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From Young and Hot to Old and Cold: Comparing White Dwarf Cooling Theory to Main-Sequence Stellar Evolution in Open Clusters

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FROM YOUNG AND HOT TO OLD AND COLD: COMPARING WHITE DWARF COOLING THEORY TO MAIN-SEQUENCE STELLAR EVOLUTION IN OPEN CLUSTERS

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ABSTRACT

I explore the current ability of both white dwarf cooling theory and main-sequence stellar evolution theory to accurately determine stellar population ages by comparing ages derived using both techniques for open clusters ranging from 0.1 to 4 Gyr. I find good agreement between white dwarf and main-sequence evolutionary ages over the entire age range currently available for study. I also find that directly comparing main-sequence turnoff ages to white dwarf ages is only weakly sensitive to realistic levels of errors in cluster distance, metallicity, and reddening. Additional detailed comparisons between white dwarf and main-sequence ages have tremendous potential to refine and calibrate both of these important clocks, and I present new simulations of promising open cluster targets. The most demanding requirements for these white dwarf studies are very deep ($V \geq 25-28$) cluster observations made necessary by the faintness of the oldest white dwarfs.

Subject headings: open clusters and associations: general — stars: evolution — white dwarfs

1. INTRODUCTION

White dwarf (WD) cooling theory currently provides the most reliable age for the Galactic disk (Winget et al. 1987; Oswalt et al. 1996; Leggett et al. 1998; Knox et al. 1999), whereas main-sequence stellar evolution provides the most reliable age for the Galactic halo (e.g., Salaris & Weiss 2002; Krauss & Chaboyer 2003). In order to understand the detailed sequence of formation of the Galactic disk and halo, as well as the thick disk, bulge, and local satellite galaxies, these two timescales need to be placed on the same absolute age system. The only current empirical approach available to intercalibrate these two age systems is to derive WD cooling ages and main-sequence turnoff (MSTO) ages for a number of single-age stellar populations over a wide range of ages. Since old WDs are faint ($M_V > 16$), a further constraint is that the stellar population is within a few kiloparsecs, or the target objects become too faint ($V \geq 30$) to observe. In addition, each stellar population should have a single heavy-element abundance, yet the total sample of stellar populations should cover a range of heavy-element abundances, so that detailed studies can search for any metallicity effects on age potentially missing from either theory. Many of the most well-known open clusters fit these needs for nearby, single-age, single-metallicity stellar populations well; furthermore, a sample of some of the most favorable open clusters cover a wide range of ages and a substantial range of heavy-element abundances. Globular clusters can be used to extend such a study to even greater ages and lower metallicities, although at present only a few globular clusters are near enough for observations to be performed to the limit of their coolest WDs.

The first studies to explicitly compare WD cooling and MSTO ages for star clusters were those of Claver (1995) and von Hippel et al. (1995). These studies demonstrated that the WD sequence of a cluster shows a low-luminosity terminus that is determined by the cooling age of the WD population and its comparatively short pre-WD evolution. Subsequent studies (Richer et al. 1998; von Hippel & Gilmore 2000; von Hippel 2001; Claver et al. 2001) have shown that for open clusters, WD cosmochronology and main-sequence stellar evolution give similar cluster ages. WD age studies have now been extended to one globular cluster (NGC 6121=M4) where a WD age has been derived (Hansen et al. 2002), disputed (De Marchi et al. 2004), and defended (Richer et al. 2004). Regardless of the observational reliability of the M4 study, WD cooling models are not yet at the point where they can give reliable values for the great ages of globular clusters (Hansen & Liebert 2003), as a result of uncertainties in the theory of cool WDs. The payoff of an independent, accurate, and precise age determination for globular clusters via the WD cooling technique is enormous, however, and so its calibration is of fundamental importance. Such an independent age determination would either support or contradict ages derived from main-sequence stellar evolution and should allow a more precise comparison between the age of the Galaxy and the now precise, if model-dependent, age for the universe from *WMAP* observations (Bennett et al. 2003).

Additionally, with the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope* (*HST*), it is easy to reach the terminus of the WD sequence in a number of open clusters and possible to reach the terminus in a few of the nearest globular clusters. Cluster observations of sufficient depth, $V > 26$, are often not possible with the current generation of 8–10 m telescopes, however, not only because of the low flux levels, but also because of the many contaminating, compact background galaxies with the approximate colors of cool WDs. For those clusters where the faintest WDs are brighter than the limit of 8–10 m observing capabilities, it may be possible with proper motions derived from second-epoch observations obtained some years later to remove the contaminating background galaxies. Next-generation 20–30 m ground-based telescopes should also be able to make these very deep observations, especially once their adaptive optics (AO) systems are pushed blueward into the *I* band, where contaminating faint background galaxies can be spatially resolved. These current and forthcoming instrumental capabilities, along with recent improvements in both stellar evolution and WD cooling theory, justify a renewed look at the current state of the art in both theories and an examination of which clusters would be best suited to the improved techniques and instrumentation.

