First Glimpse of the Galactic Star Formation History from the Gaia eDR3 White Dwarf Luminosity Functions

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ABSTRACT

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1 INTRODUCTION

White dwarfs (WDs) are the final stage of stellar evolution of main sequence (MS) stars with zero-age MS (ZAMS) mass less than $8\mathcal{M}_{\odot}$. Since this mass range encompasses the vast majority of stars in the Galaxy, these degenerate remnants are the most common final product of stellar evolution, thus providing a good sample to study the history of stellar evolution and star formation in the Galaxy. In this state, there is little nuclear burning to replenish the energy they radiate away. As a consequence, the luminosity and temperature decrease monotonically with time. The electron degenerate nature means that a WD with a typical mass of $0.6\mathcal{M}_{\odot}$ has a similar size to the Earth, giving rise to their high densities, low luminosities, and large surface gravities.

The use of the white dwarf luminosity function (WDLF) as a cosmochronometer was first introduced by **?**. Given the finite age of the Galaxy, there is a minimum temperature below which no white dwarfs can reach in a limited cooling time. This limit translates to an abrupt downturn in the WDLF at faint magnitudes. Evidence of such behaviour was observed by **?**, however, it was not clear at the time whether it was due to incompleteness in the observations or to some defect in the theory (e.g., **?**). A decade later, **?** gathered concrete evidence for the downturn and estimated the age[1] of the disc to be 9.3 ± 2.0 Gyr (see also **?**). While most studies focused on the Galactic discs (**???????**), some worked with the stellar halo (**????**).

Most WDs have similar broadband colour to main sequence stars, they cannot be identified using photometry alone. They are found from UV-excess, large proper motion and/or parallax. Because of the strongly peaked surface gravity distribution of WDs, photometric fitting for their intrinsic properties is possible by assuming a surface gravity. WDs fitted in such a way are useful statistically provided that the sample is not strongly biased. This is demonstrated in various studies comparing photometric and spectroscopic solutions to calibrate the atmosphere model (**??**), as well as from the agreeing shapes of the WDLFs from spectroscopic and photometric samples. The Gaia satellite provides parallactic measurements for over a billion point sources (**??**) of which 359,000 are high confidence WD candidates (**?**, hereafter, GF21). The availability of parallaxes allows much more accurate fitting, particularly without knowing the surface gravity for the photometric sample. This has completely revolutionized the field of WD sciences. In the forthcoming decade, the Simonyi Survey Telescope at the Vera C. Rubin Observatory will continue to discover more WDs at fainter magnitudes, but only accompanied by proper motion measurement at best. Furthermore, at those magnitudes, it is infeasible to collect spectrum for most of them and thus studies will mostly rely on photometric methods.

2 WHITE DWARF LUMINOSITY FUNCTION

WDLF is a common tool for deriving the age of a stellar population. A WDLF is the number density of WD as a function of luminosity, it is an evolving function with time. Its shape and normalisation are determined from only a few parameters. **?** compared an observed WDLF derived from the Luyten Half-Second (LHS) catalogue with a theoretical WDLF to obtain an estimate of the age of the Galaxy for the first time with this technique. **?** examined WDLFs with various SFH scenarios. They showed that WDLF is a sensitive probe of the star formation history (SFH) as it shows signatures of irregularities in the SFH such as bursts and lulls. **?** took it further to address this inverse problem mathematically and showed some success in recovering the SFH of the solar neighbourhood when compared against SFH computed from other methods. By decomposing the disks and halo components of the Milky Way, we can have an independent view of the past star formation history revealed by only the WD populations, where they are most useful in deriving the SFH of old stellar populations (**??**).

The mathematical construction of a WDLF is straightforward: stars were formed in a distribution of mass ($\mathcal{M}_i$), described by the initial mass function (IMF, ϕ). Then, they spend their lifetime carrying out nuclear burning (t_{MS}), and the time they spend depends mainly on their mass. Towards the end stage of stellar evolution stars shed most of the atmosphere, which is modelled by the initial-final mass relation (IFMR, ζ). Once they have become WDs, all that is left is to know how long it has been cooling (t_{cool}) in order to reach the current luminosity (M_{bol}). The heavy-duty of these computations are coming from interpolation of pre-computed lookup tables. The important part of this work is to carefully interpolate and integrate over the model

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[1] "Age" refers to the total time since the oldest WD progenitor arrived at the zero-age main sequence.

