White Dwarfs and the Ages of Open Clusters

Elizabeth J. Jeffery1, Steven DeGennaro1, Ted von Hippel1,2, David van Dyk3, William H. Jefferys1,4 and Nathan Stein1

1 Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
2 Department of Physics, Siena College, Loudonville, NY 12211, USA
3 Department of Mathematics and Statistics, University of Vermont, Burlington, VT 05405, USA
4 Department of Statistics, University of California at Irvine, Irvine, CA 92697 78712, USA
E-mail: ejeffery@astro.as.utexas.edu

Abstract.
Open clusters provide the ideal environment for the calibration of ages determined from main sequence evolutionary theory (via cluster isochrones) and ages determined from white dwarf cooling theory. In an effort to measure more precise cluster ages, our group has developed a new technique using Bayesian statistics. Here we will discuss new capabilities of the technique, as well as the first application to real data, using the Hyades as a test case. Because the faintest white dwarfs have likely evaporated from the Hyades, we also demonstrate the first successful application of the bright white dwarf technique for deriving ages from the bright cluster white dwarfs alone.

1. Introduction
Accurate age measurements are fundamental to many areas of astrophysics. Currently there are two main techniques for independently determining the ages of stellar populations: main sequence (MS) evolutionary theory (via cluster isochrones) and white dwarf (WD) cooling theory. Ages determined from the MS turnoff (MSTO) of globular clusters provide the most reliable age of the Galactic halo (Chaboyer, Demarque & Sarajedini 1996), while WD cooling ages provide the most reliable age of the Galactic disk (Winget et al. 1987). Before ages determined by these two techniques can be meaningfully compared, they must be calibrated to the same absolute scale. Additionally, such a calibrations provides insights to thoroughly understanding the physics of each.

The best way to do this calibration is to measure and compare WD ages and MSTO ages in several open clusters with a wide range of ages and metallicities. Additionally, being able to compare WD theory against MSTO theory provides an excellent opportunity to refine our understanding of both theories. Recent studies in calibrating MSTO and WD ages in open clusters have shown good agreement for cluster ages up to 4 Gyr. A summary of recent studies was done by von Hippel (2005). To aid us in the endeavor to determine more precise cluster ages, our group has developed a powerful new Bayesian statistical approach (von Hippel et al. 2006, Jeffery et al. 2007).

This paper is organized as follows: in Section 2 we briefly summarize the Bayesian technique as well as discuss its new capabilities. We review the bright WD technique as a new tool to measure cluster ages in Section 3. In Section 4 we discuss the first application of the Bayesian...
technique to real data, using the Hyades as a test case. Our result also demonstrates the power of the bright WD technique. We end with concluding remarks in Section 5.

2. The Bayesian technique

Our goal is to improve the age precision in both WD and MSTO age techniques, to about 5%. Despite many high quality datasets having been collected on open clusters, this 5% age precision is still generally out of reach. We therefore believe that the greatest gains we can currently make in age precision will require improved modeling techniques (see also work done by Tosi et al. 1991; Tosi, Bragaglia & Cignoni 2007; Hernandez & Valls-Gabaud 2008).

Briefly, the Bayesian technique we have developed derives a posterior probability distribution for a cluster’s age, metallicity, distance, and line-of-sight absorption by objectively incorporating our prior knowledge of stellar evolution, star cluster properties, and data quality estimates. Since first being presented by von Hippel et al. (2006), we have expanded the capabilities of the technique to included binary stars, field stars, as well as including additional MS models. Each of these points is expounded below.

Originally, the technique modeled each point on the color-magnitude diagram (CMD) as an individual stellar system with a single mass. We are now able to treat each system as if it were a binary, and parameterize it in terms of the primary mass, and by the ratio of the two masses. Stars without binary companions can also be modeled, by setting the mass ratio equal to 0. We are currently only considering MS-MS binaries.

During any given iteration of the technique, each object in the CMD is assigned to be a cluster member or a field star. In the final analysis, the membership probability of each star in
the cluster can be determined by dividing the number of total iterations during which it was a cluster member by the total number of iterations in the run.