2. WHITE DWARF VERSUS MAIN SEQUENCE AGES IN OPEN CLUSTERS

How do the ages derived by main-sequence stellar evolution and WD cooling ages compare in open clusters? Table 1 presents

TABLE 1
White Dwarf versus Main-Sequence Ages for Open Clusters

Cluster (1)	WD Age (Gyr) (2)	MSTO Age (Gyr) (3)	Notes (4)
M35	$0.141^{+0.083}_{-0.043}$	0.150 ± 0.06	1
Hyades	0.3 ± 0.03	$0.625^{+0.05}_{-0.125}$	2
M37	$0.57^{+0.15}_{-0.18}$	$0.52^{+0.6}_{-0.7}$	3
Praesepe	$0.606^{+0.202}_{-0.109}$	0.625 ± 0.05	4
NGC 2477	1.3 ± 0.2	$1.0^{+0.3}_{-0.2}$	5
NGC 2420	2.0 ± 0.2	2.15 ± 0.25	6
M67	$4.3^{+0.2}_{-0.8}$	4.0 ± 0.5	7

Notes.—(1) The WD age is derived from the cooling age for the oldest cluster WD from Williams et al. (2004) plus a precursor age of ~56 Myr, based on the object's initial mass (~7 $M_\odot$), which was calculated from the Weidemann (2000) initial mass–final mass relation. The MSTO ages are based on Grocholski & Sarajedini (2003), Steinhauer (2003), and Steinhauer & Deliyannis (2004). (2) The WD age is from Weidemann et al. (1992), and the MSTO age is from Perryman et al. (1998). (3) The WD and MSTO ages are from Kalirai et al. (2001). The MSTO age range is extracted from their discussion as it is not explicitly presented. (4) The WD age is derived from the cooling age of the oldest WD from Dobbie et al. (2004) plus a precursor age of 106^{+109}_{-43} Myr based on the object's initial mass of $5.3^{+1.4}_{-1.3}$ $M_\odot$, in turn derived from the Weidemann (2000) initial mass–final mass relation. The MSTO age is from Perryman et al. (1998). (5) The WD age is from von Hippel et al. (1995), and the MSTO age is from Kassis et al. (1997). (6) The WD age is from von Hippel & Gilmore (2000), and the MSTO ages represent the mean and range of the convective overshoot results of Carraro & Chiosi (1994), Demarque et al. (1994), Lee et al. (1999), Pols et al. (1998), and Twarog et al. (1999). (7) The WD age is from Richer et al. (1998), and the MSTO ages are from Demarque et al. (1992) and Dinescu et al. (1995).

a list of open clusters for which a WD (cooling plus precursor) age has been derived, along with recent age determinations from main-sequence stellar evolution studies. In choosing which MSTO ages to incorporate, I have used those studies that relied on models with core convective overshoot as past studies of NGC 2420 (von Hippel & Gilmore 2000) and M37 (Kalirai et al. 2001) have found a better match between core convective MSTO ages and WD ages for these clusters. I do not include the new WD cooling results for M4 in Table 1 owing to the current extrapolation in WD theory necessary to date this cluster. Column (1) lists the cluster name, column (2) lists the derived WD age and $\pm 1\ \sigma$ age errors, column (3) lists the MSTO age and $\pm 1\ \sigma$ age range from one or more recent studies, and column (4) points to a reference list for the WD and MSTO ages. Prior discussions of the comparison of WD and MSTO ages in open clusters can be found in von Hippel (2001) and Hansen (2004).

To graphically present the main results of Table 1, Figure 1 presents MSTO versus WD ages for these clusters. The WD age for the Hyades is a lower limit since 50%–90% of the Hyades has likely evaporated (Weidemann et al. 1992), possibly taking with it some of the oldest WDs. (Strictly speaking, cluster WD ages, unlike field star WD ages, always provide a lower age limit since the oldest WDs could be missing owing to partial cluster evaporation.) The WD age for the oldest cluster plotted here, M67, is based on a statistically measured WD luminosity function for the cluster after subtraction of a comparison field (Richer et al. 1998). For this cluster, candidate cluster WDs have not yet been spectroscopically confirmed; therefore, the WD versus MSTO comparison at this age is not yet firmly established. Figure 1 demonstrates that there is a good overall agreement between cluster ages derived via the two different techniques. Assuming that one uses modern overshoot ages, the WD and MSTO ages agree for six open clusters within their age

