mass distribution for DB degenerates, to the existence of statistical evidence for differences between the DB and DBA samples, as well as to the existence of atmospheric peculiarities in hot DB stars that might afford possible evidence for a recent episode of convective mixing. All these questions remain current, and need to be addressed for a complete understanding of the physical properties and evolutionary status of DB stars.

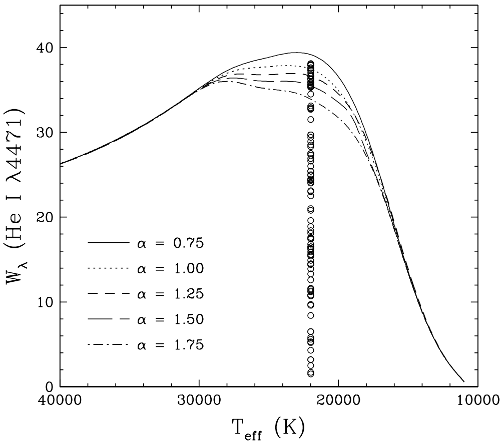

FIGURE 1. Variation of the equivalent width of the He I λ4471 transition as a function of effective temperature for different convective efficiencies, parameterized by α, the ratio of mixing length to pressure scale height within the ML2 theory. The models are characterized by log $g = 8.0$ and a pure helium composition. Also plotted at $T_{\rm eff} = 22,000$ K is the range of measured equivalent widths in our sample.

THE TASK OF ANALYZING OPTICAL SPECTRA OF DB STARS

The problems inherent to the analysis of spectra of DB stars have been well documented since the 1970s, and need not be described in detail here. Suffice it to say that, in addition to being rarer than their hydrogen-line DA counterparts, the hotter DB stars are characterized by an optical spectrum where the neutral helium transitions exhibit little sensitivity to effective temperature. As an illustration, the variation of the equivalent width of the neutral helium λ4471 transition as a function of effective temperature shows a wide plateau, about 10,000 K wide, that inhibits the determination of accurate effective temperatures from the optical spectrum of DB stars in the range between 20,000 K and 30,000 K. Luckily, we fare somewhat better with gravity indicators, and the large gravity-sensitivity of several segments containing neutral helium transitions (notably the 2^3P-6^3D λ3819 line, the region 4100-4200 Å, that contains the 2^3P-5^3S λ4121, 2^1P-6^1D λ4144, and 2^1P-6^1S λ4169 lines, as well as the strong 2^1P-5^1D λ4388 transition) [15] can be used with some success.

Less well documented is the sensitivity of the optical spectrum of DB stars to the convective efficiency, an additional parameterization first introduced by Beauchamp [1] on the basis of work carried out in the hydrogen-line DA stars. To illustrate it, we show, in Figure 1, the sensitivity of the equivalent width of the He I λ4471 transition to variations in α, the ratio of the mixing length to the pressure scale height, within the ML2 version of the mixing-length theory. The line width is sensitive to α for effective temperatures between 16,000 K and 30,000 K, and the largest predicted equivalent widths (for $\alpha = 0.75$) are larger than the largest measured values. This means that, were we to overestimate α in our models, all the stars would be shifted toward the maximum of the curve (i.e., near 30,000 K for $\alpha = 1.75$) and form a clump whereas, if we underestimate α, the stars we fit will be lumped on respective sides of the maximum

