The Mass Distribution of White Dwarfs: An Unwavering Obsession

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Abstract. We discuss some of our current knowledge of the mass distribution of DA and non-DA stars using various methods for measuring white dwarf masses including spectroscopic, trigonometric parallax, and gravitational redshift measurements, with a particular emphasis on the problems encountered at the low end of the cooling sequence where energy transport by convection becomes important.

1. An Unwavering Obsession

The unwavering obsession to which the title refers applies only to the first author since the other co-authors are still too young to be obsessed by such a thing as the mass distribution of white dwarf stars.

As early as 1976, it was suggested that below $T_{\text{eff}} \sim 12,000$ K, convective mixing between the thin superficial hydrogen layer and the more massive underlying helium layer could turn a hydrogen-rich star into a helium-rich star, provided the mass of the hydrogen layer is small enough (a modern value yields $M_H \simeq 10^{-6} M_\odot$). Furthermore, the effective temperature at which this mixing occurs is a function of the mass of the hydrogen layer: for thicker hydrogen layers, the mixing occurs at lower effective temperatures. Since the process of convective mixing is still poorly understood, the exact ratio of helium to hydrogen after the mixing occurs remains unknown. In particular, it is possible that instead of turning a DA star into a featureless helium-rich DC star, convective mixing may simply enrich the hydrogen-rich atmosphere with large quantities of helium, leading to a mixed hydrogen and helium atmospheric composition. Such a hypothesis is difficult to test, however, since helium becomes spectroscopically invisible below $T_{\text{eff}} \sim 12,000$ K, and its presence can only be inferred through indirect methods.

Such a method has been proposed by Liebert & Wehrse (1983) who showed that the atmospheric helium abundance could 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 method has been put forward on a more quantitative basis by Bergeron et al. (1990) who analyzed 37 cool DA stars using the spectroscopic method of fitting high Balmer
line spectroscopy with the predictions of detailed model atmospheres with mixed hydrogen and helium compositions. Their analysis first showed that the effects produced on the hydrogen lines at high log $g$ could not be distinguished from those produced by the presence of large amounts of helium. Hence, the problem could only be approached from a statistical point of view by assuming a mean value of log $g = 8$ for all stars, and then by determining individual helium abundances. Under this assumption, the analysis of Bergeron et al. revealed that the atmospheres of most objects below $T_{\text{eff}} \sim 11,500$ K were contaminated by significant amounts of helium, with abundances sometimes as high as $N(\text{He})/N(\text{H}) \sim 20$.

We show in Figure 1 an update of this result using a sample of 232 DA stars analyzed with our most recent grid of model atmospheres. On the left panel we show the surface gravity as a function of effective temperature for each object. Clearly, the values determined here are significantly higher than the canonical value of log $g = 8$ for DA stars (shown by the dashed line); the mean surface gravity of this sample is actually log $g = 8.167$. If we assume instead that our sample is representative of other DA stars and adopt log $g = 8$ for each object, we can determine individual helium abundances. This is shown on the right panel of Figure 1. As can be seen, non-negligible amounts of helium in the range $N(\text{He})/N(\text{H}) = 0.1 - 10$ at the surface of these DA stars can easily account for the high log $g$ values inferred under the assumption of pure hydrogen compositions.

![Figure 1](image_url)

Figure 1. Atmospheric parameters for a sample of 232 DA stars obtained under the assumption of a pure hydrogen atmospheric composition (left panel) and under the assumption of an average surface gravity of log $g = 8.0$ (right panel).
2. The Spectroscopic Method at High Effective Temperatures

The results discussed above rest heavily on the ability of the models to describe accurately the physical conditions encountered in cool white dwarf atmospheres, but also on the reliability of the spectroscopic method to yield accurate measurements of the atmospheric parameters. It is with this idea in mind that Bergeron, Saffer, & Liebert (1992, BSL hereafter) decided to test the spectroscopic method using DA white dwarfs at higher effective temperatures ($T_{\text{eff}} > 13,000$ K) where the atmospheres are purely radiative and thus do not suffer from the uncertainties related to the treatment of convective energy transport, and where the assumption of a pure hydrogen composition is certainly justified. From the analysis of a sample of 129 DA stars, BSL determined a mean surface gravity of $\log g = 7.909$, in much better agreement with the canonical value of $\log g = 8$ for DA stars.

![Figure 2. Mass distribution of 677 DA stars above $T_{\text{eff}} = 13,000$ K (solid line; left axis) compared with that of 54 DB and DBA stars above $T_{\text{eff}} = 15,000$ K (hatched histogram; right axis). The average masses are 0.585 and 0.598 $M_\odot$, respectively.](image)

More recently, Liebert, Bergeron, & Holberg (2005) obtained high signal-to-noise spectroscopy of all 348 DA stars from the Palomar Green Survey and determined the atmospheric parameters for each object using NLTE model atmospheres. If we restrict the range of effective temperature to $T_{\text{eff}} > 13,000$ K, the mean surface gravity of their sample is $\log g = 7.883$, in excellent agreement with the results of BSL. The corresponding mean mass for this sample is 0.603 $M_\odot$ using evolutionary models with thick hydrogen layers. As part of our ongoing survey aimed at defining more accurately the empirical boundaries of the instability strip (see Gianninas, Bergeron, & Fontaine, these proceedings),
we have been gathering for several years optical spectroscopy of DA white dwarfs from the McCook & Sion catalog using the Steward Observatory 2.3 m telescope facility. The mass distribution for the 667 DA stars above 13,000 K is displayed in Figure 2, together with the mass distribution for 54 DB and DBA stars taken from [Beauchamp et al. (1996)]; for the latter, uncertainties with the line broadening theory of helium lines limits the accuracy of the spectroscopic method to $T_{\text{eff}} > 15,000$ K. Both mass distributions are in excellent agreement.