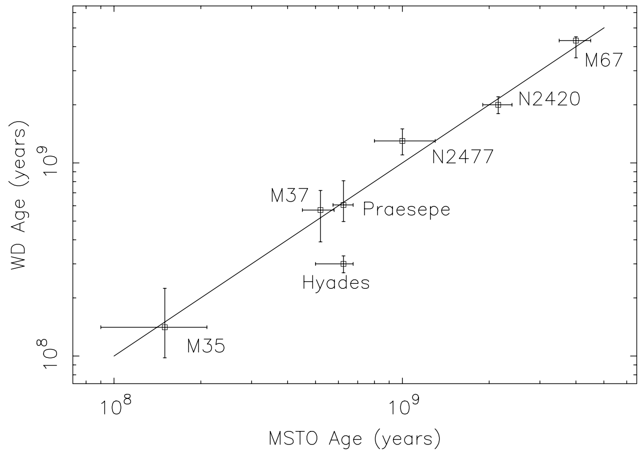

Fig. 1.—MSTO vs. WD ages from recent studies. The WD age for the Hyades is a lower limit to a greater degree than are the WD ages for the other clusters, since 50%–90% of the Hyades has likely evaporated (Weidemann et al. 1992).

errors, and the remaining cluster (the Hyades) is consistent with this age agreement. Stellar evolution and WD cooling provide consistent ages over the broad age range that we can currently test, from 0.1 to at least 2 Gyr and probably to 4 Gyr.

To further study the utility of Figure 1, I calculated the effects of typical observational errors in this diagram. I considered three types of observational error. For the first type of error, I overestimate the distance by 0.2 mag, due for example to a combination of photometric calibration errors and errors in deriving the main-sequence fitting distance. For the second type of error, I overestimate the metallicity by 0.2 dex. For the third type of error, I also overestimate the metallicity by 0.2 dex, but now I also adjust the reddening to compensate for the color change in the MSTO caused by the metallicity error. One or more of these three types of error are present in just about any study of open or globular clusters, and the values have been set to be in the range of typical to somewhat conservative. To convert these assumed errors into an age error, I use the cluster models outlined in the next section.

Figure 2 presents the effect of these three types of error on the derived MSTO age versus the ratio of the WD to MSTO age over the range of 100 Myr to 4 Gyr. The thick lines show the effect of overestimating distances by 0.2 mag, which forces the cluster MSTO and WD ages to be underestimated since both turnoff stars and WDs are then assumed to be brighter than they actually are. The thin lines show the effect of overestimating metallicity by 0.2 dex, in which case overly red isochrones are force-fitted to the turnoff stars and the MSTO ages change. In the cluster models there is no significant change in the WD ages with this small metallicity change, as metallicity is assumed to enter only through the slightly modified ages of the high-mass precursors to the oldest WDs, and the latter effect is included. The dotted lines show the effect of overestimating metallicity by 0.2 dex and then compensating by underestimating reddening to keep the cluster turnoff at the same color. This type of error affects the WD ages since a change in reddening changes the apparent magnitude of the WD terminus. Of course, for some real clusters with low reddening, it is not possible to lower the reddening enough to match some erroneous metallicity determinations, and in these cases there are additional limitations on errors in this third category. It is comforting to see that the net effect of realistic errors on the WD and MSTO ages is small, typically changing the ratio of ages by ~10% through much

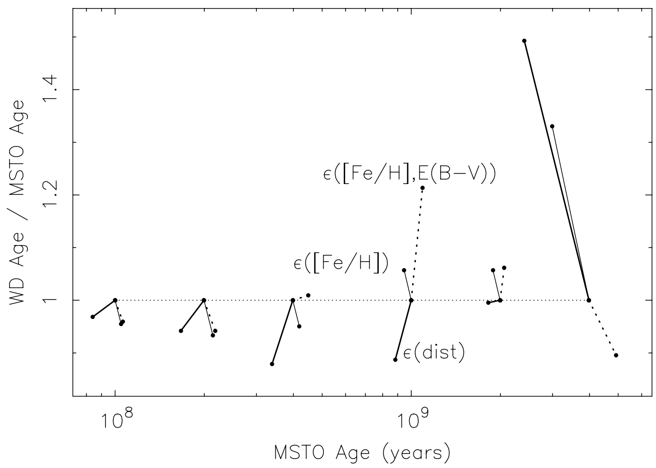

FIG. 2.—Effect of three types of errors on the derived MSTO age vs. the ratio of the WD to MSTO age over the range of 100 Myr to 4 Gyr. Calculations are performed at log (age) = 8.0, 8.3, 8.6, 9.0, 9.3, and 9.6. The thick lines show the effect of overestimating distance by 0.2 mag. The thin lines show the effect of overestimating metallicity by 0.2 dex. The dotted lines show the effect of overestimating metallicity by 0.2 dex and then compensating by decreasing reddening to keep the MSTO at the same color.

of this age range, although reaching a maximum for distance errors amounting to ~50% at 4 Gyr. The derived absolute MSTO ages change by <25%, except at 4 Gyr where the effect of an overestimated distance by 0.2 mag lowers the implied MSTO age by 40% to ~2.4 Gyr. In this case the implied WD age drops by 10% to ~3.6 Gyr.