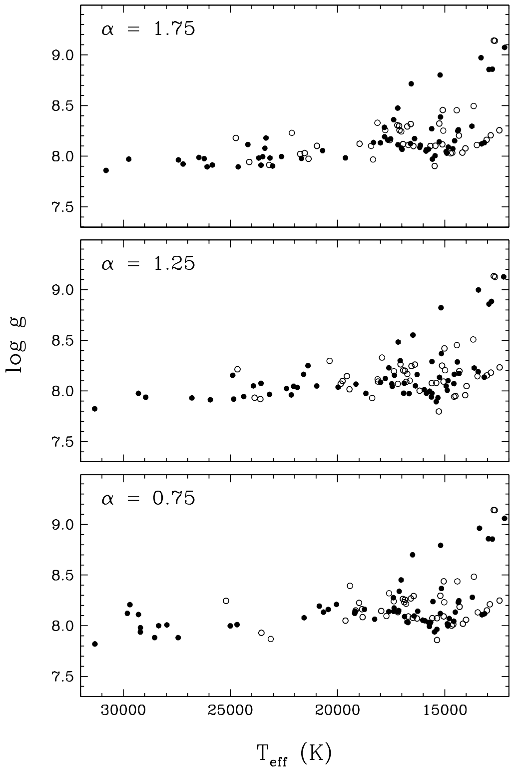

FIGURE 2. Distribution of DB (solid circle) and DBA (open circle) stars in the log g *vs.* $T_{\rm eff}$ plane for three values of α, the ratio of the mixing length to the pressure scale height.

of the curve (i.e., near 18,000 K and 30,000 K for $\alpha = 0.75$), and gaps will develop in the distribution of stars with respect to effective temperature. This behavior can be used to constrain α, as we show below.

THE SAMPLE, AND CURRENT STATUS OF THE ANALYSIS

The sample of DB stars under study includes 103 DB, DBA and DBZ stars. In comparison, a recent analysis based on the SPY sample [13], the largest completed up to now, included 69 objects. Most of our objects were observed at high S/N ratio in the blue region of the optical spectrum (3700–5200 Å) with the Steward Observatory 2.3 m Bok Telescope. Additional blue spectra were secured at the du Pont 2.5 m telescope of the Carnegie Observatories. Because coverage of the Hα line is essential for the determination of accurate atmospheric parameters for DB stars, we complemented our blue data with red spectra obtained from four distinct sources: the KPNO 4 m data used by Hunter et al. [10], spectra secured at the du Pont 2.5 m telescope, the SPY spectra of Voss et al.

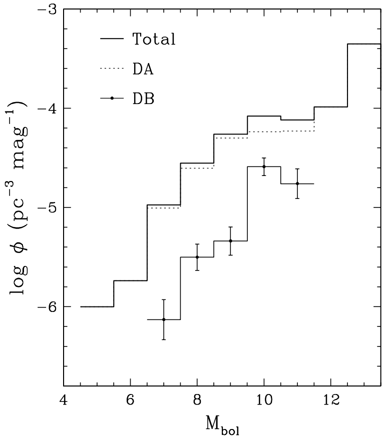

FIGURE 3. Luminosity function for the DB stars extracted from the complete PG sample. The luminosity function of the DA stars [11] and that for the total (DA+DB) sample are also plotted.

[13], and spectra extracted from Data Release Four of the SDSS.

On the theoretical side, our work has greatly benefited from the calculation of detailed profiles for over twenty lines of neutral helium, observable in the optical [4]. These profiles take into account the transition from quadratic to linear Stark broadening, the transition from impact to quasi-static regime for electrons, as well as forbidden components. In addition, our models and synthetic spectra include the Hummer-Mihalas occupation probability formalism along with the treatment of pseudo-continuum opacity.

The analysis of the hot DB star PG 0112+104 we recently completed [8] made use of the latest version of our grid of models and illustrates its capabilities. A summary of our determinations of effective temperature and surface gravity is shown in Figure 2, where we display the results of our analyses using three different values of α, the efficiency parameter discussed above. On the basis of the gaps that appear in the distribution of stars for $\alpha = 0.75$ (near 22,500 K and 27,000 K) and of the large clump observed for $\alpha = 1.75$ (near 24,000 K), we opt in our analysis for an intermediate value $\alpha = 1.25$. With that choice, there is a good correlation between optical temperatures and temperatures based on IUE energy distributions, although there remains a systematic, and unaccounted for, offset of $\sim$ 1500 K between temperature scales (in the sense that the ultraviolet temperature is higher than the optical one) in the range between 15,000 K and 22,000 K.

