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Gaia, White Dwarfs, and the Age of the Galaxy

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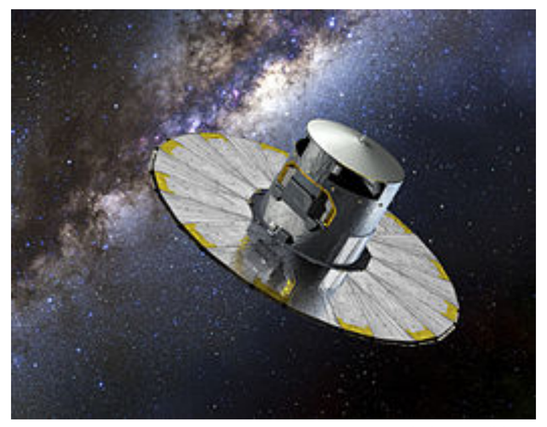
Abstract. The Milky Way is composed of four major stellar populations: the thin disk, thick disk, bulge, and halo. At present, we do not know the age of any of these populations to better than one or two billion years. This lack of knowledge keeps us from answering fundamental questions about the Galaxy: *When did the thin disk, thick disk, and halo form? Did they form over an extended period, and if so, how long? Was star formation continuous across these populations or instead occur in distinct episodes?* The Gaia satellite is providing precise trigonometric parallaxes for a plethora of white dwarfs in each of these populations. We combine these parallaxes (and hence, distances) with photometry and analyze them using a modeling technique that relies on Bayesian statistics. This allows us to ***derive precise ages for individual white dwarfs and determine the age distribution and star formation history for each of the constituents of our Galaxy***. Here we will present current progress in this endeavor, with emphasis on the ages of individual white dwarfs in the Hyades. Measuring the ages of individual white dwarfs in well-studied clusters provides proof of concept for our technique, as well exploration of any systematic offsets caused from timescales from main sequence models, as well as the initial-final mass relation.



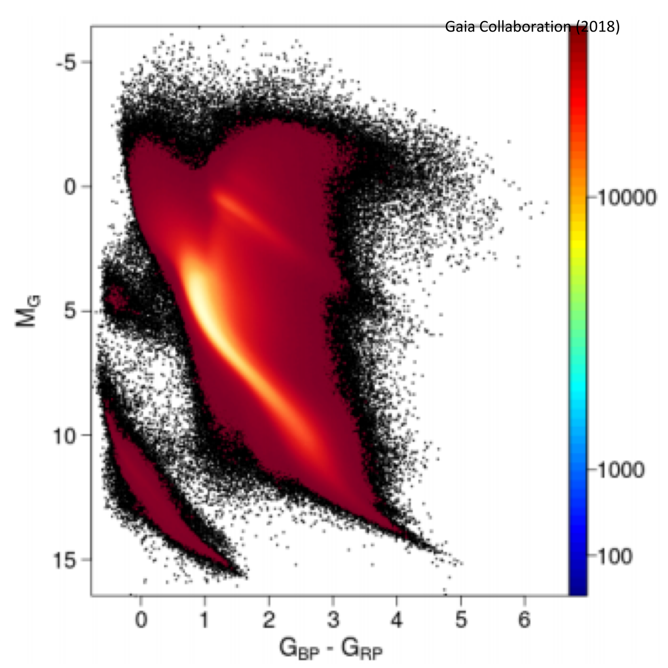


Figure 1. **(LEFT)** The Gaia satellite will measure high-precision parallaxes for ~ 1.6 billion stars. **(RIGHT)** Gaia DR2 (Apr '18) includes parallaxes for ~ 26,000 white dwarfs.

We will measure the individual age of every white dwarf in the Gaia catalog.

- The Gaia satellite is measuring **high-precision parallaxes** for over a billion stars. (see Fig. 1)
- Using a powerful Bayesian analysis technique we can **measure ages of individual white dwarfs**. (see Figs. 2 – 3)
- Informative distance priors allow for **high precision age measurements**. (see Fig. 4)
- We are using the **Hyades cluster white dwarfs** as a testbed for our methods. (see Tab. 1 and Fig.5 – 7)

With precise (1-5%) ages for many of the white dwarfs in the Gaia catalog, we expect to:

- Use available data to distinguish between white dwarfs from different Galactic populations (e.g., thin disk vs. halo).
- Measure the age of each individual white dwarf.
- Investigate age distributions (i.e., star formation history) of each Galactic constituent.

