Stellar archaeology with Gaia: the Galactic white dwarf population

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Abstract. Gaia will identify several 10^5 white dwarfs, most of which will be in the solar neighborhood at distances of a few hundred parsecs. Ground-based optical follow-up spectroscopy of this sample of stellar remnants is essential to unlock the enormous scientific potential it holds for our understanding of stellar evolution, and the Galactic formation history of both stars and planets.

1. White dwarfs as tracers of the Galactic star formation history

The local white dwarf population preserves detailed information on the Galactic star formation history. Nearly 95% of all stars will end their lives as white dwarfs, and most $\gtrsim 1.2 M_\odot$ stars ever formed are now stellar remnants. White dwarf cooling is well understood in terms of the underlying physics (Fontaine et al. 2001), and has been used to estimate the age of the Galactic disc (e.g. Oswalt et al. 1996), individual open clusters (e.g. García-Berro et al. 2010), and the halo (Kalirai 2012).

Broader application of this method has been prevented so far by the small and incomplete samples of known white dwarfs. Because of their small radii, white dwarfs are intrinsically faint, requiring moderately large telescope apertures for their study. Consequently the currently available luminosity functions contain at best a few thousand stars (Harris et al. 2006; De Gennaro et al. 2008), based on white dwarfs identified by SDSS. However, incompleteness and selection biases severely limit the constraints that can be drawn from these studies. Tremblay et al. (2014) demonstrated the potential of a complete and well-characterised white dwarf sample to derive the local star formation history and initial mass function, using only the 117 white dwarfs known within 20 pc of the Sun, though obviously limited by small number statistics.

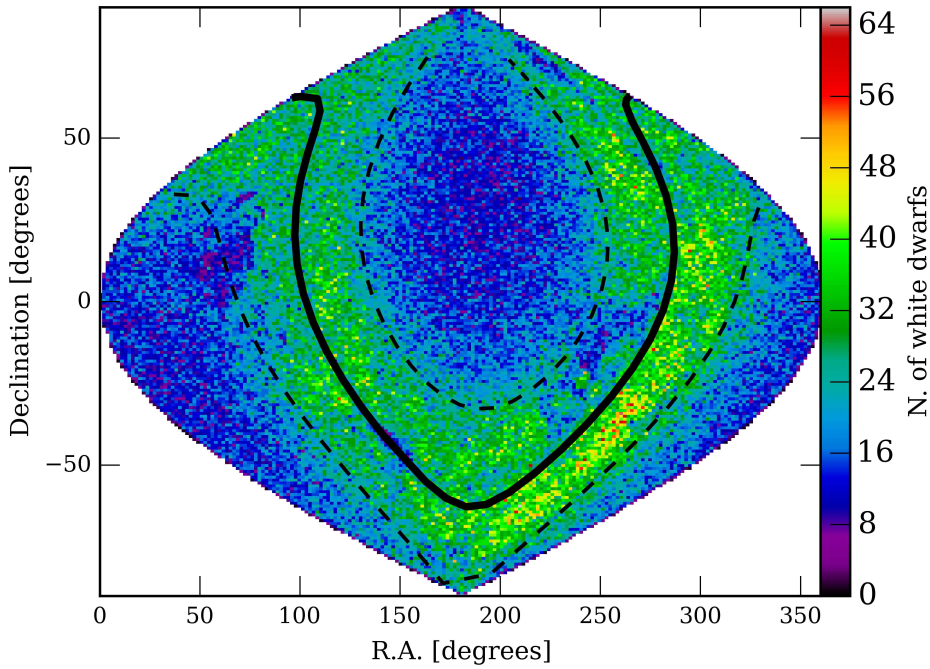

Figure 1. Based on the GUMS-10 simulation (Robin et al. 2012), Gaia will detect $\simeq 575\,000$ white dwarfs with $G < 20$. The surface density of white dwarfs varies (shown here in $\deg^{-2}$) between $\simeq 5\,\deg^{-2}$ near the Galactic poles and $\simeq 45\,\deg^{-2}$ in the Galactic plane (solid line, the dashed lines are $|b| = \pm 30°$). The increase at low $|b|$ is largely due to young, bright, and more distant white dwarfs.

Combining parallax, apparent magnitude, proper motion and BP/RP colour, Gaia will overcome all the traditional limitations in the discovery of white dwarfs. The $\simeq 5 \times 10^5$ white dwarfs that Gaia will identify (Fig. 1) will be 100 % complete within $\simeq 50$ pc, and $\simeq 50$ % out to 300 pc (Jordan 2007; Carrasco et al. 2014). The sample of Gaia white dwarfs will be sufficiently large to reconstruct the stellar formation history and initial mass function for the thin/thick disc and halo separately and assess the ages of these three components individually.

