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White Dwarfs in Open Clusters: New Tests of Stellar Evolution and the Age of the Galaxy

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Abstract. White dwarf cooling theory and very deep observations in star clusters provide a new tool to test stellar evolution theory and time scales. In particular, white dwarf cooling theory is now testing the degree of enhanced core mixing in stars with turnoff ages of 1 to 2 Gyr. More generally, I show the good overall agreement between white dwarf and modern isochrone ages over the range 0.1 to 4 Gyr.

1. Introduction

One of the primary results of stellar evolution theory is a detailed understanding of the ages of star clusters throughout our Galaxy. But what are the limitations of stellar evolution theory and how might an independent technique be applied to determine the ages of star clusters and check stellar evolution theory? In the next section I discuss the difficulties encountered by and the success of stellar evolution theory. In the following section I discuss the viable alternative presented by white dwarf (WD) cooling theory. In the final section I compare the results of stellar evolution and WD cooling ages in open clusters spanning the age range of 0.1 to 4 Gyr.

2. Stellar Ages From Main Sequence Evolution Theory

Stellar structure models assume as basic parameters the hydrogen (X), helium (Y), and heavy element ($1 - X - Y = Z$) fractions, as well as mass (M) and age. Unfortunately, the helium content cannot be measured directly in the vast majority of stars since their stellar atmospheres are too cool to excite helium. Furthermore, the heavy element fraction is an oversimplification; many stars, especially those with significantly non-solar iron abundances, do not have the solar heavy element abundance pattern. The understanding of energy transport in stars is also limited by an incomplete theory of convection (but see recent developments by Canuto & Dubovikov 1998 and Canuto 1999), as well as an incomplete understanding of rotation and opacity, despite extensive and laborious calculations.

The result of an incomplete theory of energy transport, particularly due to an incomplete understanding of convection, is that theorists cannot calculate the radii of stars with surface convection from first principles. The standard approach to this dilemma and the absence of stellar helium abundances is to use the known solar mass, luminosity, radius, temperature, age, and heavy element abundance pattern to constrain the solar helium abundance and determine the solar mixing length. Two unknowns are extracted by fitting models to the Sun since the helium abundance primarily affects luminosity while the mixing length primarily affects radius. Unfortunately, mixing length theory is a gross simplification of convective process and there is no reason why this simple parameterization, fixed for the Sun, should apply to stars with different surface temperatures or abundances. Nevertheless, the solar helium abundance and mixing length form the basis for applying stellar evolution to stars throughout the Galaxy. To be sure, there are helpful constraints on the mixing length from the shapes of the giant branches in open and globular clusters as well as on the helium abundance from the mass–luminosity relation derived from binary stars.

Other problems arise since the mapping between the observational color–magnitude plane and the theoretical temperature–luminosity plane is not precisely known. Even the magnitude and color of the Sun are known to only 3 or 4% ($M_{\rm bol} = 4.72$ to $4.75, B-V = 0.63$ to 0.67).

Given what we are still learning about the Sun, it is remarkable how much we can learn about the ages of star clusters. Particularly encouraging are the advances due to helioseismology measurements and analyses (Gough, these proceedings) which constrain the solar helium abundance, yield a precise solar age, and elucidate key details connected with diffusion and convection (e.g., Elliott & Gough 1999; Baturin et al. 2000).

Assuming theoretical uncertainties are well in hand, due either to direct theoretical advances or careful relative comparisons, one can derive the ages for star clusters depending only on observational parameters. One such useful parameterization (Renzini 1991) is

$$\log T_9 = -0.41 + 0.37 M_V({\rm TO}) - 0.43Y - 0.13[{\rm Fe/H}] - 0.12[{\rm O/H}],$$

where T_9 is the cluster age in Gyr, and M_V(TO), the absolute magnitude of the main sequence turnoff, depends on the measured apparent magnitude of the turnoff and distance. The above constants in Renzini's parameterization indicate that a given percentage error in distance propagates directly to the same percentage error in age and that the derived age depends critically on the heavy element abundances. The last ten years have seen considerable advances in stellar evolution theory but the above equation still provides a good demonstration of the limitations of isochrone fitting.