3. Moving Towards Lower Effective Temperatures

The results discussed in the last section indicate that the atmospheric parameters of hot ($T_{\text{eff}} > 13,000$ K) DA stars are reasonable, and that the high log $g$ values obtained for cool DA stars are not related directly to the spectroscopic method itself. One of the largest uncertainties in cool white dwarf atmospheres is the treatment of convective energy transport. In an effort to parameterize the convective efficiency in DA stars, [Bergeron et al. (1995)] studied a sample of 22 ZZ Ceti stars and showed that the so-called ML2/α = 0.6 version of the mixing-length theory yields the best internal consistency between optical and UV effective temperatures, trigonometric parallaxes, $V$ magnitudes, and gravitational redshift measurements. The mass vs. temperature distribution for our complete sample of DA stars using this parameterization is displayed in Figure 3.

![Figure 3](image_url)

Figure 3. Spectroscopic masses as a function of effective temperature for our complete sample of DA stars (open circles) and DB/DBA stars (open squares). Filled circles correspond to ZZ Ceti stars.

The problem with the high masses — or high log $g$ values — towards low effective temperatures is clearly apparent here. However, this increase in mass begins not only where convective mixing is believed to occur, but even in the temperature range where ZZ Ceti stars are found. If the larger-than-average mass for ZZ Ceti stars is explained in terms of helium enrichment from the deeper helium convection zone, the hydrogen layers in ZZ Ceti stars need to be
as thin as $M_H \sim 10^{-12} M_\odot$ (see Fig. 4 of Dufour & Bergeron, these proceedings), in sharp contrast with values determined for ZZ Ceti stars from asteroseismology.

4. Alternative Means of Measuring White Dwarf Masses

Further insight into the problem with high masses at low effective temperatures may be gained by comparing the masses inferred from the spectroscopic method with those obtained from other methods, namely from trigonometric parallax and gravitational redshift measurements. We have thus secured high signal-to-noise spectroscopy for 129 DA stars, 92 of which have parallaxes available, and 49 of which have gravitational redshifts. In Figure 4 we reproduce the spectroscopic masses as a function of effective temperature for our complete sample of DA stars discussed in the previous section, and we overplot in the top and bottom panels the masses derived from trigonometric parallax and gravitational redshift measurements, respectively.

![Figure 4. Spectroscopic masses of DA stars (solid dots) compared with masses derived from trigonometric parallax measurements (open circles, top panel) and from gravitational redshift parallax measurements (open circles, bottom panel). All three samples correspond to a different set stars.](image)

The parallax method relies on optical $BVRI$ and infrared $JHK$ photometric measurements to constrain the effective temperature and the solid angle $\pi (R/D)^2$ between the flux received at Earth and that emitted at the surface of the star. Given the distance $D$ obtained from the parallax, we obtain directly the radius $R$ and thus the photometric mass using evolutionary models. One
of the most obvious features of the distribution of photometric masses in the top panel of Figure 4 is the large number of low mass \( M < 0.4 \, M_\odot \) white dwarfs. Most of these objects are probably unresolved double degenerates for which the flux received at Earth corresponds to the contribution of both stars. Hence the radii are overestimated and the masses are underestimated. If we ignore these low mass objects, the photometric masses do exhibit higher than average masses when compared with the spectroscopic masses at higher temperatures, which are closer to the canonical value of \( \sim 0.6 \, M_\odot \), although the dispersion of the photometric masses is also significantly larger. In some, but not all cases, the photometric mass exceeds the spectroscopic mass. It is then possible to adjust individually the atmospheric helium abundances until both methods yield consistent masses. Since the parallax method uses broadband energy distributions that are not affected significantly by the presence of helium (Boudreault & Bergeron 2005, Fig. 4), the photometric masses are almost completely independent of the assumed atmospheric composition, in sharp contrast with the spectroscopic method. We finally note that in the case of the massive \( (M = 1.3 \, M_\odot) \) DA star LHS 4033 (Dahn et al. 2004), the parallax and spectroscopic masses agree to within 0.01 \( M_\odot \).

The gravitational redshift method used in the bottom panel of Figure 4 is based on the relation between the measured redshift velocity, the mass \( M \), and the radius \( R \) of the star, \( v_{\text{GR}} = GM/Rc \). This method provides mass measurements that are almost completely independent of anything else, although the velocity measurements are intrinsically more difficult to obtain than the other types of measurements used with other techniques. In particular, since the redshift mass measurements scale linearly with velocity, low mass white dwarfs are intrinsically more difficult to measure, and the errors are correspondingly larger. Nevertheless, if we take at face value the results shown in Figure 4, the redshift masses do not reveal any particular trend at low effective temperatures. More accurate trigonometric parallax and gravitational redshift measurements of individual stars may be required, together with some unwavering obsession, to help us further understand the high mass problem observed at low temperatures.

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