White Dwarf	Gaia Parallax (mas)	Total Age (Gyr) [Precision]
HZ14	20.247 ± 0.051	0.99 ± 0.17 [17%]
VR16	20.895 ± 0.057	1.00 ± 0.25 [25%]
HZ7	21.140 ± 0.062	1.23 ± 0.30 [24%]
VR7	22.227 ± 0.052	0.96 ± 0.22 [23%]
HZ4	28.589 ± 0.053	0.80 ± 0.02 [3%]
LB227	19.94 ± 0.093	0.61 ± 0.01 [2%]

Table 1. For the six white dwarfs in the Hyades, Gaia parallaxes are good to less than 0.5%. The total age determined by BASE-9 for each white dwarf, as well as the precision. We note that higher age uncertainty for the hotter white dwarfs is likely due to the greater dependence on the IFMR compared to the cooler white dwarfs.

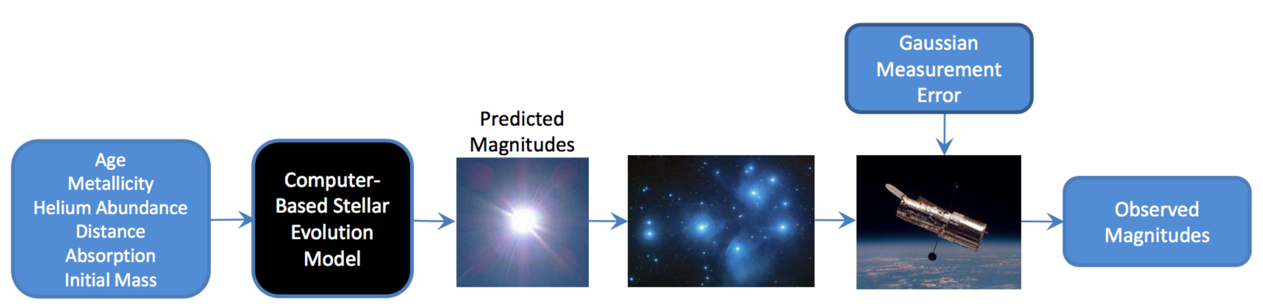


Figure 2. Our technique utilities Bayesian statistics to recover the total age of an individual white dwarf via a Markov chain Monte Carlo (MCMC) technique. We call our software package BASE-9 (**B**ayesian **A**nalysis of **S**tellar **E**volution with **9** variables). Each step in the MCMC chain consists of a set of stellar parameters (e.g., age, metallicity, etc.). To produce these parameters at each step, BASE-9 uses stellar models to generate theoretical photometry values and compares them to observed photometry, including photometric errors. The convergent MCMC chain provides a sample from the posterior distribution of the stellar parameters and can be used to compute means and intervals as parameter estimates and uncertainties.

For more information on BASE-9, see e.g., von Hippel, et al. 2006; DeGennaro et al. 2009; van Dyk et al. 2009; Stenning et al. 2016.

BASE-9 is freely available for download and use; for more information, see von Hippel et al. 2014 (arXiv:1411.3786) and `https://github.com/argiopetech/base`