When applying stellar evolution isochrones to Galactic clusters the disk is found to contain stars with a wide variety of ages, ranging from newly formed stars to clusters $\gtrsim 8$ Gyr old (e.g., NGC 6791 and Berkeley 17; Phelps, Janes, & Montgomery 1994). Likewise, the thick disk is probably 11 or 12 Gyr old (e.g., 47 Tuc), and the halo is approximately 12 to 14 Gyr old (see contributions by Chaboyer and by Aparicio, these proceedings).

These age results are a remarkable achievement. Given the theoretical and observational difficulties outlined above and the potential for systematic errors, however, it is important to check these results with an independent technique. In the following sections we focus on how white dwarfs provide just this independent technique. The study of radioactive isotopes in stellar atmospheres also holds much promise in this regard, and readers are referred to the many excellent papers on radioactive dating in these proceedings.

2001ASPC..245..190V

3. Stellar Ages From White Dwarf Cooling Theory

The physics governing white dwarf cooling are largely independent of the physics of main sequence evolution. We thus expect that cooling WDs can provide an independent means of estimating the ages of stellar populations. Additionally, where both WD and main sequence ages are derived for the same star cluster, any conflict between the two results may highlight limitations in WD cooling or main sequence evolutionary theory. Such a test is especially important for checking that the ages derived via the WD luminosity function technique (see contributions by Fontaine, by Leggett et al., and by Harris et al., these proceedings) are on the same age scale as the open and globular cluster ages derived traditionally from stellar evolution theory.

Of course, WD cooling theory has limitations and complications of its own, but rapid progress is being made (see Fontaine, these proceedings). The major difficulties in modeling WD cooling are determining the equation of state in the high density, partially degenerate, partially ionized WD atmospheres, understanding the interplay between convection and gravitational settling, and constraining uncertainties in carbon and oxygen separation during crystallization.

White dwarfs cool through five stages. Stage 1 lasts for 60 to 80 Myr when cooling is dominated by neutrino losses. Stage 2 is usually called fluid cooling and is both well understood and checked by the cooling rate of variable WDs (see Mukadam, these proceedings). In Stage 3 envelope variations as a function of mass and composition become important, so further information and theoretical work is needed on a star-by-star basis. In Stage 4 the WD begins to crystallize. Finally, in Stage 5, after the WD has finished crystallizing, the star enters a state known as Debye cooling in which the latent heat depends on the temperature, and the star cools towards invisibility. Gilles Fontaine (these proceedings) further explains these stages and the present state of their theoretical understanding. For the purposes of comparing WD cooling and stellar evolution in open clusters, the good news is that WD cooling is relatively well-understood for the first 6 to 8 Gyr, depending on the WD mass and atmosphere composition, so that WD age uncertainties due to theoretical difficulties should be less than or approximately equal to main sequence stellar evolution age uncertainties. Readers may wonder why main sequence stellar evolution uncertainties themselves do not play a larger role in WD age uncertainties, since all WDs were once main sequence stars. The answer to this apparent paradox comes from the fact that the oldest WDs in any stellar population came from 5 to 8 solar mass progenitors, whose main sequence lifetimes are $\approx$ 35 to 7 Myr, respectively, so even large uncertainties in the progenitor lifetimes are unimportant for stellar populations more than a few hundred million years old.

The result of WD cooling theory applied to the WD luminosity function indicates that the Galactic disk at the solar annulus is 9 ± 2 Gyr old (Winget et al. 1987; Liebert, Dahn, & Monet 1988; Oswalt et al. 1996; Leggett, Ruiz, & Bergeron 1998; see also Leggett et al., these proceedings).

