White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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The completeness of Gaia-selected samples of white dwarfs

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Abstract. The Gaia DR2 has dramatically increased the ability to detect faint nearby white dwarfs. The census of the local white dwarf population has recently been extended from 25 pc to 50 pc, effectively increasing the sample by roughly an order of magnitude. Here we examine the completeness of this new sample as a function of variables such as apparent magnitude, distance, proper motion, photometric color index, unresolved components, etc.

Keywords. stars, white dwarfs, Gaia

1. The Nearby White Dwarf Sample Revisited

Surveys to detect white dwarfs (WDs) have been conducted for almost a century, usually via astrometric and photometric criteria. Such samples tend to be magnitude-limited and are rarely complete. Drawing candidates from all available sources and confirming WDs via spectroscopy, Holberg *et al.* (2016) presented a 25 parsec WD sample, expanding the local WD census by about a factor of two over prior work (Holberg, Oswalt & Sion 2002). Based on number counts vs. trigonometric and spectroscopic parallaxes, this sample is about 68 percent complete and is among the most thoroughly vetted and well-defined samples of nearby WDs.

The Sloan Digital Sky Survey (SDSS) spectroscopically identified over 40,000 WDs (Kleinman *et al.* 2013; Kepler *et al.* 2019), increasing the census of WDs by nearly an order of magnitude. However, the SDSS primarily samples the youngest and most luminous WDs. It therefore provides little information on the large fraction of cool WDs and binary systems that contain WDs. Also, due to its bright magnitude limit the SDSS overlaps very little with searches for WDs within about 100 pc. For example, the 25 pc Holberg *et al.* (2016) sample contains only 5 WDs in common with the SDSS DR7.

With the advent of the Gaia mission DR2 (Gaia Collaboration 2016), the potential to construct extremely large samples of WDs is being realized. Recently, Gentile Fusillo *et al.* 2019) compiled a catalog of almost 500,000 WD candidates from the DR2. Using the SDSS sample of spectroscopically identified WDs to map the parameter space, multidimensional cuts in the Gaia astrometric and photometric data were used to identify 260,000 high confidence WD candidates.

Independently, our group extracted a sample of 2310 WD candidates within 50 pc of the Sun using Gaia DR2 trigonometric parallaxes and the properties of the Holberg *et al.* (2016) spectroscopically identified 25 pc sample. The result is shown in Figure 1, which