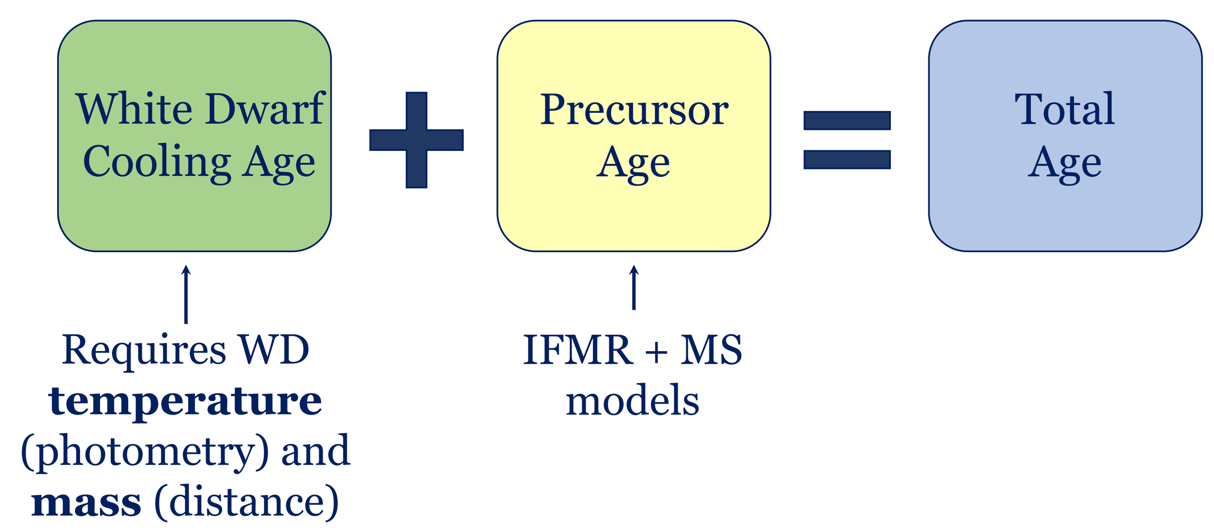


Figure 3. The total age of a white dwarf is found by adding its cooling time and its precursor age. The cooling time of a white dwarf can be found by knowing its temperature (from photometry) and mass, which can be determined as follows:

- Distance (from Gaia parallax) combined with apparent magnitude will yield absolute magnitude (luminosity).
- Determine white dwarf radius from Bergeron et al. (2011) atmosphere models.
- Utilize the unique mass-radius relation for white dwarfs to convert the radius to a mass.

The precursor age of the white dwarf relies on an understanding of the initial-final mass relation (IFMR) and modeling of main sequence time scales. (For more information see O'Malley et al. 2013; von Hippel et al. 2015.)