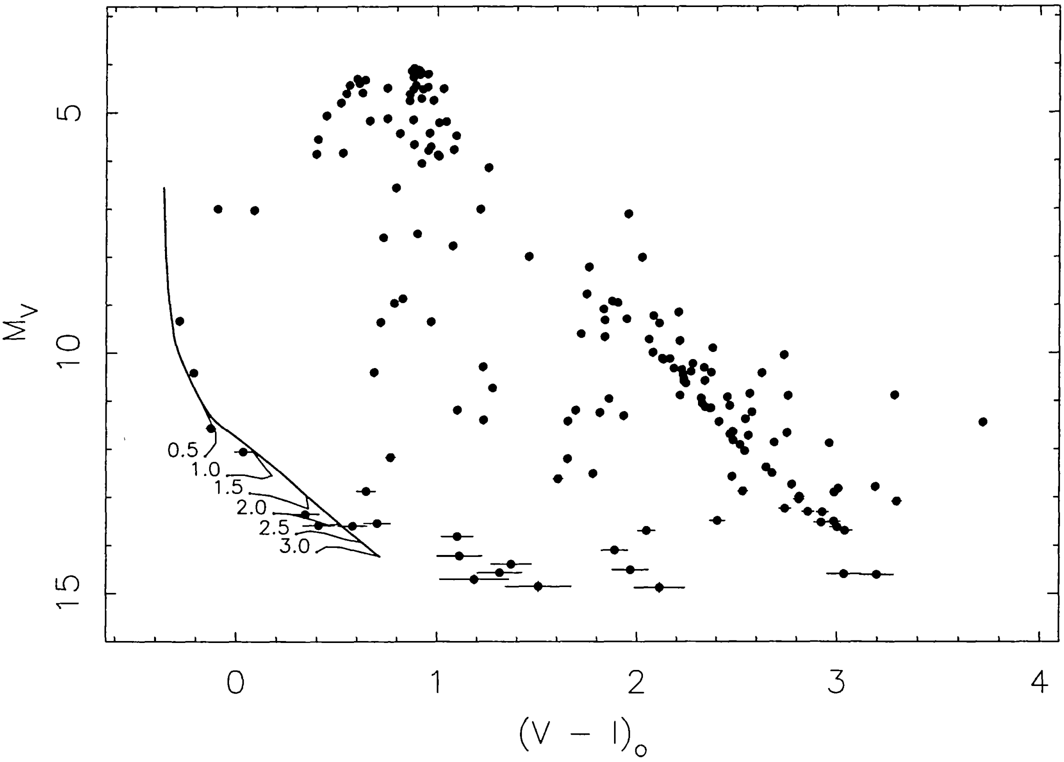

Figure 1. NGC 2420 color–magnitude diagram with the preferred distance modulus, $(m-M)_V = 12.10$, and reddening, $E(B-V) = 0.04$, removed. The 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 Gyr isochrones (Ahrens 1999) and 0.6 solar mass WD cooling track (Wood 1992) are overplotted.

4. White Dwarf Versus Main Sequence Ages in Open Clusters

To date white dwarfs have been found in a number of open and globular clusters (see von Hippel 1998 for a recent compilation), though the WD cooling limit has not yet been identified in globular clusters due to their great ages and distances. Figure 1 shows a color–magnitude diagram obtained via deep HST imaging of the open cluster NGC 2420 (see von Hippel & Gilmore 2000). Eight objects appear to be excellent WD candidates based on their proximity to the expected WD isochrones and the apparent pile-up near $V = 26$ ($M_V \approx 13.5$). WD isochrone fits to this sequence depend on the assumed distance modulus, which is not precisely known for this cluster. Figure 2 (derived from figure 8 of von Hippel & Gilmore 2000) shows the derived WD age and 1σ uncertainty age range as a function of distance along with the derived ages and distances from recent main sequence stellar evolution studies. The canonical main sequence ages and distance fits are those of Anthony-Twarog et al. (1990; 3.4 Gyr), Castellani, Chieffi, & Straniero (1992; 1.7 Gyr), Castellani, degl'Innocenti, & Marconi (1999; 1.5 Gyr), and Dominguez et al. (1999; 1.6 Gyr). The convective overshoot isochrone age and distance fits are those of Carraro & Chiosi (1994; 2.1 Gyr), Demarque, Sarajedini, & Guo (1994; 2.4 Gyr), Pols et al. (1998; 2.35 Gyr),