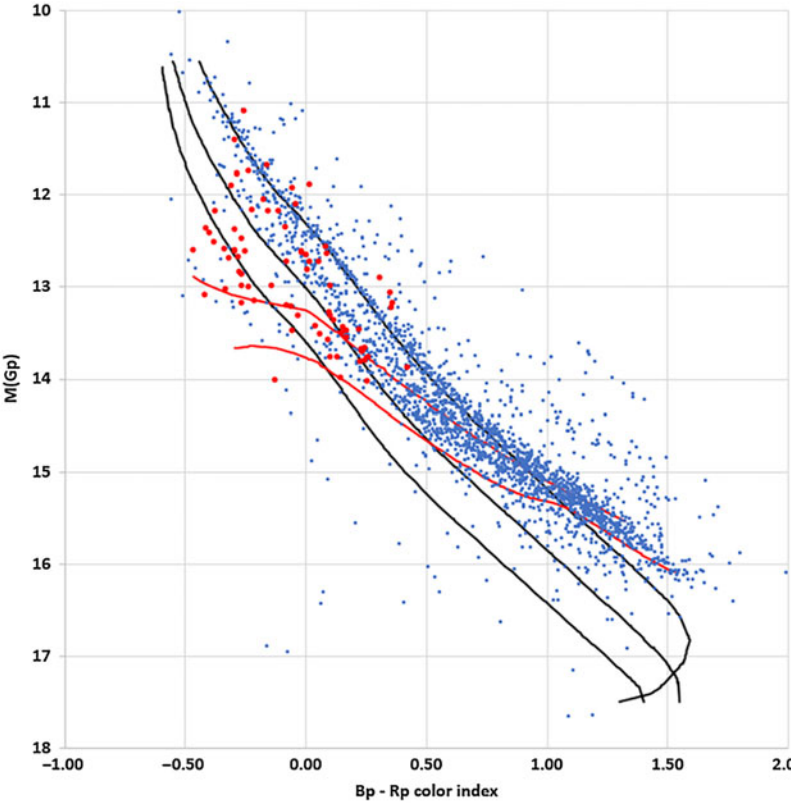

Figure 1. H-R diagram for 2310 WDs (blue dots) extracted from the Gaia DR2 using Gp magnitudes, trigonometric parallaxes and Bp - Rp color indices and spectroscopic information from Holberg *et al.* (2016). Red dots indicate known magnetic WDs identified by Kepler *et al.* (2013). Black curves indicate cooling sequences for WDs of 0.6, 0.9 and 1.1 solar mass (top to bottom, respectively) from Fontaine, Brassard & Bergeron (2001). Red curves indicate where evolutionary models by Tremblay *et al.* (2019) predict 20 percent (top) and 80 percent (bottom) of the total WD mass has crystallized.

is an H-R diagram constructed from Gaia trigonometric parallaxes, Gp magnitudes and Bp-Rp color indices. The 2310 WD candidates within 50 pc are represented by blue dots. The bifurcation of their distribution in this diagram results from the well-known effects of H-rich and He-rich atmospheres. Red dots identify magnetic WDs spectroscopically identified by Kepler *et al.* (2013) in the SDSS DR7. From top to bottom, black curves indicate cooling sequences for 0.6, 0.9 and 1.1 solar masses by Fontaine, Brassard & Bergeron (2001). This sample is large enough that a hint of the pile-up arising from the release of latent heat as the cores of WDs crystallize can be seen; red curves indicate where the evolutionary models of Tremblay *et al.* (2019) predict 20 percent (top) and 80 percent (bottom) of the total WD mass has crystallized.

Figure 1 suggests that our 50 pc sample and other Gaia DR2 WD samples are strongly affected by a number of factors. First, the scatter above the most populated 0.6 solar mass cooling curve suggests the sample includes many unresolved binaries. Based upon outliers in a Gaia color-color plot, we estimated that about 8 percent of our 50 pc sample are unresolved WD+MS binaries, comparable to the 6 percent contamination in the Holberg *et al.* (2016) 25 pc sample. Second, magnetic WDs are an important source of scatter. Unfortunately, only a small fraction of the Gaia WD candidates have spectra of sufficient

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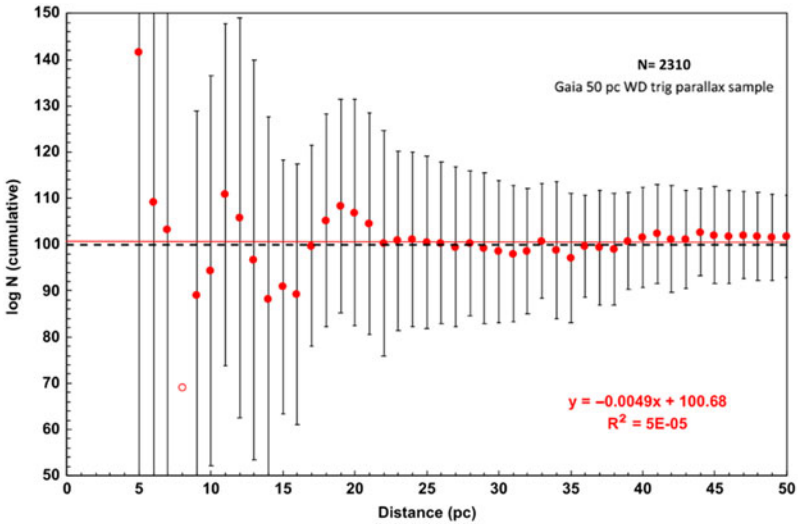

Figure 2. Completeness of the Gaia DR2 50 pc WD sample derived from cumulative counts vs. distance. Distances were directly obtained from Gaia trigonometric parallaxes. Error bars computed from $N^{-1/2}$ scatter in each bin.

resolution to detect line profile splitting and most of the WDs in the lower portion of the cooling sequence have featureless spectra. Third, stars with high tangential velocity and/or proper motion are missing from DR2; DR3 will remedy this.