However, while Gaia will identify the entire local white dwarf population, it will not provide the data that is necessary to determine accurate masses and temperatures, which are the key parameters for measuring the white dwarf cooling ages. The spectral resolution of the BP/RP spectra is too low to apply the standard method for measuring temperatures and surface gravities from the Stark-broadened Balmer line profiles (Fig. 2; e.g. Bergeron et al. 1992). This implies that ground-based follow-up is essential to unlock the diagnostic potential that the Gaia white dwarfs have for investigating the Galactic star formation history. To break the degeneracy between temperature and surface gravity requires spectroscopy covering the higher Balmer lines down to $\simeq 380$ nm (e.g. Kepler et al. 2006), which are most sensitive to surface gravity, and hence mass. Several of the forthcoming wide-area MOS instruments are perfectly suited for this goal, including DESI, WEAVE, and 4MOST.

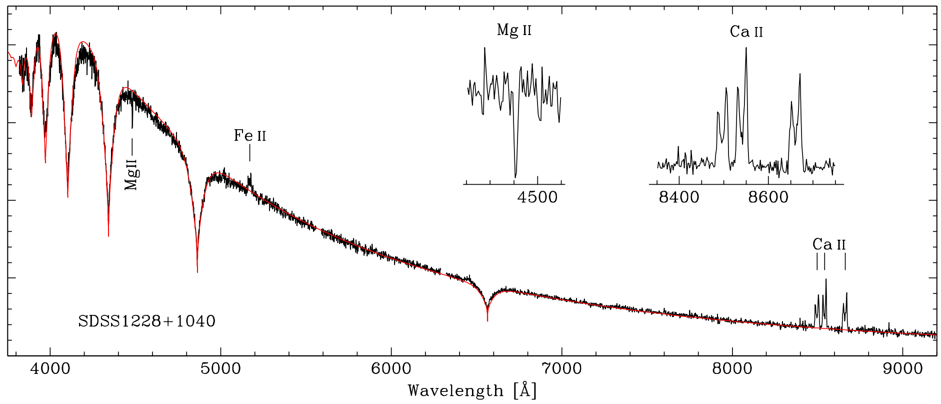

Figure 2. Most white dwarfs have hydrogen-dominated atmospheres (black). $T_{\rm eff}$ and log g are measured from fitting the Stark-broadened Balmer lines (red). Ground-based spectroscopy of the Gaia white dwarfs is essential, as the BP/RP spectra have insufficient spectral resolution. SDSS demonstrated the potential for serendipitous discoveries, such as this white dwarf accreting metal-rich planetary debris (Gänsicke et al. 2006).

Gaia will also not obtain radial velocities of white dwarfs, as they typically have no spectral features in the RVS wavelength range, and are too faint for RVS spectroscopy anyway. To establish the Galactic orbits, and hence thin/thick disc or halo membership, radial velocities of the Gaia white dwarfs have to be obtained from the ground. This is most efficiently done by intermediate-resolution ($R \simeq 5000$) spectroscopy of the sharp NLTE core in Hα (Pauli et al. 2006; Falcon et al. 2010).

2. Additional science goals

The initial-to-final mass (IFM) relation. The physics of mass loss on the RGB/AGB is still poorly understood, and lacks stringent observational constraints. Yet, it is of crucial importance for the Galactic lifecycle of matter, and for the chemical evolution of galaxies (e.g. Maraston 1998). Traditionally, the IFM relation has been investigated using white dwarfs in open clusters (Casewell et al. 2009), and Gaia will significantly add to the known population of white dwarfs in open clusters. Gaia, coupled with ground-based spectroscopy will also fully enable the potential of wide binaries to constrain the low-mass end of the IFM relation (Catalán et al. 2008; Girven et al. 2010).

The mass-radius (M-R) relation. Despite its fundamental importance, from predicting white dwarf masses to understanding the nature of SN Ia, this relation is very poorly constrained by observations (Holberg et al. 2012). Spectroscopic observations of white dwarfs cannot directly determine both mass and radius, and therefore parallaxes are needed to independently determine the radius. Currently only a handful of white dwarfs have parallaxes accurate to better than 5 %, but Gaia will improve this situation dramatically, both in terms of raw numbers of white dwarf parallaxes, as well as their accuracy. Spectroscopic follow-up covering the higher Balmer lines is essential to reach a few percent precision on both mass and radius. The internal stratification of white dwarfs can then be constrained by comparing the observed M-R relation with theoretical relations assuming different interior compositions (3–5 % effect on the M-R relation). Accurate knowledge of the core compositions will also vastly improve the derived cooling ages, which are essential for the Galactic archeology applications.