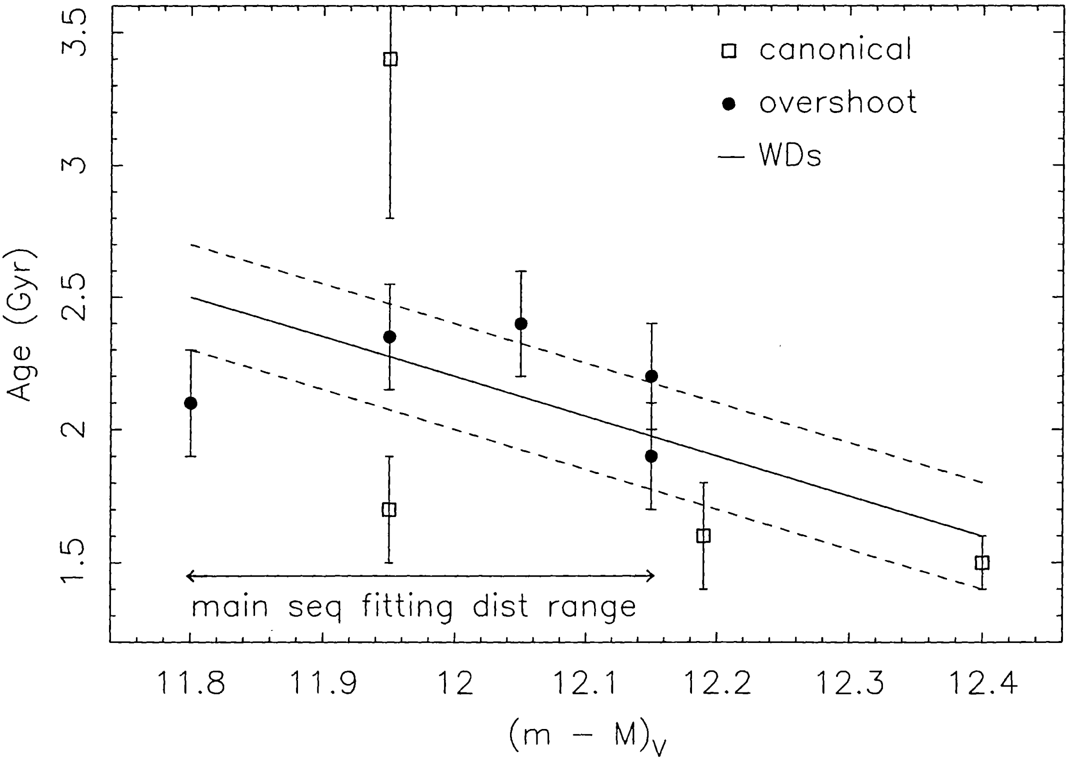

Figure 2. Comparison between all modern isochrone ages determined for NGC 2420 and the WD cooling age as a function of assumed distance modulus.

Twarog, Anthony-Twarog, & Bricker (1999) employing Bertelli et al. (1994) isochrones (1.9 Gyr), and Twarog et al. (1999) employing Schaller et al. (1992) and Schaerer et al. (1993) isochrones (2.2 Gyr). Models with core convective overshoot are a better match to the WD age and the current distance constraints. As it happens, NGC 2420 is in the key age range of 1 to 2 Gyr where an independent age assessment is the most sensitive to the existence or degree of core convective overshoot, which is a current subject of debate (e.g., Demarque et al. 1994; Dominguez et al. 1999). Other rich open clusters in this important age range are NGC 2477, NGC 752, and possibly NGC 7789.