Our Gaia 50 pc sample is confined well within the Galactic plane so simple star counts can be used to derive its completeness and the WD space density. As shown below, it is also large enough and complete enough to eliminate the need for the 1/Vmax method or more sophisticated statistical methods to construct the white dwarf luminosity function (WDLF), which is susceptible to small number fluctuations, observational biases, and/or incompleteness (see Garcia-Berro & Oswalt (2016) for a discussion of these problems).

2. Completeness as a Function of Distance

Assuming a uniform space density of stars, cumulative counts scale with the cube of the distance. Gaia DR2 provides an unprecedented quantity of precise trigonometric parallaxes, enabling this straightforward assessment of completeness. Oswalt, Holberg & Sion *et al.* (2017) outline several other ways, which we have also applied to our 50 pc sample. Figure 2 displays the bin-by-bin completeness of our 50 pc sample as a function of distance. Subject to the caveats outlined in the previous section, the 50 pc sample is formally 100 percent complete. The implied space density is 0.0041 WDs pc^{-3}, in very good agreement with Holberg *et al.* (2016) and the WD space densities compiled from various sources by Garcia-Berro & Oswalt (2016).

3. The White Dwarf Luminosity Function

The Gaia 50 pc sample enables the most straightforward approach to determining the WDLF: simple star counts within a volume-limited sample that is demonstrably complete. Figure 3 displays the WDLF for our Gaia 50 pc sample. The total space density implied is about 0.0044 pc^{-3}, slightly higher than that derived from number counts but well within uncertainties imposed by assuming H-rich atmospheres and bolometric corrections. The slight bump at the bright end near $M_{bol} = 9$ noted by Holberg *et al.* (2016) in the 25 pc sample is still visible. More noteworthy is a significant dip near

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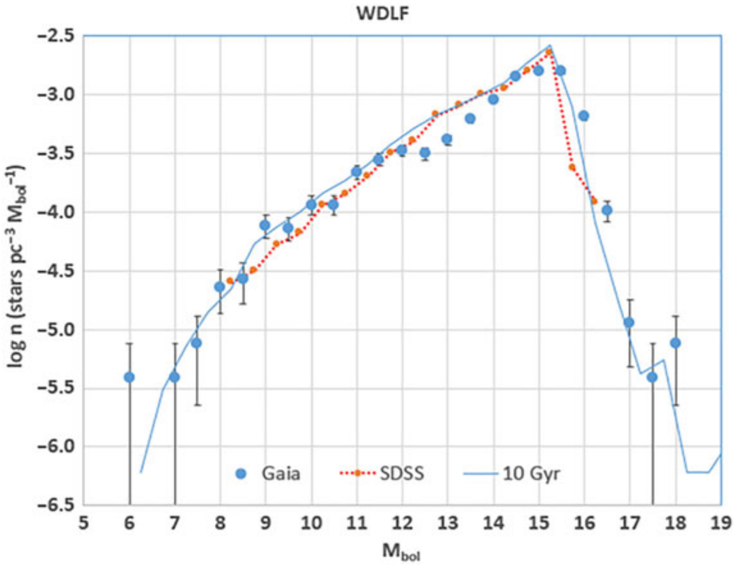

Figure 3. WDLF derived from the 50 pc Gaia sample (blue dots). The observed WDLF from the SDSS by Harris *et al.* (2016, orange dashed line) and a model WDLF for a Galactic disk age of 10 Gyr computed by Garcia-Berro & Oswalt (2016, priv. comm.; blue line) are shown for comparison. Error bars are as in Figure 1.

$M_{bol} = 13$, which may be related to crystallization among older WDs shown by Tremblay *et al.* (2019). It should be noted that unresolved pairs, Sirius-like binaries, magnetic WDs, etc., move individual objects into bins that do not reflect their actual luminosity. However, using a population synthesis approach, Rebassa-Mansergas *et al.* (2019) recently showed that unresolved double WDs and WD+MS pairs are unlikely to significantly affect the WDLF.

4. Conclusions

Our analysis of other properties, such as reduced proper motions, space motions, color indices, spectroscopic and population subtypes, etc. of the 50 pc sample is ongoing. In parallel with other groups (e.g., Jimenez-Esteban *et al.* 2018; Gentile Fusillo *et al.* 2019; Tremblay *et al.* 2019; Torres *et al.* 2019) we are also working to construct a complete volume-limited Gaia WD sample to 100 pc WD...and beyond.

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