White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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A Bayesian analysis of white dwarfs in open clusters observed with Gaia

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Abstract. We analyze individual white dwarfs in open clusters observed by Gaia. In particular, we determine ages when different model ingredients are used. We also explore fundamental properties of the white dwarfs, including temperature and mass, when using different filter combinations. Such tests are important to understanding any systematic effects when applying similar techniques to field stars.

Keywords. Galaxy: stellar content, stars: evolution, stars: white dwarfs

1. Introduction

Open clusters provide an excellent environment for many tests of stellar evolution. The coeval formation of stars in a cluster from the same parent cloud gives its members approximately the same age, distance, and metallicity. By studying the white dwarfs (WDs) in open clusters, we are able to gain additional insight into WD formation and cooling, as well as ages measured by these objects.

The *Gaia* satellite has created a wealth of data (including parallaxes and photometry) for a huge number of stars, including a vast number of WDs. These data are a treasure trove for the community in many ways. *Gaia* has observed a number of open clusters (Gaia Collaboration 2018), including WDs in some. Here we will focus our attention on the WDs observed in the Hyades and Praesepe open clusters. Specifically, we will explore and compare results of temperature and age obtained for these individual cluster WDs, using a variety of filter combinations and model ingredients.

2. Data and Methodology

Data for this study includes parallaxes from *Gaia* and photometry from *Gaia*, Sloan Digital Sky Survey (SDSS), and Pan-STARRS surveys. In total, we analyzed six WDs from the Hyades and nine WDs from Praesepe.

For analysis, we used a Bayesian statistical method for fitting stellar evolution models to photometry (see von Hippel *et al.* 2016; van Dyk *et al.* 2009; Stenning *et al.* 2016). The software package (Bayesian Analysis of Stellar Evolution in Nine Variables, or BASE-9) is freely available for download (https://github.com/argiopetech/base) and its use is described in von Hippel *et al.* (2014). BASE-9 returns parameters such as total age, metallicity, and distance (or parallax), and additional features can be employed to determine an individual WD cooling age, zero age main sequence (ZAMS) mass, $log(g)$, and T_{eff} values.

Table 1. Cluster white dwarfs included

Hyades WDs	**Praesepe WDs**	
WD0352+096 (HZ 4)	WD0833+198	WD0840+200
WD0421+162 (VR 7)	WD0836+197	WD0840+209
WD0425+168 (VR 16)	WD0836+201	WD0843+186
WD0431+125 (HZ 7)	WD0837+189	
WD0438+108 (HZ 14)	WD0837+218	
WD0406+169 (LB 277)	WD0840+190	

The required prior distributions on metallicity, parallax, and reddening are Gaussian (with reddening truncated at zero). Prior mean and sigma values on parallaxes were the *Gaia* values and errors. For the Hyades, a prior distribution on metallicity of [Fe/H] = +0.103 ± 0.05 (Taylor & Joner 2005) and reddening (A_V) of 0.0031 ± 0.0031 (Taylor 2016). For Praesepe, we used a metallicity prior of 0.01 ± 0.04 and reddening prior of 0.0837 ± 0.0124 (Taylor 2016).

Briefly, the total age of a WD is found by determining its cooling age and adding its precursor age. The cooling age can be found by combining temperature (constrained by multiband photometry) and parallax (which leads to mass when the WD's absolute luminosity is combined with temperature and the WD mass-radius relation). Once the mass of the WD has been determined, an initial-final mass relation (IFMR) is assumed to obtain the star's ZAMS mass; a main sequence (MS) model is then employed to determine the pre-WD lifetime of a star with that ZAMS mass. For more information on using BASE-9 to determine ages of individual WDs, see O'Malley, von Hippel & van Dyk (2013). and the contribution in these proceedings by von Hippel *et al.*

In our analysis we use WD cooling models of Bischoff-Kim & Montgomery (2018), and updated WD atmosphere models from Bergeron *et al.* (1995). Stellar evolution models available in BASE-9 include the Dartmouth Stellar Evolution Database (DSED, Dotter *et al.* 2008); PAdova & TRieste Stellar Evolution Code (PARSEC, Marigo *et al.* 2017); the Yale-Potsdam Stellar Isochrones (YaPSI, Spada *et al.* 2017); and the MESA Isochrones and Stellar Tracks (MIST, Dotter *et al.* 2016; Choi *et al.* 2016), both with rotation ($v/v_{crit} = 0.4$) and without rotation. Different IFMRs used included Williams *et al.* (2009), Weidemann (2000), and Salaris *et al.* (2009) linear and piecewise.

