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THE WHITE DWARF COOLING SEQUENCE IN NGC 6791

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ABSTRACT

In the old, populous, and metal-rich open cluster NGC 6791, we have used deep *Hubble Space Telescope* Advanced Camera for Surveys images to track the white dwarf cooling sequence down to $m_{\rm F606W} \simeq 28.5$. The white dwarf luminosity function shows a well-defined peak at $m_{\rm F606W} \simeq 27.4$ and a bending to the blue in the color-magnitude diagram. If this peak corresponds to the end of the white dwarf cooling sequence, the comparison with theoretical isochrones provides a cluster age estimate of ∼2.4 Gyr, in sharp contrast with the age of 8–9 Gyr inferred from the main-sequence turnoff. If the end is at fainter magnitudes, the peak at $m_{\rm F606W} \simeq 27.4$ is even more enigmatic. We discuss possible causes, none of them very convincing.

Subject headings: open clusters and associations: individual (NGC 6791) — white dwarfs

1. INTRODUCTION

NGC 6791 is one of the richest open clusters, with an age older than 8 Gyr and [Fe/H] ∼ +0.4. Because of these unusual properties, it has been the target of several studies, the most recent by Carney et al. (2005).

NGC 6791 is close enough that *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) imaging can hope to reach the bottom of the white dwarf (WD) cooling sequence and therefore estimate its age independently of the main-sequence (MS) turnoff (TO). For clusters older than 3 Gyr this kind of age estimate has been previously attempted only in the ∼4 Gyr old open cluster M67 (Richer et al. 1998) and the globular cluster M4 (Hansen et al. 2002, 2004). In the latter case the end of the cooling sequence was not detected, and the age estimate was based on modeling the shape of the observed part of the WD luminosity function (LF).

The data on which this Letter is based were originally taken to reach the bottom of the MS in NGC 6791, but when we first saw the color-magnitude diagram (CMD) it was clear that the WD cooling sequence (WDCS) was equally exciting. A forthcoming paper will describe the CMD and the MS LF of NGC 6791 and compare the observations with models (King et al. 2005). Here we focus on the WD sequence.

2. OBSERVATIONS AND MEASUREMENTS

The data were taken on 2003 July 16–17, with *HST*'s ACS WFC (GO 9815), and consist of six long (∼1150 s) and three short exposures of ∼30 s through each of the filters F606W and F814W. A detailed discussion of the data reduction, photometric calibration, and artificial star tests is presented in our forthcoming paper (King et al. 2005). Briefly, the images in each filter were corrected for distortion according to Anderson (2002) and combined into a stack in which pixels are subsampled by a factor of 2 to remove undersampling. The photometry was performed with DAOPHOT (Stetson 1987). Artificial stars were added in order to determine the completeness curve. The calibration to the ACS Vega magnitude system was done following the recipes in Bedin et al. (2005).

Figure 1 summarizes our observational results. Panel *a* shows the CMD, while panel *b* displays the completeness-corrected WD LF. There is a clear peak of density at $m_{\rm F606W} \sim 27.4$, after which the LF drops but stays well above zero down to $m_{\rm F606W} \sim 28.2$, where our completeness becomes ≤50%. The peak in the LF coincides with a bending in the CMD of the WDCS. At $m_{\rm F606W} \sim 28.2$ there seems to be a second peak, but its significance remains to be investigated. Panel *c* shows the input (*solid line*) and the output CMD from the artificial-star experiments, and panel *d* the corresponding joint (two filters) completeness curve for WDs. Panels *e* and *f* show a blowup of the CMD focused on the observed and artificial WDs, respectively.

It is evident from panels *b* and *d* that at the level of the density peak in the WD LF the completeness is still ∼85%, and therefore the peak and the bending to the blue are real. At $l \sim 70°$, $b \sim +11°$ we expect the contribution of field WDs in our small field to be negligible, and because we rejected all non-pointlike sources by visual inspection, we expect the number of contaminating galaxies also to be negligible.