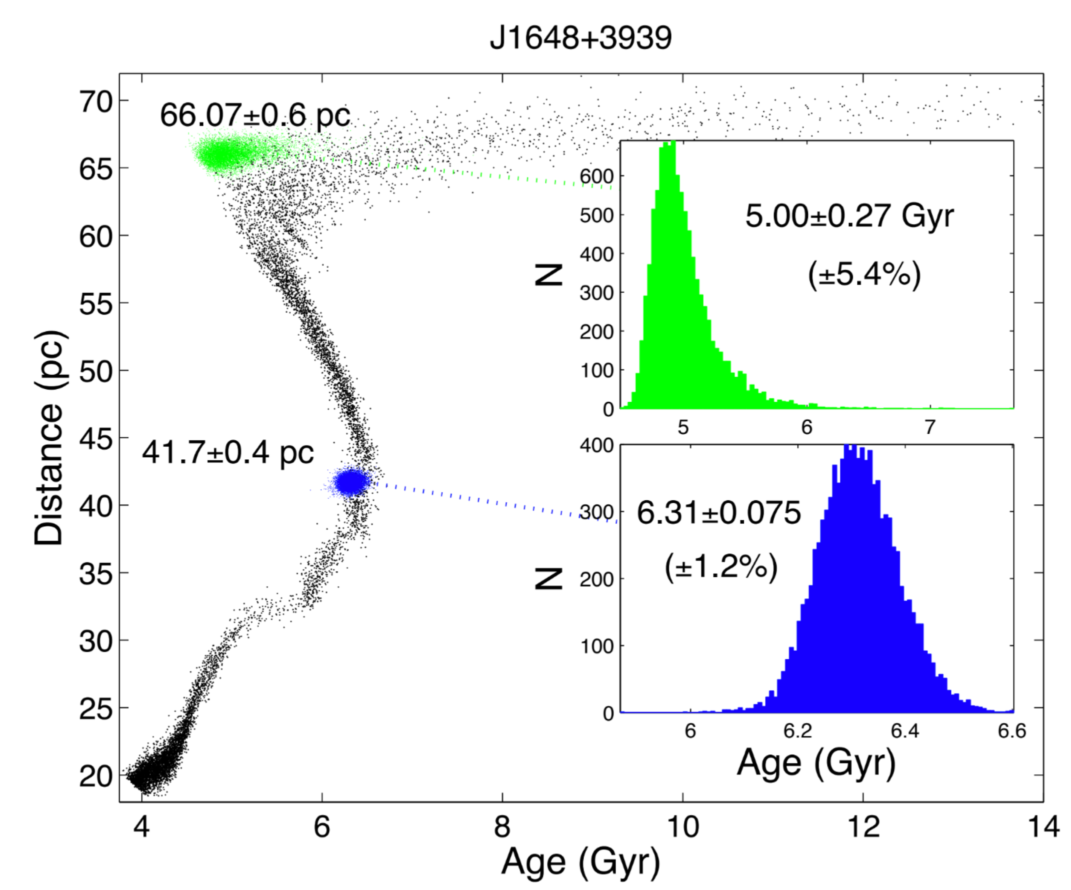
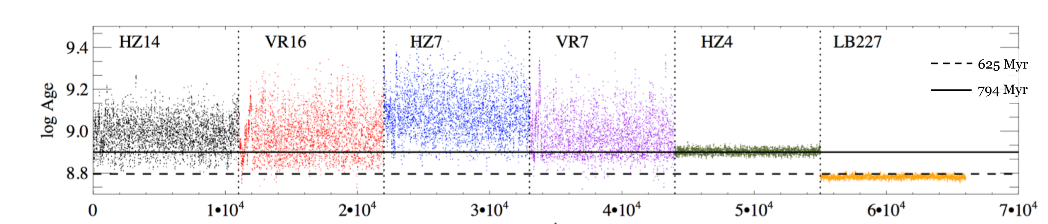


Figure 4. The joint posterior distribution for age and distance for J1648+3939. The black points indicate the posterior distribution based only on SDSS *griz* and 2MASS *JHK* photometry. When informative distance priors are also used, we are able to determine the age very precisely. The distances selected are examples of the precision that Gaia achieves for these nearby white dwarfs.

Distance with precision of ~ 1% will often result in age precision of 2-5%.



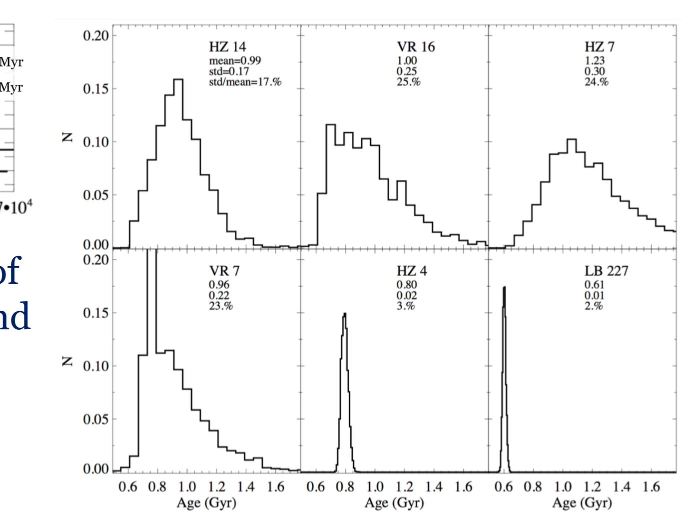


Figure 5. **(ABOVE)** Posterior distributions of the ages of the six Hyades white dwarfs, from BASE-9. The dashed and solid lines are ages 625 Myr (the typically accepted age of the Hyades) and 794 Myr (age found by the Gaia collaboration 2018); **(RIGHT)** These same posterior distributions, plotted as histograms.

