White Dwarf Mass Distribution

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Abstract. We present the mass distribution for all $S/N \geq 15$ pure DA white dwarfs detected in the Sloan Digital Sky Survey up to Data Release 12, fitted with Koester models for $ML2/\alpha = 0.8$, and with $T_{\text{eff}} \geq 10000$ K, and for DBs with $S/N \geq 10$, fitted with $ML2/\alpha = 1.25$, for $T_{\text{eff}} > 16000$ K. These mass distributions are for $\log g \geq 6.5$ stars, i.e., excluding the Extremely Low Mass white dwarfs. We also present the mass distributions corrected by volume with the $1/V_{\text{max}}$ approach, for stars brighter than $g=19$. Both distributions have a maximum at $M = 0.624 M_\odot$ but very distinct shapes. From the estimated $z$-distances, we deduce a disk scale height of 300 pc. We also present 10 probable halo white dwarfs, from their galactic U, V, W velocities.

1. Introduction

Stars born with initial masses up to $8.5–10.6$ M\odot (Woosley & Heger 2015), corresponding to at least 95% of all stars, become white dwarfs when they cannot fuse nuclear elements in the core anymore. For single star evolution, the minimum mass of the white dwarf is around $0.30–0.45$ M\odot (e.g. Kilic et al. 2007). Considering the mass-radius relation of white dwarfs, this corresponds to a $\log g \geq 6.5$. Progenitors that would become lower mass white dwarfs live on the main sequence longer than the age of the Universe. We therefore determine our mass distribution only for white dwarfs with $\log g \geq 6.5$.

We estimated the masses of all DA white dwarfs found by Kleinman et al. (2013), Kepler et al. (2015) and Kepler et al. (2016a) among the 4.5 million spectra acquired by the Sloan Digital Sky Survey Data Release 12. For the mass distribution we only consider spectra with $S/N \geq 15$ to have reliable mass determinations. The spectra were fitted with synthetic spectra from model atmospheres of Koester (2010), using $ML2/\alpha = 0.8$ for DAs, and $ML2/\alpha = 1.25$, for DBs. We use the mass-radius relations of Althaus et al. (2005), Renedo et al. (2010) and Romero et al. (2015), to calculate the mass of our stars from the $T_{\text{eff}}$ and $\log g$ values obtained from our fits, after correcting to 3D convection following Tremblay et al. (2013).

2. Mass Distribution

Figure 1 shows the mass distribution by number for DAs with $T_{\text{eff}} \geq 13000$ K, where convection is unimportant, and for DBs with $T_{\text{eff}} \geq 16000$ K reported by Koester
& Kepler (2015). Because our surface gravities show an unexplained decrease below $T_{\text{eff}} = 10000$ K, Figure 2 shows the mass distribution for different cutoff temperatures.

3. Discussion

With our population synthesis analysis, we computed a theoretical mass distribution through a Monte Carlo simulation fitting single star initial mass functions, initial-to-final mass relations for masses $0.45 M_\odot \leq M < 1.0 M_\odot$, to obtain a history of star formation for the DAs with $T_{\text{eff}} \geq 13000$ K. Figure 3 shows the mean mass around $0.64 M_\odot$ requires a burst of star formation in the last 2 Gyr, as a white dwarf with such mass has a short lived progenitor mass with a mass around $2.5 M_\odot$. This is in
Figure 2. Mass distribution corrected by the $1/V_{\text{max}}$ method for DAs for different cutoff temperatures, and DB with $T_{\text{eff}} \geq 16000$ K. DAs with $T_{\text{eff}} \geq 10000$ K, $N=4054$, $<M> = 0.647 \pm 0.002 \, M_\odot$ in black, $T_{\text{eff}} \geq 13000$ K, $N=3637$, $<M> = 0.646 \pm 0.002 \, M_\odot$ in violet, $T_{\text{eff}} \geq 16000$ K, $N=3012$, $<M> = 0.641 \pm 0.002 \, M_\odot$ in gold, $T_{\text{eff}} \geq 25000$ K, $N=1121$, $<M> = 0.613 \pm 0.003 \, M_\odot$ in green.

contrast with the uniform star formation estimated by Catalán et al. (2008) from the ML2/$\alpha = 0.6$ mass distribution of Kepler et al. (2007).

Convolving the intensities from the theoretical models with filter transmission curves, and appropriate zero-points, we estimated the corresponding absolute magnitudes. Comparing with the observed g-filter photometry we estimated the distance modulus, obtaining the distances. From distances and the galactic latitude, we estimated the distance of each star from the galactic plane $z$. Figure 4 shows the distance above the galactic plane for each star studied, showing the disc scale height is around 300 pc for DAs and a few parsecs larger for DBs.