In von Hippel et al. (2006), we incorporated a Miller & Scalo (1979) initial mass function, MS and giant branch stellar evolution time scales of Girardi et al. (2000), the initial-final mass relation from Weidemann (2000), WD cooling timescales of Wood (1992), and WD atmosphere colors from Bergeron, Wesemael & Beauchamp (1995). We now include two additional sets of MS models – Yale-Yonsei (Yi et al. 2001), and a finer grid of models from the Dartmouth Stellar Evolution Database (DSED, Dotter et al. 2008), as well as updated versions of Bergeron WD atmosphere models. Figure 1 shows CMDs for the Hyades with the three MS models overlaid. Solid lines are the Girardi models, dotted lines are the Yale-Yonsei models, while the dashed lines are the DSED models.

3. The bright white dwarf technique
In Jeffery et al. (2007) we demonstrated the theoretical feasibility of determining WD ages of clusters using the brighter WDs alone. Briefly, this technique relies on the subtle differences in slope and position of the WD cooling sequence relative to the MS for clusters of different ages (as illustrated in Figure 2).

The bright WD technique assumes that the initial-final mass relation (IFMR) is universal and single-valued, which is the general consensus among researchers (Weidemann 2000). Because of this dependence on the IFMR, this technique is a relative age indicator and requires calibration. As will be discussed in the next section, this work is the first step in such a calibration.

Figure 2. Simulated clusters for several different ages. The expanded region shows the regime of the brighter WDs, clearly showing the subtle differences in the slopes and positions of the WD cooling sequences relative to the MS for clusters of different ages. This makes it possible to extract age information without observing the faintest WDs.
4. The Hyades

The Hyades is one of the most well-studied open clusters. Perryman et al. (1998) report a MSTO age for this cluster of $625 \pm 50$ Myr and a distance to the center of the cluster (based on trigonometric parallaxes from Hipparcos) of $m - M = 3.33 \pm 0.01$. High resolution spectroscopy has been used to determine the metallicity to high accuracy, $[\text{Fe/H}] = +0.103 \pm 0.008$ (Taylor & Joner 2005), based on their re-analysis of Paulson, Sneden & Cochran (2003). In order to apply our Bayesian technique to real data for the first time, this cluster was the logical choice.

Data used here for our analysis of the Hyades is taken from The General Catalog of Photometric Data (GCPD – http://obswww.unige.ch/gcpd/gcpd.html – Mermilliod, Mermilliod & Hauck 1997). They determine a weighted mean and dispersions in the V band photometry in addition to the B - V and U - B color indices.

4.1. Results

Because we are presently interested in measuring the WD age of the cluster, we removed all stars brighter than $V = 4.5$ (i.e., the MSTO). The divergence among MS models in the lower MS (see Figure 1) was also a point of concern, as our ability to fit the best model to the data relies on the models being accurate. In order to test the sensitivity of our results and errors on the poorly modeled lower MS, we performed the Hyades analysis with varying amounts of MS. Each data set contains all the WDs and the MS between $V = 4.5$ and some low cutoff, in half magnitude intervals.

The results of this analysis are shown in Figures 3 through 6. In each of these figures, triangles represent the Girardi models, squares are the DSED models, and the circles are the Yale-Yonsei models. The horizontal lines are the most recently accepted values for the parameters and their standard errors. As demonstrated by these figures, all three models give very reasonable results for all the parameters.

These figures demonstrate how the choice of model and amount of MS included affect the results. We see there is a clear difference between $V \leq 8.5$ and $V > 8.5$, for all models in each parameters as the MS diverges from the models. Assuming the models are accurate down to $V = 8.5$, we take a weighted average of the three models for each parameter for the runs which include MS stars down to $V = 8.5$. Errors were determined rather conservatively, by adding
the standard deviations for the three determinations in quadrature to the average error of the individual determinations.

Therefore, we measure a WD age for the Hyades of $648 \pm 45$ My; an $[\text{Fe/H}]$ of $0.078 \pm 0.065$; m-M of $3.35 \pm 0.02$, and $A_V$ of $0.014 \pm 0.007$.