3. Results

In a recent paper, Bergeron *et al.* (2019) posit that effective temperatures and masses determined from Pan-STARRS photometry alone suffer from systematic effects, especially for hotter WDs. They compare temperatures determined from SDSS (*ugriz*) filters to those from the full Pan-STARRS filter set (*grizy*), a subset of Pan-STARRS filters (*griz*), a subset of the SDSS filters (*griz*) and a combination of SDSS *u* + Pan-STARRS *grizy*. They find that the addition of the SDSS *u* filter brings temperatures back into good agreement. Similar effects are found when they compare photomtric temperature and masses to those determined spectroscopically.

We performed a similar analysis on these cluster WDs included here and find a similar result. We show these tests in Figure 1. This figure is a modified reproduction of Bergeron's Figure 5, with corresponding points for the Hyades (diamonds) and Praesepe (stars). We note that only two of the six Hyades WDs were used because not all of the Hyades WDs fall within the footprint of SDSS observations.

Figure 2 is similar to Figure 1, but for only the cluster WDs. Here we compare the temperatures determined using Gaia photometry, Pan-STARRS, and SDSS *u* + Pan-STARRS to those determined with SDSS photometry. We note that there is more scatter when using *Gaia* photometry alone compared to the other filter combinations. Because

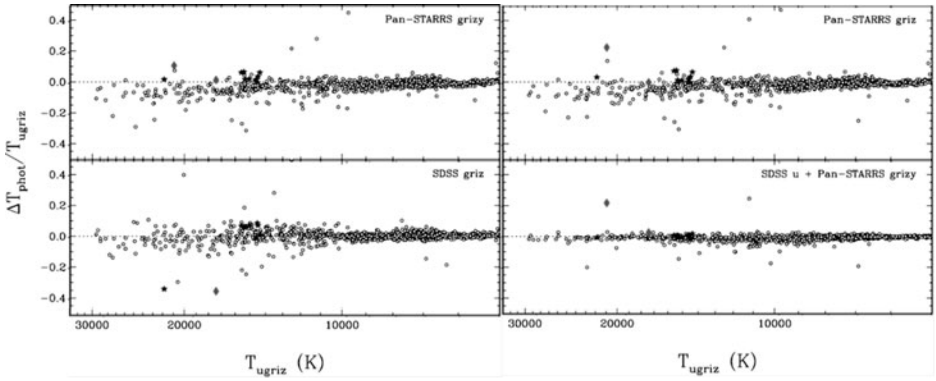

Figure 1. Modified Figure 5 from Bergeron *et al.* (2019) showing the effects of filter combination on determining temperature, compared to the temperature determined using the full SDSS filter set ($ugriz$). Overplotted are values determined for the Hyades (diamonds) and Praesepe (stars), showing similar results to those determined by Bergeron.

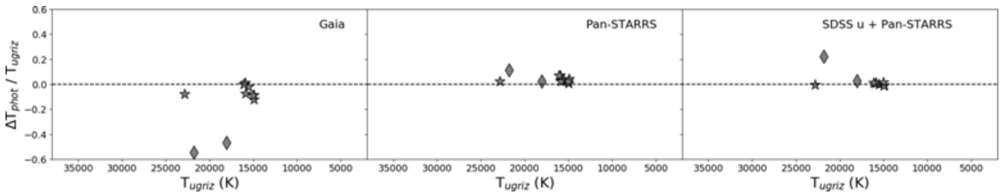

Figure 2. Temperatures determined for cluster WDs using Gaia, Pan-STARRS, and SDSS + Pan-STARRS compared to temperature determined by SDSS photometry. Temperatures from Gaia photometry alone are not as precise as those determined using other filter combinations.