Figure 2 also shows interesting responses to these sources of error for clusters as a function of age. While overestimating distances always causes an underestimate in both the MSTO and WD ages, the ratio of these two underestimated ages changes around 2 Gyr. For younger clusters, the sensitivity of the location of the WD terminus to age is slightly greater (up to 10%) than the sensitivity of the location of the MSTO to age; thus, the WD approach underestimates age to a slightly greater degree than the MSTO approach. At 2 Gyr, both the MSTO and WD age techniques are equally sensitive to direct displacements in luminosity, and at 4 Gyr the MSTO age is the more sensitive technique and thus underestimates age to a greater degree than the WD technique. The change in relative sensitivity of the two techniques to metallicity errors near 1 Gyr is predominantly due to the effect of metallicity changes on the MSTO, since the WD technique is largely insensitive to metallicity errors. The dominant effect is that the MSTO becomes fainter if metallicity is overestimated for clusters between 0.1 and 0.4 Gyr, whereas the MSTO becomes brighter for clusters between 1 and 4 Gyr, at least for the input stellar models (Girardi et al. 2000) near solar metallicity. The final type of error, with combined and offsetting errors in metallicity and reddening, is somewhat more complicated. For the youngest clusters and our input models, a change in metallicity causes only a small color change and therefore induces only a small error in reddening. The color change increases rapidly as age increases to 1 Gyr, reaching a maximum color difference of $B - V \approx 0.08$ mag for a change in metallicity of 0.2 dex, and then decreases slowly as age increases to 4 Gyr. The basic effect is that the MSTO ages are overestimated with this particular coupling of errors (overestimating metallicity by 0.2 dex, then compensating by underestimating reddening), since the underestimated reddening forces one to compensate and assume that the MSTO is fainter than it really is. The effect on the implied WD ages from this type of error is determined by the size of the reddening error and the sensitivity of the WD technique to shifts in luminosity as a function of age. For young clusters the effect is small since the underestimated reddening is small. As the offsetting error in reddening increases, its effect on the WD ages becomes significant.

In Figure 3 I again present the three categories of error studied in Figure 2, now in the same observational plane of Figure 1. In this diagram of direct age comparison, it is clear that the effects of typical errors are to move the derived ages largely along the one-to-one correspondence line. This is both good news and bad news for comparing WD and MSTO ages in clusters. The bad news is that independent ages via the two techniques offer little leverage on the other cluster parameters of distance, metallicity, and reddening. The good news is that the relative ages of the clusters change little with these types of errors, especially for clusters younger than 2 Gyr, and so comparing these two ages remains a powerful way of checking on the consistency between main-sequence evolutionary theory and WD cooling theory. At 4 Gyr the departure from the correspondence line is greater for a distance error of 0.2 mag, but fortunately the cluster in that position in Figure 1, M67, is one of the best studied old open clusters, and its distance uncertainty is likely to be substantially less (Sarajedini et al. 2004 and references therein). Figure 3 also demonstrates at least part of the reason why the clusters in Figure 1 agree so well in their MSTO and WD ages: this diagram, at least in this age range, is insensitive to reasonable errors in cluster distance, metallicity, or reddening.

While the agreement between MSTO and WD ages should give us confidence in both methods of age dating stellar populations with ages of ≤4 Gyr, we need to remain cautious when interpreting and comparing ages for older populations such as the Galactic disk and halo. It is also important to increase the precision of age dating clusters younger than 4 Gyr, as increased precision could help tease out subtle effects that may not be correctly modeled in WD or main-sequence stellar evolution. Such effects could include the degree of core overshooting and its metallicity dependence, as well as the transition from the CNO bi-cycle to PP burning in main-sequence stars, or for WDs, mass loss on the asymptotic giant branch and the initial mass–final mass relation, envelope effects and dredge-up, and carbon-oxygen phase separation during crystallization. Future observations and