Beyond the details of which stellar evolution models provide ages which best match WD ages for a given cluster, we can ask the general question of how the modern but heterogeneous application of stellar evolution models to open clusters compares to the WD ages for these same clusters. Although the WD isochrones have been created and applied by a few groups the range of models applied to clusters in this age range is not as heterogeneous as those within the stellar evolution community. Table 1 presents a list of open clusters for which a WD isochrone (cooling plus precursor) age or limit has been derived, along with recent age determinations from main sequence stellar evolution studies. The first column lists the cluster name, the second column lists the derived WD age, the third and fourth columns list the −1 and +1σ WD ages, respectively, the fifth column lists a recent isochrone age from the literature, and the sixth

Table 1. White dwarf versus isochrone ages for clusters.

Cluster	WD	WD_{low}	WD_{high}	Iso	Iso_{low}	Iso_{high}
NGC 2168	0.094	0.057	0.137	0.160	0.120	0.200
Hyades	0.3	....	....	0.625	0.500	0.675
Praesepe	0.8	0.6	1.0	0.76	0.62	0.82
NGC 2477	1.3	1.1	1.5	1.0	0.8	1.3
NGC 2420	2.0	1.8	2.2	2.2	1.9	2.5
M 67	4.3	3.7	4.5	4.0	3.5	5.0

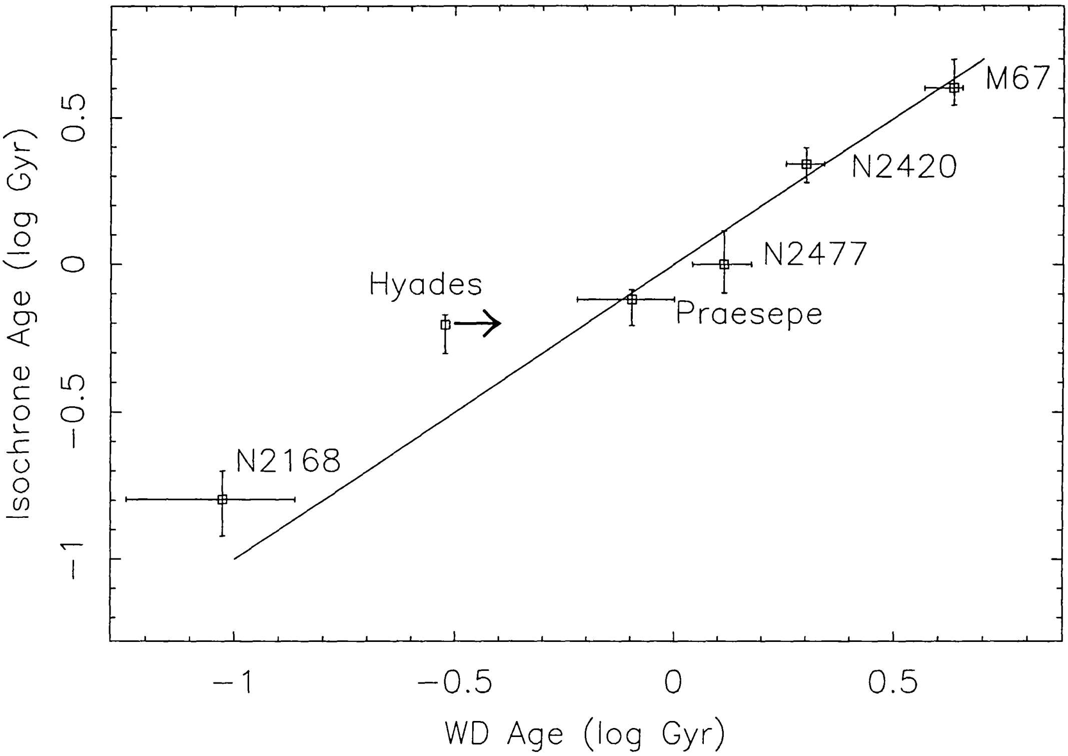

Figure 3. White dwarf versus isochrone ages from recent studies.