Rare white dwarfs. SDSS has thoroughly demonstrated the *huge* discovery potential of a large spectroscopic survey of white dwarfs. Follow-up of the Gaia white dwarfs will be essential to improve our understanding of rare evolution channels such as C/O-atmosphere white dwarfs, that may be remnants of S-AGB stars (e.g. Dufour et al. 2007; Gänsicke et al. 2010), strongly magnetic white dwarfs that can be used as laboratories for physics under extreme conditions (Külebi et al. 2009), and dynamically active evolved planetary systems (e.g. Gänsicke et al. 2006, see Fig. 2). Throughout the last decade, it has become clear that white dwarfs serve not only as tracers of stellar evolution and star formation, but provide equally important information on the formation, structure, and evolution of planetary systems. Many white dwarfs ($> 30\,\%$) show signatures of planetary systems in the form of metal-pollution of their otherwise gravitationally settled pure-H/He atmospheres (e.g. Zuckerman et al. 2010). These metals, accreted from disrupted planetary bodies, provide the only method to directly measure the bulk composition of extra-solar planetary systems, including the detection of water-rich planetesimals (e.g. Farihi et al. 2013). Gaia follow-up spectroscopy will be essential to increase the known sample of metal-polluted white dwarfs. The strongest tracer of planetary debris is the Ca H/K doublet, again requiring blue coverage down to $\simeq 380$ nm at intermediate-resolution to detect the most polluted objects.

SN Ia progenitors. Although double-degenerate white dwarf binaries are one of the likely populations to produce SN Ia, the current census of these stars is utterly inadequate to test population models and predictions of SN Ia rates and delay time distributions (Maoz et al. 2014). The largest dedicated search for double-degenerates covered only a few hundred stars (Napiwotzki et al. 2001), and found a close binary fraction of $\sim 5\,\%$. Time-resolved spectroscopy of the Gaia white dwarfs using DESI/WEAVE/4MOST sub-spectra has the potential to identify 1000s of close double-degenerates, spanning the entire parameter space in mass, mass ratio, and orbital period.

3. Survey requirements

The key goal is to obtain low resolution ($R \simeq 5000$) spectroscopy of the entire local white dwarf population identified by Gaia to maximize the number of thick disk and halo white dwarfs, as well as massive ($> 0.8\,M_\odot$) white dwarfs in the thin disk. Massive white dwarfs make up $\simeq 10\,\%$ of the population (e.g. Tremblay et al. 2013), and a luminosity function of $\simeq 10\,000$ of these stars will determine the star formation rate of short-lived A/B stars to within $\simeq 5\,\%$ throughout the age of the thin disk with a time resolution of a few 100 Myr (Torres et al. 2005). The necessary number of fibres is small, $\simeq 10\,\mathrm{deg}^{-2}$ (Fig. 1), only $\simeq 1-3\,\%$ of the fibres available in each DESI, WEAVE, or 4MOST field. White dwarfs are intrinsically faint, and hence to zeroth order isotropically distributed, and should be multiplexed into all wide-area spectroscopic surveys to maximise the total survey area / number of observed targets.

The bulk of the Gaia white dwarf population will have $15 < V < 20$. Given the proximity of most white dwarfs, even at the faint end, the Gaia parallaxes will still be spectacularly good (5 % at 100 pc for the faintest white dwarfs in the sample). Based on our experience with SDSS (2.5m aperture), a MOS on a 4 m aperture should deliver a signal-to-noise ratio of $\simeq 20-30$ in a typical 1 h exposure, which is amply sufficient for the stellar parameter determination. Also based on SDSS ($R \simeq 1800$), we expect a radial velocity uncertainty from the $H\alpha$ line cores measured from DESI, WEAVE, or 4MOST low-res spectra to be $\simeq 5 - 10$ km/s, well sufficient to determine the Galactic population membership.

The Gaia-based selection of white dwarfs relies on the second data release (positions, proper motions, parallaxes, integrated XP photometry, and G-magnitudes) expected in early 2017. Because of their small radii ($\simeq 0.01R_{\odot}$), white dwarfs will be extreme outliers in the Gaia Hertzsprung-Russell diagram, and their identification will be trivial and free of contaminants. Should there be a delay in this data release, we will fall back onto an efficient multi-colour plus reduced proper motion selection that works very well in the SDSS footprint (Gentile Fusillo et al. 2015). We are in the process of extending this selection to the southern hemisphere making use of the VST/ATLAS survey, as well as PanSTARRS 3pi and SkyMapper in the near future.

Higher-resolution ($R \simeq 20\,000$) WEAVE and 4MOST spectroscopy of the brightest Gaia white dwarfs ($V \lesssim 16.5$) would help to increase the radial velocity resolution obtained from Hα, and to improve the sensitivity to metal pollution in Ca H/K, or Mg II 447 nm (Fig. 2).

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