MASSES, LUMINOSITY FUNCTION, AND HYDROGEN CONTENT OF DB STARS

Our review [7] already featured a preliminary discussion of the mass distribution of DB white dwarfs. In our updated analysis, we find that *i)* there is no significant mass difference between the DB and the DBA samples (in contrast to our preliminary conclusion [7]); *ii)* the peak of the mass distribution of the DB and DBA stars agrees with that which

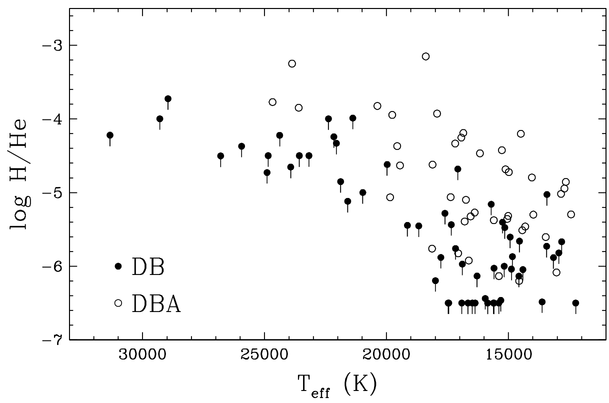

FIGURE 4. Distribution of the hydrogen abundance (or upper limit on H/He) as a function of effective temperature for the DB (solid circle) and DBA (open circle) stars.

characterizes the DA stars; *iii)* there are no low-mass DB stars (in agreement with our preliminary conclusion [7]).

Also of interest is the luminosity function of DB stars. We show, in Figure 3, that derived on the basis of the subsample of stars that are part of the complete PG survey. In the bolometric magnitude range over which DB stars are detected (roughly $M_{\rm bol} = 7-11$), the DB/DA+DB ratio is of the order of 0.2. We note, however, a large and significant increase in the value of log ϕ in the range from $M_{\rm bol} = 9-10$, that corresponds to an effective temperature near 20,000 K. Thus, the DB/DA ratio is lower than the nominal value of 1 out of 4 white dwarfs at high effective temperatures, but increases sharply for stars below 20,000 K. This, it turns out, is also the temperature at which the bottom of the helium convection zone sinks sharply into the envelope along the cooling sequence.

As a final item of interest, we discuss briefly the pattern of hydrogen abundance as a function of effective temperature shown in Figure 4. Several aspects of this plot are noteworthy. For values of $T_{\rm eff}$ above 25,000 K, the measured abundances are of the order of H/He $\sim 10^{-4}-10^{-5}$. If the hydrogen observed at these temperatures is associated with the complete convective mixing of a thin hydrogen layer into an underlying helium convection zone, and if this mixing has already occurred at $T_{\rm eff} \sim 25,000$ K, MacDonald & Vennes [12] show that the required hydrogen layer mass has to be $\sim 10^{-15} M_{\odot}$. This mass, it turns out, is comparable to the mass of the helium convection zone at these temperatures. The complete dilution of hydrogen should thus lead to a H/He ratio ~ 1 instead of the observed value H/He $\sim 10^{-4}-10^{-5}$. The hydrogen content of these hot DB stars is thus unlikely to be associated with convective mixing in a DA star. More likely, these stars are the progeny of the DB stars observed in the DB gap [9].

Below 20,000 K, some of the upper limits on the hydrogen abundance are quite stringent, H/He $< 10^{-6.5}$. These DB stars are observed in the same range as some DBA stars, characterized by hydrogen abundances of the order of H/He $\sim 10^{-4.5}$, a factor 100 higher. It is thus difficult to understand why accretion of hydrogen, often invoked to account for the presence of hydrogen, could be effective for some stars, and not for others at the same temperature. In addition, the required hydrogen layer mass has to be

$\gtrsim 10^{-14} M_\odot$ in order for convective mixing to occur at $T_{\rm eff} < 20,000$ K. If we convert the observed abundances in DBA stars below 20,000 K to hydrogen layer masses, we find layer masses in the range between $10^{-12} M_\odot$ and $10^{-10} M_\odot$. In other words, we observe much more hydrogen in those stars than would be expected on the basis of the *complete mixing* of the hydrogen layer in the underlying helium convection zone. The problem is not new, but the easy way out of calling on accretion now seems out of favor, given that the DBZ stars are unlikely to be associated with accretion from the ISM. Perhaps it is time to question the assumption of *complete mixing* of the hydrogen envelope: in that case, it remains conceivable that the amount of hydrogen present is $\sim 10^{-14} M_\odot$, but that it somehow floats on top of the photosphere rather than being forcefully mixed by the helium convection zone.

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