and seventh columns list the −1 and $+1\sigma$ isochrone ages, respectively. The NGC 2168 WD and isochrone ages are from Reimers & Koester (1988a, 1988b). The Hyades WD age is from Weidemann et al. (1992) and the isochrone age is from Perryman et al. (1998). The Praesepe WD and isochrone ages are from Claver (1995). The NGC 2477 WD age is from von Hippel, Gilmore, & Jones (1995) and the isochrone age is from Kassis et al. (1997). The NGC 2420 WD age is from von Hippel & Gilmore (2000) and the isochrone ages are from the references listed above for Figure 2. The M 67 WD age is from Richer et al. (1998) and the isochrone ages are from Demarque, Green, & Gunther (1992) and Dinescu et al. (1995). Figure 3 presents WD versus isochrone ages for these clusters on a logarithmic age scale. The WD age for the Hyades is a lower limit since 50 to 90% of the Hyades has likely evaporated (Weidemann et al. 1992), possibly taking with it some of the oldest WDs. It is clear that even despite the heterogeneous application of stellar evolution models to derive star cluster ages, at the present time there appears to be a good overall agreement between cluster ages derived via the two different techniques over the broad age range of 0.1 to 4 Gyr.

5. Conclusion

White dwarf cooling theory and very deep observations in star clusters provide a new tool to test stellar evolution theory and time scales. In particular, white dwarf cooling is now testing the degree of enhanced core mixing in stars with turnoff ages of 1 to 2 Gyr. More generally, it is also encouraging to see the good overall agreement between WD and modern isochrone ages over the range 0.1 to 4 Gyr. Future application of WD isochrones to open clusters with a variety of ages and metallicities will test the consistency and limitations of WD and stellar evolution theory. Eventually, very deep observations of globular clusters, perhaps with NGST, will yield WD ages for at least a few Galactic globular clusters, comparing the theories of WD cooling with stellar evolution at the greatest possible ages, and thereby improving our estimate in the age of the Galaxy.

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Discussion

Michael Rich: We (Harvey Richer is the PI) are attempting to do the WD age experiment in the globular cluster M 4. We have 123 orbits on HST: the first data have just been taken, so we'll see if we can reach down to 31st magnitude. From the modeling that we've done with realistic errors, thanks to the blueing of the cooling curves at large ages, we think we can constrain ages between 10 and 13 Gyr.

Ted von Hippel: Good point. Such deep HST observations of M 4 may determine the WD age for this globular cluster. That would be an important result. If it turns out that the globular cluster ages are on the young side of what Brian [Chaboyer] or others say then it may just be possible. If they're on the old side I don't think that HST can go deep enough.

Michael Rich: No, actually, we used Hansen's best tracks and we put in conservative assumptions and we think that there really is the possibility of seeing the color distribution change because so much of the energy emerges, thanks to the molecular hydrogen cooling, around 6000 Å. We'll just have to see.

Oscar Straniero: Ted, let me comment on the comparison of models with and without overshoot and your white dwarf age. What you are really showing is that you need larger mixed cores due to convection or due to other effects. There are a dozen different model ways to increase the size of the mixing zone; convective overshoot is one of them. For example, increasing opacity increases the convectively unstable regions. Rotationally-induced mixing may also produce larger mixed cores. So there are multiple ways to increase the core and get better agreement with the white dwarf age.

Ted von Hippel: I've taken all the main sequence models that have been applied to NGC 2420 to date and I find the one major difference is the use or absence of convective overshooting. Thanks for your clarification. More generally, the white dwarf cooling age for this cluster supports some mechanism that effectively increases the core size.