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grids, because they are both susceptible to significant rounding errors given the huge dynamic ranges the variables cover. For example, in the case of a simple starburst of $O(10^6)$ yrs, it requires a relative error tolerance of 10^{-10} in order to integrate properly for an old population.

The integral for a WDLF when parameterised with bolometric magnitude (as opposed to luminosity) can be written as

$$n(M_{\mathrm{bol}}) = \int_{\mathcal{M}_l}^{\mathcal{M}_u} \tau(M_{\mathrm{bol}}, \mathcal{M}_f) \psi(T_0, M_{\mathrm{bol}}, \mathcal{M}_i, m, Z) \phi(\mathcal{M}_i) d\mathcal{M}_i \tag{1}$$

where n is the number density, τ is the inverse cooling rate, ψ is the relative star formation rate, ϕ is the initial mass function; and their dependent variables: M_{bol} is the absolute bolometric magnitude, $\mathcal{M}_f$ is the WD mass, T_0 is the look-back time, $\mathcal{M}_i$ is the progenitor MS mass, Z is the metallicity, $\mathcal{M}_l$ is the minimum progenitor MS mass that could have singly evolved into a WD in the given time, and $\mathcal{M}_u$ is the maximum progenitor MS mass.

The inverse cooling rate

$$\tau(M_{\mathrm{bol}}, \mathcal{M}_f) = \frac{dt_{\mathrm{cool}}}{dM_{\mathrm{bol}}} (M_{\mathrm{bol}}, \mathcal{M}_f) \tag{2}$$

is a quantity taken from the pre-computed grid of cooling models.

The relative star formation rate is expressed as a function of look-back time,

$$\psi(T_0, M_{\mathrm{bol}}, \mathcal{M}_i, \mathcal{M}_f, Z) = \tag{3}$$

$$\psi \left[T_0 - t_{\mathrm{cool}} \left(M_{\mathrm{bol}}, \mathcal{M}_f \right) - t_{\mathrm{MS}} \left(\mathcal{M}_i, Z \right) \right] . \tag{4}$$

The absolute normalisation is not needed when the total stellar mass is coming from observations; the theoretical WDLF only needs to multiply with a constant (the total number density) to account for the normalisation.

The IFMR takes a simple form of

$$\mathcal{M}_f = \zeta(\mathcal{M}_i), \tag{5}$$

although there is evidence that more metal-rich stars lose more envelope (**?**), there is insufficient empirical data to derive an IFMR at metallicity much lower or higher than solar abundance.

3 RETRIEVING STAR FORMATION HISTORY FROM A WD POPULATION

(**?**) (**?**)

3.1 Spectroscopic Volume Complete Sample

(**?**) (**?**)

3.2 WDLF Inversion of a Statistical Sample

With the inversion algorithm, it is possible to resolve the SFH in high time resolution (**?**). However, it is prone to amplify noise into enhanced star formation upon the inversion (**?**). This is due to the large number of degenerate solutions that can yield the WDLF agree to within the uncertainty.

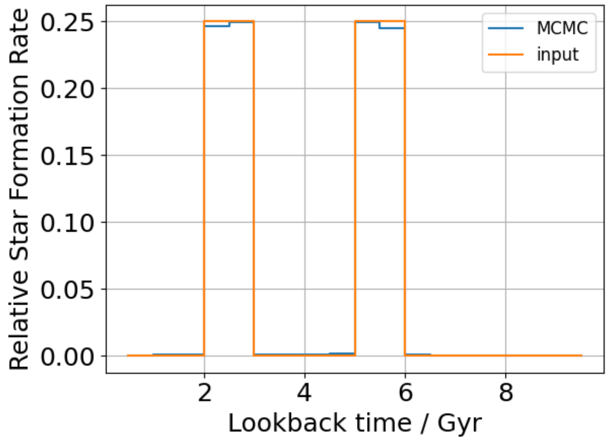

Figure 1. Caption

3.3 Forward modelling of WDLFs

4 A NEW METHOD

Historically, all the luminosity funtions of the solar neighbourhood were reported in the bolometric magnitudes. Essentially, all works were reporting the WD-Bolometric-LF. To address the problem of degeneracy in the solution, we explore the use of colour information from the luminosity function, where we are using the WDLF in multiple filters .