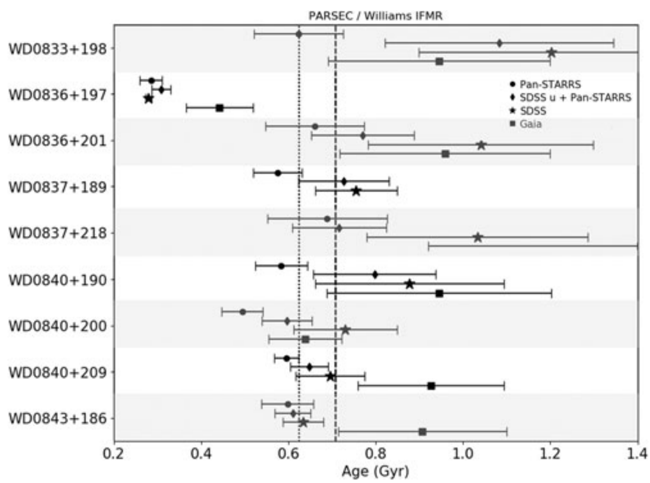

Figure 3. Total age for the individual WDs in Praesepe using different filter combinations.

of this, we would encourage other researchers to not rely on *Gaia* photometry alone in determining WD temperatures; if additional photometry is available, make use of it.

We also compare the effect of filter combination on the total age determined for the WDs. We use the IFMR from Williams *et al.* (2009) and the PARSEC MS models. We display these results in Figure 3. In this figure, the points represent the mean of the posterior distribution and the error bars are one standard deviation. The vertical dotted

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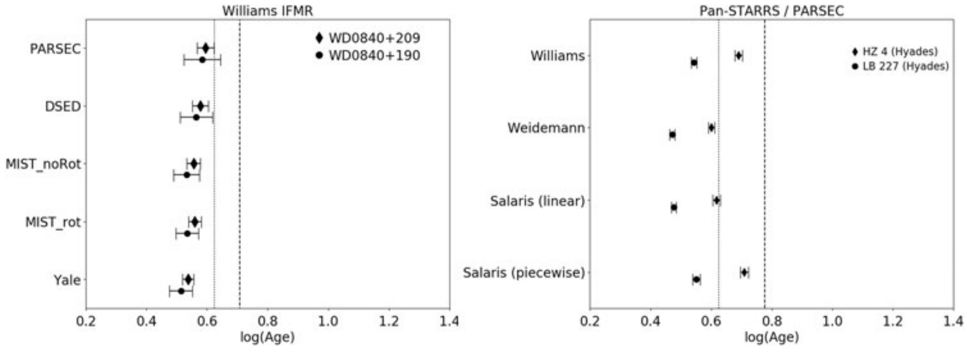

Figure 4. Left: Total age for two WDs in Praesepe, using different MS model sets. Right: Total age of two WDs in the Hyades using different IFMRs and the same MS models.

line represents a cluster age of 625 Myr (Dobbie *et al.* 2006) and the dashed line is an age of 708 Myr (log(Age) = 8.85), determined using PARSEC models (Marigo *et al.* 2017) in the Gaia H-R Diagram study (Gaia Collaboration 2018). We again note that ages determined from Gaia photometry alone tend to return older ages than other photometry sets, and have the highest standard deviation, likely due to high uncertainties in T_{eff}.

Because determining the total age of a WD is model dependent (in the use of the IFMR, along with MS timescale models), we explore effects in age when using different model ingredients. In the left panel of Figure 4, we show ages for the two coolest WDs in Praesepe using the Williams IFMR and a variety of MS models. In the right panel of Figure 4, we show results for the two coolest Hyades WDs using PARSEC MS models and use different IFMRs.

4. Summary

In this contribution we have shown the effects of different filter combinations on WD temperatures, mass, and individual age. As seen in Bergeron *et al.* (2019), we see that use of the SDSS u filter is important for photometric temperatures being consistent with spectroscopic temperatures. We find it is important to avoid using Gaia filters alone for determining WD temperatures or total age; other filters should be used, if available. Additionally, we explore the effects of using different model ingredients on total WD age.

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