Finally, using the distances, our measured radial velocities and the proper motions obtained from APOP (Qi et al. 2015) only for those stars which has a measured proper motion larger than three times its uncertainty, we estimated the galactic velocities U, V, and W for each star (e.g Johnson & Soderblom 1987). We compared the proper motions from APOP (Qi et al. 2015) with those of Munn et al. (2014) and they are very similar. In Figure 5, we show the galactic velocities we infer for each star. As expected, most white dwarfs observed by SDSS belong to the thin and thick disk. Because of the saturation limit around $g = 14.5$, nearby white dwarfs only if very cool are included. The SDSS observations are also preferentially for directions across the galactic disk.
Figure 3. Mass distribution corrected by the $1/V_{\text{max}}$ method for the 3637 DAs with $T_{\text{eff}} \geq 13000$ K, $\langle M \rangle = 0.646 \pm 0.002$ $M_\odot$, and DBs with $T_{\text{eff}} \geq 16000$ K. The blue line shows a population synthesis with a 30% burst 2 Gyr ago, to account for the high mean mass. The theoretical mass distribution represented by the population synthesis does not include either He-core or O-Ne-core models.

In Table 1 we list the 10 stars with galactic velocities outside the thin and thick disk ellipsis of Kordopatis et al. (2011), which are probably halo white dwarfs, or the result of a binary interaction.

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References
Althaus, L. G., García-Berro, E., Isern, J., & Córnsico, A. H. 2005, A&A, 441, 689
Catalán, S., Isern, J., García-Berro, E., & Ribas, I. 2008, MNRAS, 387, 1693
Johnson, D. R. H., & Soderblom, D. R. 1987, AJ, 93, 864
Kepler, S. O., Kleinman, S. J., Nitta, A., et al. 2007, MNRAS, 375, 1315
Kepler, S. O., Pelisoli, I., Koester, D., et al. 2015, MNRAS, 446, 4078
Kepler, S. O., Pelisoli, I., Koester, D., et al. 2016, MNRAS, 455, 3413
Kepler, S. O., Koester, D., & Ourique, G. 2016, Science, 352, 67
Kilic, M., Stanek, K. Z., & Pinsonneault, M. H. 2007, ApJ, 671, 761
Figure 4. Histogram of the distribution of DAs and DBs versus the $z$ distance above the galactic plane. The $1/e$ line drawn shows the scale height for the plane is around 300 pc for DAs and a few parsecs larger for DBs.

Table 1. DA white dwarfs for which their galactic velocities indicate probable halo members.

| SDSS J          | S/N | $g$  (mag) | $\sigma_g$ (mag) | $T_{\text{eff}}$ (K) | $\sigma_T$ (K) | $\log g$ (cgs) | $\sigma_{\log g}$ (cgs) | dist $z$ (pc) |
|-----------------|-----|------------|------------------|----------------------|----------------|---------------|-----------------------|----------------|
| 081514.42+511311.39 | 33  | 17.647     | 0.014            | 74528                | 644            | 7.354         | 0.027                 | 1142            |
| 091734.49+020924.37 | 15  | 18.882     | 0.015            | 16261                | 268            | 7.660         | 0.053                 | 448             |
| 113219.73+075441.94 | 22  | 19.068     | 0.033            | 33820                | 256            | 8.122         | 0.057                 | 1431            |
| 115045.04+191854.61 | 15  | 19.112     | 0.026            | 19135                | 247            | 8.122         | 0.040                 | 407             |
| 121731.31+610520.36 | 31  | 18.075     | 0.017            | 41495                | 443            | 7.895         | 0.038                 | 655             |
| 123827.80+312138.30 | 26  | 17.743     | 0.022            | 60285                | 1551           | 7.730         | 0.080                 | 802             |
| 125816.99+000710.24 | 20  | 18.135     | 0.015            | 14910                | 159            | 7.870         | 0.035                 | 256             |
| 152658.83+021510.19 | 17  | 18.871     | 0.016            | 48853                | 1297           | 7.200         | 0.098                 | 1739            |
| 225513.66+230944.14 | 36  | 17.771     | 0.024            | 30007                | 118            | 7.522         | 0.020                 | 529             |
| 230228.08+231747.90 | 21  | 19.441     | 0.010            | 40716                | 720            | 7.740         | 0.064                 | 1054            |
Figure 5. Galactic velocities obtained from the radial velocity, proper motion and distance modulus for each DA white dwarf. The ellipses plotted are the 3σ mean velocities of stars in the thin disk, thick disk and halo (Kordopatis et al. 2011). The blue cross labeled DOX represents the oxygen atmosphere white dwarf found by Kepler et al. (2016b) and its uncertainties can be used as reference.

Kleinman, S. J., Kepler, S. O., Koester, D., et al. 2013, ApJS, 204, 5
Koester, D. 2010, MemSAI, 81, 921
Koester, D., & Kepler, S. O. 2015, A&A, 583, A86
Kordopatis, G., Recio-Blanco, A., de Laverny, P., et al. 2011, A&A, 535, A107
Munn, J. A., Harris, H. C., von Hippel, T., et al. 2014, AJ, 148, 132
Qi, Z., Yu, Y., Bucciarelli, B., et al. 2015, AJ, 150, 137
Renedo, I., Althaus, L. G., Miller Bertolami, M. M., et al. 2010, ApJ, 717, 183
Romero, A. D., Campos, F., & Kepler, S. O. 2015, MNRAS, 450, 3708
Schmidt, M. 1968, ApJ, 151, 393
Tremblay, P.-E., Ludwig, H.-G., Steffen, M., & Freytag, B. 2013, A&A, 552, A13
Woosley, S. E., & Heger, A. 2015, ApJ, 810, 34