4.2. The bright white dwarf age of the Hyades

Previous studies to determine the WD age of the Hyades cluster have produced a result (300 Myr; Weidemann et al. 1992) that is about half the measured MSTO age (625 Myr; Perryman et al. 1998). Weidemann et al. (1992) suggested that this discrepancy is due to the dynamical evaporation of stars from this cluster; the coolest WDs are no longer present. In the absence of any data on these missing faint WDs, traditional techniques to determine WD ages can provide at best a lower limit to the WD age.

As summarized earlier, in Jeffery et al. (2007) we showed the possibility of determining cluster WD ages from just the bright WDs, when the coolest WDs are not observed. Because the coolest WDs are missing from the Hyades, we require the bright WD technique to measure the true WD age (rather than a lower limit, as was done previously). Our Hyades results provide empirical evidence that the Bright WD technique yields reasonable and precise ages for real data, as well as providing an important step in calibrating the technique.

Figure 7 is an updated version of Figure 1 from von Hippel (2005), plotting WD age vs. MSTO age for open clusters up to 4 Gyr. Our measurement of the bright WD age of the Hyades brings the WD age into agreement with the MSTO age for the first time. The gray point shows the previously most reliable WD age for the Hyades (Weidemann et al. 1992). The solid line is the one-to-one correspondence between WD and MSTO ages.

5. Conclusions

We are continuing in an effort to calibrate WD and MSTO ages using open clusters. In order to improve accuracy of the measured ages, our group has developed a technique using Bayesian statistics. We have presented current progress on our Bayesian technique, including an expansion of the code to include more MS models as well as treatment of binaries and field stars.

We have demonstrated the technique by applying it on the Hyades as a test case. Results for cluster parameters, namely WD age, metallicity, distance, and reddening, have yielded results consistent with previous measurements. Of particular interest is the determination of the bright WD age of the Hyades, required due to the missing cool WDs in this cluster. Our results bring...
**Figure 7.** WD versus MSTO age for seven clusters, adapted and updated from von Hippel (2005). The age we derive from the WDs in the Hyades using our bright WD technique brings the WD age of the Hyades into agreement with the MSTO age for the first time (solid triangle). The solid line shows the one-to-one correspondence between the WD and MSTO ages, and the gray point shows the most reliable WD age of the Hyades prior to this work (Weidemann et al. 1992).

the WD age of this cluster in agreement with the MSTO age for the first time, as well as provide a first step in calibrating the bright WD technique.

**Acknowledgments**

This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. NAG5-13070 issued through the Office of Space Science.

**References**

Chaboyer B Demarque P & Sarajedini A 1996 *ApJ* **459** 558

Winget D E Hansen C J Liebert J van Horn H M Fontaine G Nather R E Kepler S O & Lamb D Q 1987 *ApJ* **315** L77

von Hippel T 2005 *ApJ* **622** 565

von Hippel T Jefferys W H Scott J Stein N Winget D E DeGennaro S Dam A & Jeffery E J 2006 *ApJ* **645** 1436

Jeffery E J von Hippel T Jefferys W H Winget D E Stein N & DeGennaro S 2007 *ApJ* **658** 391

Tosi M Greggio L Marconi G & Focardi P 1991 *AJ* **102** 951

Tosi M Bragaglia A & Cignoni M 2007 *MNRAS* **378** 730

Hernandez X & Valls-Gabaud D 2008 *MNRAS* **383** 1603

Miller G E & Scalo J M 1979 *ApJS* **41** 513

Girardi L Bressan A Bertelli G & Chiosi C 2000 *A&AS* **141** 371

Weidemann V 2000 *A&A* **363** 647

Wood M A 1992 *ApJ* **386** 539

Bergeron P Wesemael F & Beauchamp A 1995 *pasp* **107** 1047
Yi S Demarque P Kim Y-C Lee Y-W Ree C H Lejeune T Barnes S 2001 ApJS 136 417
Dotter A Chaboyer B Jevremovic D Kostov V Baron E & Ferguson J W 2008 ApJS in press arXiv:0804.4473
Perryman M A C et al. 1998 A&A 331 81
Taylor B J & Joner M D 2005 ApJS 159 100
Paulson D B Sneden C & Cochran W D 2003 AJ 125 3185
Mermilliod J-C Mermilliod M & Hauck B 1997 A&AS 124 349
Weidemann V Jordan S Iben I J & Casertano S 1992 AJ 104 1876