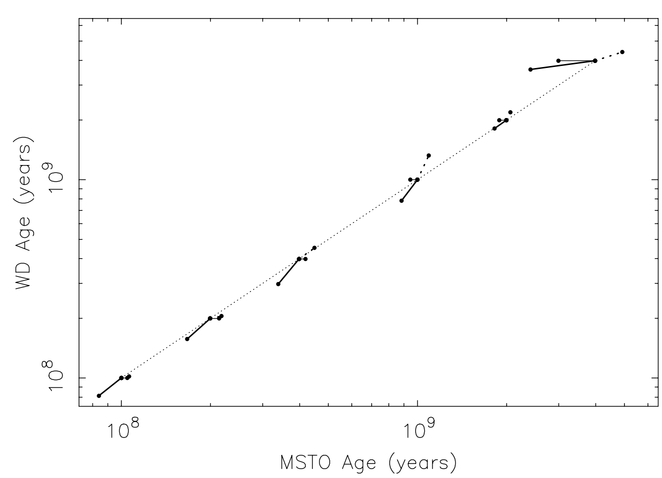

FIG. 3.—Three categories of error presented in the MSTO age vs. WD age diagram. The symbols are the same as in Fig. 2. The diagonal dotted line crossing most of the diagram is the one-to-one correspondence line where MSTO ages and WD ages are identical.

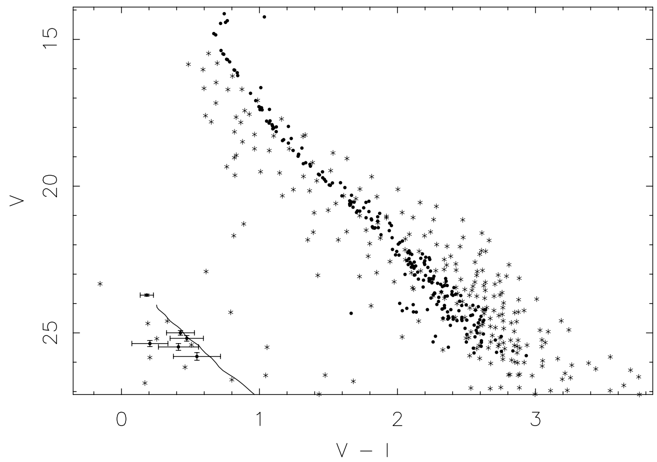

FIG. 4.—Simulated *VI* CMDs for the open cluster NGC 1245, with cluster parameters as listed in Table 2.

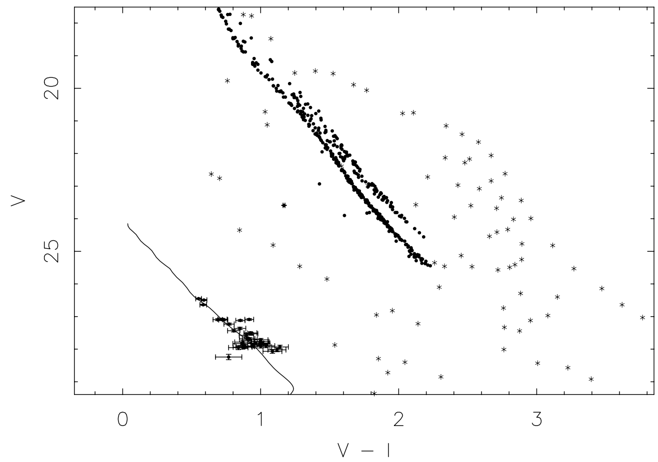

FIG. 6.—Same as Fig. 4, but for NGC 2243.

analyses of more star clusters over a broad age range are therefore needed to increase age dating precision, refine current WD and main-sequence theory, and improve the analyses of ages for older stellar populations, particularly those older than 4 Gyr. Additionally, age studies for clusters nominally at the same age, but with different metallicities, are needed to test the dependence of both WD cooling theory and main-sequence theory on heavy-element abundance, since we know the most about the high-metallicity Sun and solar neighborhood yet wish most to age date the low-metallicity Galactic halo.

3. IMPROVING WHITE DWARF AGE DETERMINATIONS: NEW OBSERVATIONS AND NEW TECHNIQUES

How do we build on and refine the present, carefully collected set of observations and results comparing WD ages and MSTO ages? Certainly, *HST* with the ACS offers new capability, and capability well matched to this problem. The next generation of very large ground-based telescopes should also easily recover the coolest WDs in many open clusters and probably also in a few of the nearest globular clusters, especially if their AO systems can be pushed into the *I* band, a wavelength sensitive to cool WDs and to background galaxy morphology. To motivate further studies comparing MSTO to WD ages in clusters, I present here a handful of simulated clusters that appear to be good candidates for investigation. These simulations allowed me to explore the trade-offs between cluster parameters, the contaminating Galactic field, and observational difficulty and thereby reject some clusters that would be poor candidates for WD age studies.