3. COMPARISON WITH THEORY

In Figure 2, DA WD isochrones for ages of 2, 4, 6, 8, and 10 Gyr are compared with the observed WD sequence. The isochrones came from the WD models by Salaris et al. (2000), transformed into the ACS Vega magnitude system using the most up-to-date on-orbit transmission curves (Sirianni et al. 2005), and color transformations generously provided by P. Bergeron, based on the model atmospheres used in Bergeron et al. (2001). In addition to the cooling models, we have adopted the empirical relation between WD mass and progenitor mass initial-final mass relation (IFMR) by Weidemann (1987). The progenitor lifetimes come from the Pietrinferni et al. (2004) grid of stellar models.

In the WD model fitting we adopted the distance and reddening found in our forthcoming paper (King et al. 2005), in which we showed that the best fit to the MS TO and subgiant branch (reproduced also in Fig. 2) is obtained with [Fe/H] = 0.26, an

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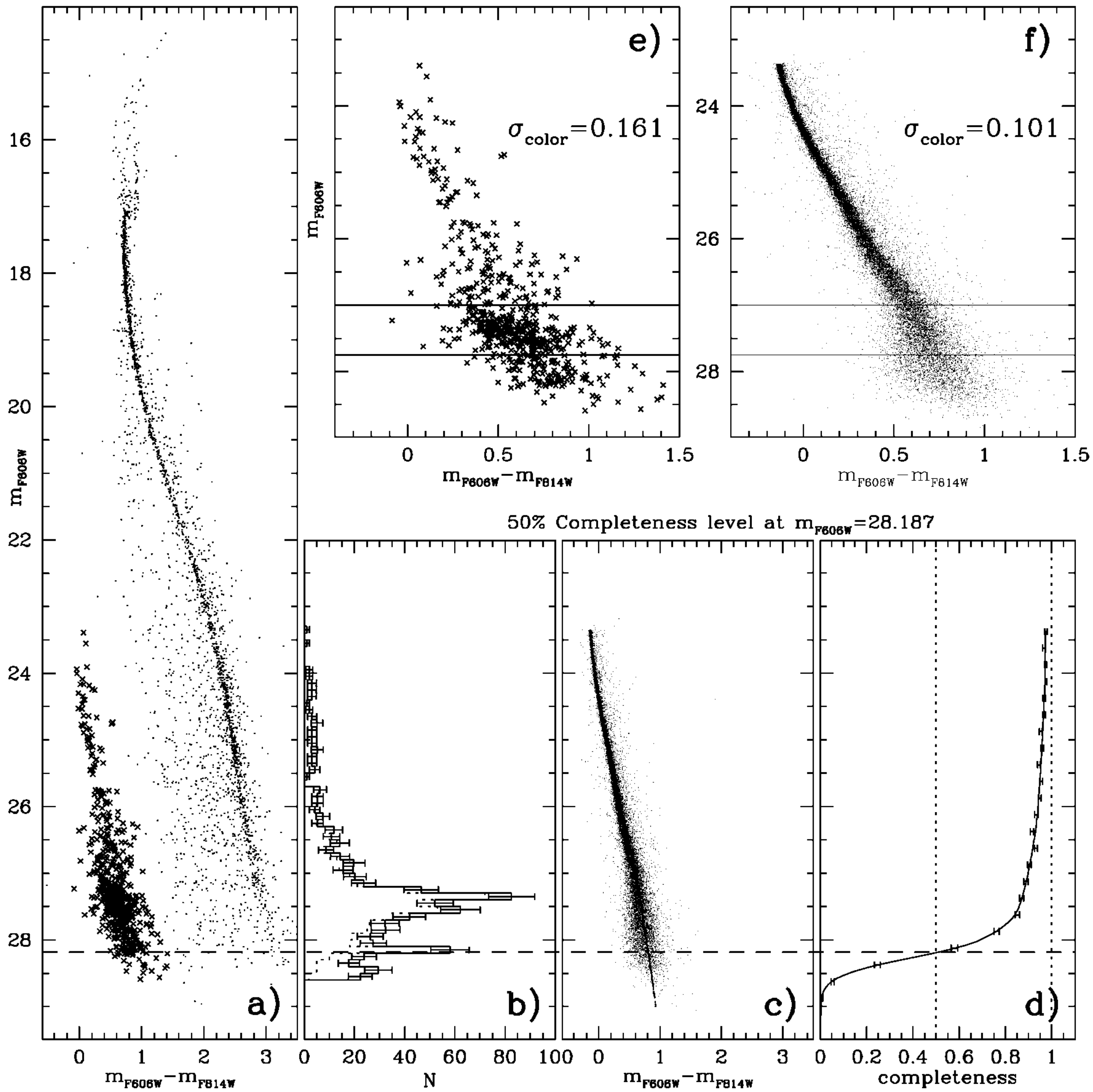

FIG. 1.—CMD and WD LF of NGC 6791 and the artificial-star results (see text). The broadening in color of the observed CMD at the level of the WD peak is ~60% larger than for artificial stars.