4.1 Partial WDLFs

Inspired by the partial CMD designed in (**?**), we use partial WDLFs as building blocks of the fitting models.

4.2 Model Fitting

4.2.1 Bolometric Luminosity/Magnitude

The likelihood function to be maximized is essentially minimising the χ^2 between the observed and the measured WDLFs weighted by the variance.

When the function is properly smoothed and weighted, the parametrisation with luminosity and magnitude should give identical results.

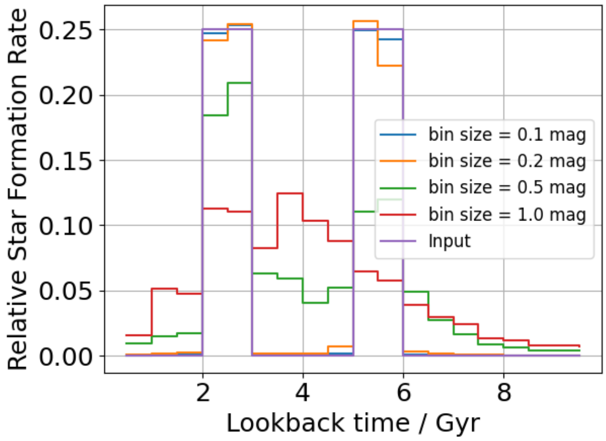

Figure 2. Caption

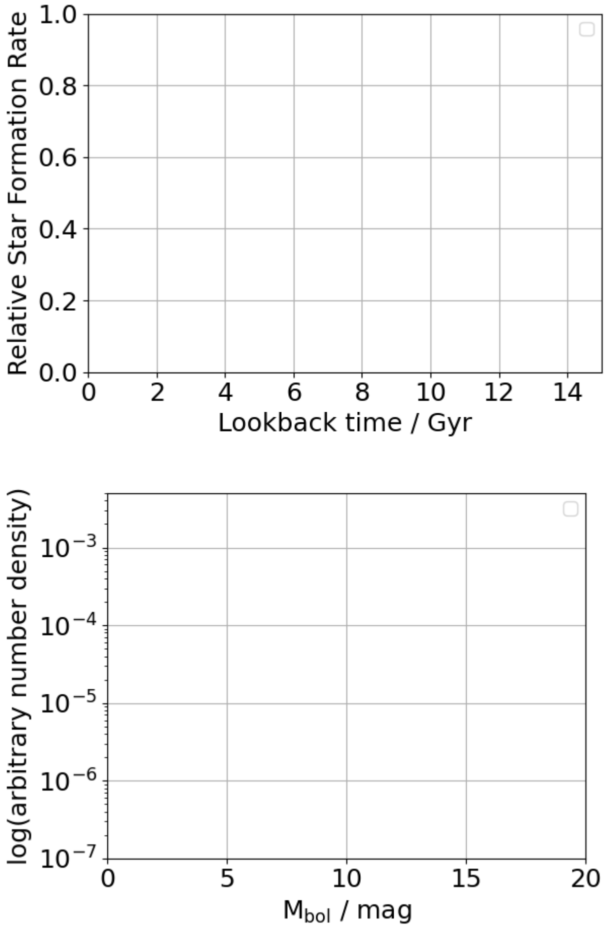

Figure 3. Caption

4.3 Effect of magnitude bin size

4.4 Effect of time bin size

4.5 Effect of choice of models

5 APPLICATION TO THE EARLY GAIA DATA RELEASE 3

5.1 Comparison with WDLF inversions

5.2 Comparison with previous studies

6 CONCLUSIONS

ACKNOWLEDGEMENTS

DATA AVAILABILITY

APPENDIX A: SOME EXTRA MATERIAL

This paper has been typeset from a TEX/LATEX file prepared by the author.