In Figures 4–10 I present simulated *VI* color-magnitude diagrams (CMDs) for the open clusters NGC 1245, NGC 2204, NGC 2243, NGC 2360, NGC 2506, NGC 2660, and NGC 7789. The major characteristics of these clusters are listed in Table 2. These clusters were chosen since they are relatively nearby, are rich in members, have moderate or low interstellar absorption, and are in the important age range for WD age studies—these are good candidates for *HST* ACS observations. Two older clusters, NGC 188 (∼7 Gyr; Sarajedini et al. 1999) and NGC 6791 (∼8 Gyr; Chaboyer et al. 1999), are not presented here, although they are good, but difficult, observational targets. At this point, I am not simulating such clusters since their highest mass, crystallizing WDs are not yet modeled (see below) in a sufficiently realistic manner for ages greater than 5 Gyr.

The cluster simulations of Figures 4–10 incorporate a Miller & Scalo (1979) initial mass function (IMF), main-sequence and giant branch stellar evolution timescales of Girardi et al. (2000), the initial (main sequence) mass–final (WD) mass relation of Weidemann (2000), WD cooling timescales of Wood (1992), and WD atmosphere colors of Bergeron et al. (1995). Each star is randomly drawn from the IMF and, based on an appropriate binary star fraction (here set to 50%, typical for open clusters), randomly assigned to be a single star or a binary

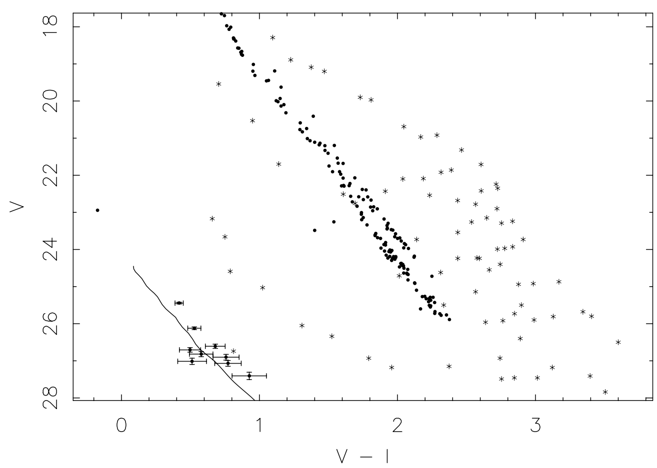

FIG. 5.—Same as Fig. 4, but for NGC 2204.

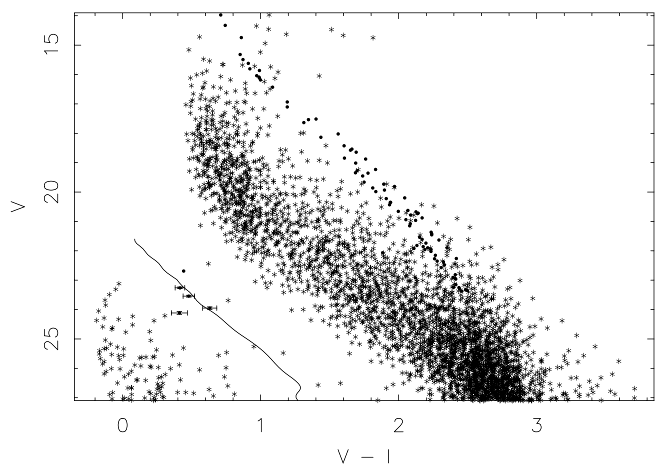

FIG. 7.—Same as Fig. 4, but for NGC 2360.

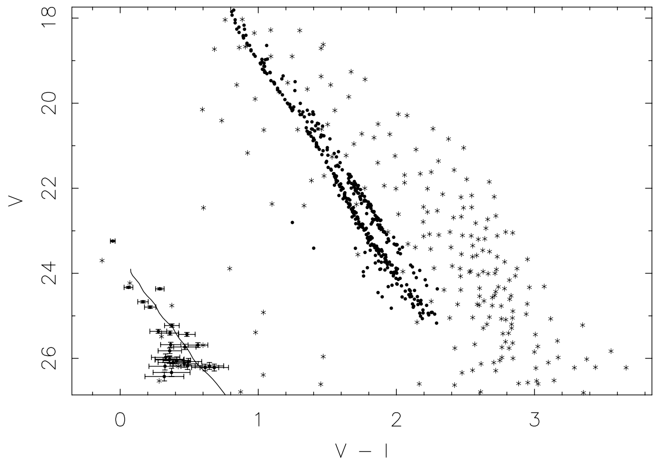

FIG. 8.—Same as Fig. 4, but for NGC 2506.