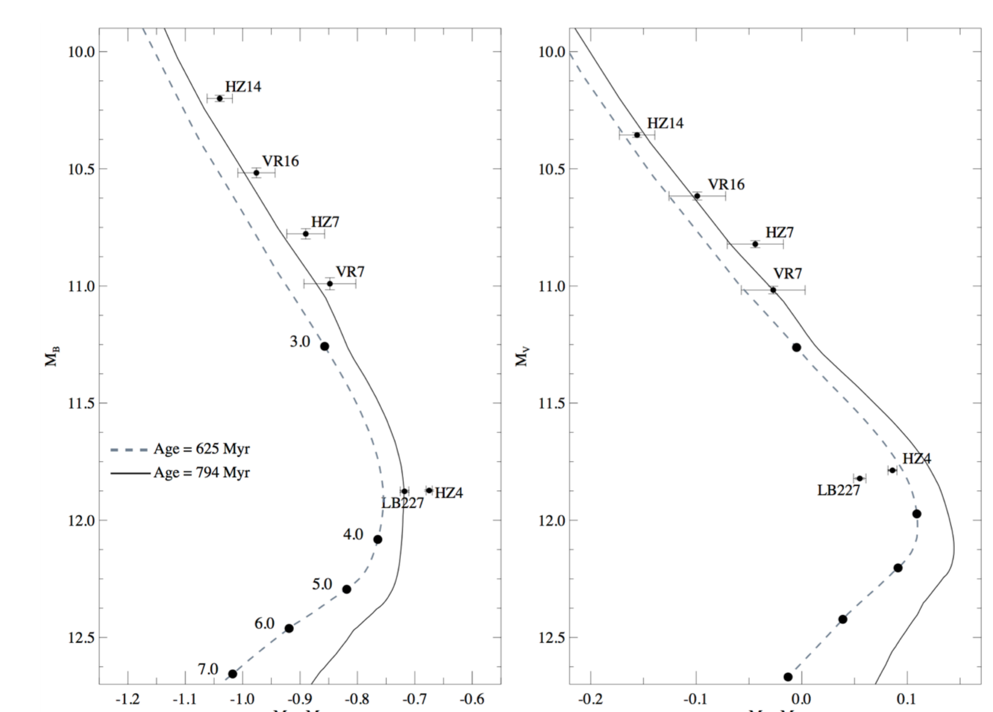


Figure 6. Color-(absolute) magnitude diagram of the six Hyades white dwarfs with white dwarf isochrones overlaid, with ages as indicated. This analysis supports the more recent Hyades age of 794 Myr (log[age] = 8.9), found by the Gaia collaboration (2018).

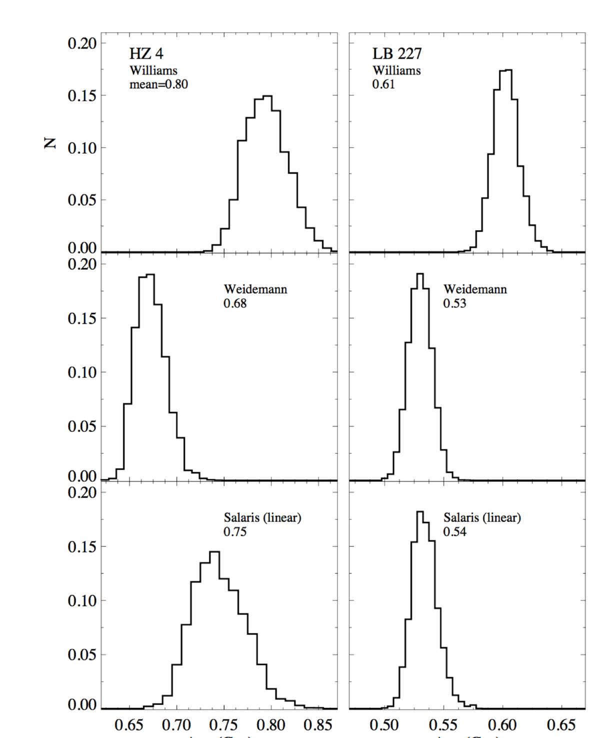


Figure 7. Testing different IFMRs and their effect on the ages measured for HZ4 and LB227.

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