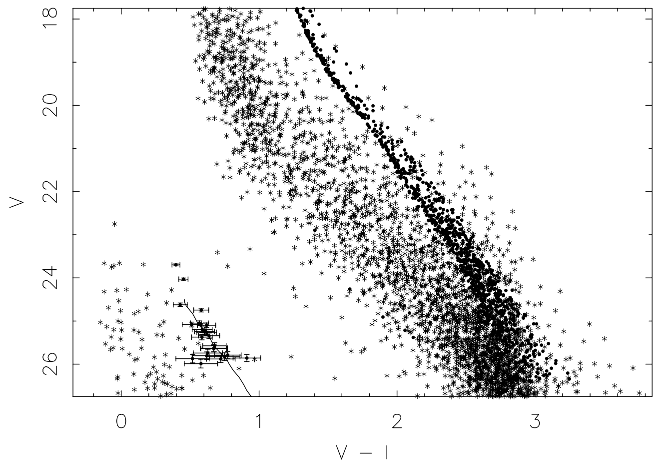

FIG. 9.—Same as Fig. 4, but for NGC 2660.

with a companion also randomly drawn from the IMF.[1] Other stellar evolution (e.g., Yi et al. 2001; Baraffe et al. 1998; Siess et al. 2000) and WD cooling (e.g., Benvenuto & Althaus 1999; Hansen 1999) models could have been used, but for the present purposes, these often-used models adequately cover parameter space. The simulated CMDs incorporate realistic photometric errors, for observational depths set to match $V = 26$ or 0.5 mag beyond the WD terminus, whichever is fainter, at signal-to-noise ratio $S/N = 15$.[2] The simulated CMDs also incorporate field stars as predicted by the model of Reid & Majewski (1993). These simulations do not include mass segregation or other dynamical processes, which can be important in open clusters, especially for the lowest mass stars, but which typically have little effect on the measured WD mass fraction (von Hippel 1998; see also Hurley & Shara [2003], who find that the WD luminosity and mass functions are insensitive to dynamical effects at 0.5–1 half-mass radii). The cluster stars are denoted by filled circles, whereas the field stars are denoted by asterisks. The 1 σ error bars are included for the cluster WDs only. To guide the eye to the expected location of the WDs in these CMDs, the cooling track for a 0.7 $M_\odot$ WD cooler than $T_{\rm eff} = 15{,}000$ K from Hansen (1999) is presented in each CMD. A clear limitation of these simulations is that stars with masses $\leq 0.15\ M_\odot$ are not included, thus the unrealistic lower limit to the main sequence and the limited variety of binaries among the lowest mass stars. Since the focus of this study is on stars that can become WDs, this simplification is merely one of presentation. The number of simulated cluster stars should be approximately the number that one would observe near the cluster centers in an *HST* ACS field ($3.'37 \times 3.'37$). This number is determined by normalizing the star counts of each cluster to the known brighter stars in these clusters from the published CMDs (see reference list in Table 2). This technique, although dependent on an extrapolation of the IMF, has worked well enough in the past, providing the approximate predicted number of cluster stars in *HST* WFPC2 observations of NGC 2420 (von Hippel & Gilmore 2000).

Even a quick study of these simulated clusters shows some of the difficulties in planning and analyzing observations of the faint cluster WDs. While the main sequence typically stands out against the background Galactic field stars, the WD sequence is often harder to distinguish. The contaminating objects in the WD region, however, are simulated Galactic field WDs, whose number counts at these faint flux levels are unknown. It is also important to remove the abundant background galaxies at the faint flux levels where the WDs are found, as these galaxies outnumber cluster WDs and have similar colors. These contaminating background galaxies are not included in the cluster simulations, which assume that some technique is applied effectively to remove them. The need to remove background galaxies is one of the primary reasons *HST* is so appropriate for this study. Next-generation ground-based telescopes with *I*-band AO systems could also morphologically reject the background galaxies, but at present this is not possible from the ground. Among these simulated clusters some (NGC 2243 and NGC 2660) display enough WDs that there is a clear pileup near

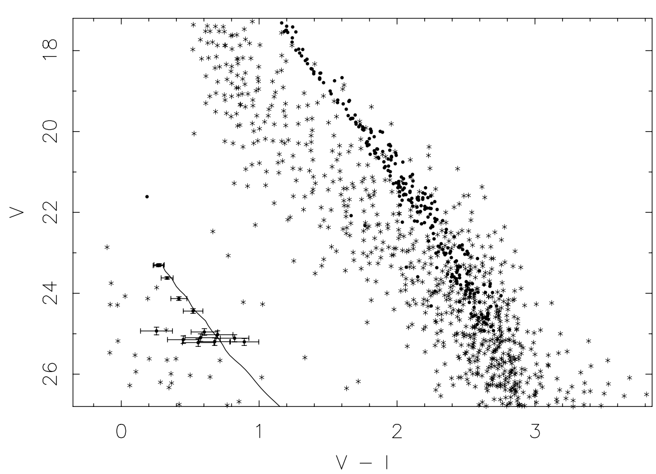

FIG. 10.—Same as Fig. 4, but for NGC 7789.

[1] The implied age from either the MSTO technique or the WD technique is insensitive to the IMF. The IMF serves only to populate the particular mass region that is currently at the MSTO or at the faint end of the WD sequence. If there are insufficient stars, particularly if the cluster is young, then the few cluster stars coupled with the IMF can create an additional, statistical uncertainty to locating the MSTO or faintest WDs. Binaries of nearly any mass ratio have a similar effect. WDs in such systems are generally not recognized and MSTO stars in such systems are found brighter and generally redder than the MSTO; therefore, they do not help define the MSTO.

[2] From experience, $S/N = 15$ is required to obtain good morphological rejection of background galaxies at *HST* resolution. By placing this value 0.5 mag below the expected terminus of the WD sequence, one has a bit of insurance against the cluster being older than expected. While not strictly necessary, even if the cluster is as old as expected, the clear gap below the WD sequence, now devoid of contaminating background galaxies, makes a convincing case that the WD terminus has been properly identified. If the WD terminus is at $V < 25.5$, it is easiest to still observe to $V = 26$, since this depth can be achieved in a single *HST* orbit.

TABLE 2
OPEN CLUSTER PARAMETERS FOR SIMULATIONS

Cluster (1)	V-M_V (2)	A_V (3)	Age (4)	l (5)	b (6)	References (7)
NGC 1245	12.95	0.68	1.0	146.63	−8.92	1
NGC 2204	13.35	0.25	2.5	226.02	−16.07	2
NGC 2243	13.05	0.12	5.	239.50	−17.98	3
NGC 2360	10.5	0.25	2.2	229.80	−1.40	4
NGC 2506	12.8	0.22	1.9	230.60	9.97	5
NGC 2660	13.4	1.2	0.9	265.84	−3.03	6
NGC 7789	12.2	0.81	1.6	115.49	−5.35	7

REFERENCES.—(1) Burke et al. 2004; (2) Frogel & Twarog 1983; (3) Bergbusch et al. 1991; (4) Mermilliod & Mayor 1990; (5) Marconi et al. 1997; (6) Sandrelli et al. 1999; (7) Gim et al. 1998.

the WD terminus. Others (NGC 2204 and NGC 2506) should be uncrowded enough that cluster WDs will dominate the lower left of the CMD. The remaining three clusters may pose greater difficulties, especially if crowding is worse than predicted, although there are additional means to extract the cluster WDs. The easiest approaches are to observe additional cluster fields in order to build up the number of cluster WDs, to observe nearby control fields to better estimate Galactic field star and background galaxy contamination, and to add a third, blue-sensitive filter to the observation sequence. While field WDs will not separate as well from cluster WDs with the addition of another filter, the greater color baseline and three-filter information will help separate the warmer WDs (those with strong Balmer lines, with $T_{\rm eff} \gtrsim 8000$ K) from background main-sequence stars. Should these techniques prove insufficient and where a particular cluster is a good example in age-metallicity parameter space, a second *HST* epoch a few years later (King et al. 1998) or ground-based epoch about a decade later (see Platais et al. 2003) can be obtained to isolate the cluster stars based on common proper motion.

4. CONCLUSIONS

WD cooling theory and very deep observations in star clusters provide a new tool to test stellar evolution theory and timescales, as well as place two different age dating techniques on the same calibrated scale. Fortunately, directly comparing MSTO ages to WD ages is only weakly sensitive to realistic levels of errors in cluster distance, metallicity, and reddening. More generally, it is encouraging to see the good overall agreement between WD and modern MSTO ages over the range 0.1–4 Gyr. Future application of WD isochrones to open clusters with a variety of ages and metallicities, such as those open clusters I have simulated, will test the consistency and limitations of WD and main-sequence evolution theory. Eventually, very deep observations of globular clusters with *HST* ACS and future, large ground-based facilities, calibrated by extensive *HST* and ground-based observations and analyses of stars in open clusters, will yield accurate and precise WD ages for the Galactic halo. These same open cluster observations will calibrate ongoing (Kilic et al. 2005) work on the age of the Galactic disk via field WDs. The latter technique can date individual WDs (Bergeron et al. 2001), and its improved calibration will allow WD researchers to determine not just the age of the Galactic disk, but also the age and age distribution of the Galactic thick disk and halo.

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