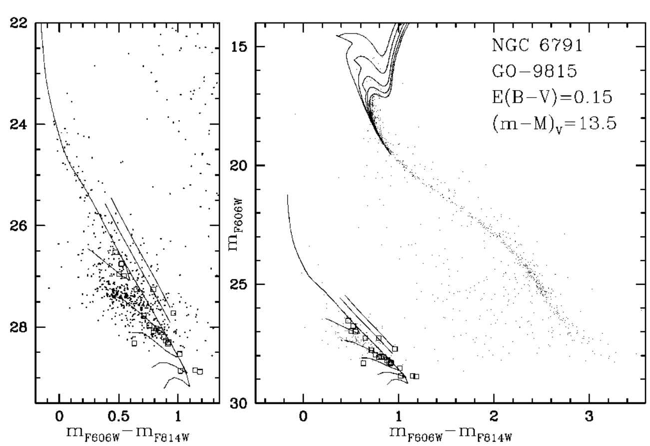

FIG. 2.—MS and the WDCS of NGC 6791, fitted with 2, 4, 6, 8, and 10 Gyr isochrones, with the same distance modulus and reddening. The lines on the red side of the WD isochrones indicate the loci of WDs with pure helium cores of 0.32 and 0.41 $M_\odot$.

apparent modulus $(m-M)_{F606W} = 13.44$, and a reddening $E(m_{F606W} - m_{F814W}) = 0.14$. These correspond to $(m-M)_V = 13.50$ and $E(B-V) = 0.15$ in the Johnson bandpasses (Bedin et al. 2005). Notably, the age derived from the fitting of the TO is between 8 and 9 Gyr, as discussed in more detail in King et al. (2005). All these values are in broad agreement with the recent analysis by Carney et al. (2005).

The brighter parts of our WD isochrones are populated by objects with mass of ~0.54 $M_\odot$—i.e., WDs produced by the stars currently at the asymptotic giant branch (AGB) tip. The isochrones reproduce well the main body of the observed WD sequence between $m_{F606W} \sim 24$ and 26. A few objects in this magnitude range lie to the red side of the main locus of the WDCS, most probably a mixture of field contamination, He-core WDs, and possibly unresolved binary WD-WD systems.

The bottom of the WD isochrones shows a turn to the blue due to the appearance of larger WD masses, from the more massive stars that evolved off the AGB early in the cluster's history. The brightness of this turn to the blue is a function of cluster age (see, e.g., Salaris et al. 2000; Richer et al. 2000). It is clear from Figure 2 that even the bottom of the 6 Gyr WD isochrone is at a brightness where the peak in the WD population has already dropped.

Figure 2 highlights a potentially serious mismatch between the MS TO and WD ages for NGC 6791 . For comparison we also show in Figure 2 the location of the sample of cool WDs in the solar neighborhood (*open squares*) analyzed by Bergeron et al. (2001), translated into the same ACS Vega magnitude system with the transformations adopted in this Letter. As expected, the local WDs reach fainter magnitudes than the bulk of the cluster WDCS, down to a brightness consistent with our 8 Gyr isochrone.

To investigate further this age mismatch, we consider again the LF of the cluster WDCS (see Fig. 3, *top panel*), with its well-defined peak at $m_{\rm F606W} \sim 27.4$. From a theoretical point of view, one can determine an LF for a given age starting from the appropriate WD isochrone and adopting an initial mass function (IMF) for the progenitors (see, e.g., Richer et al. 2000); all theoretical LFs show a peak at the faint end that moves toward fainter luminosities as the cluster age increases, reflecting the behavior of the underlying isochrones. This peak is caused by the "piling up" at the bottom of the WD isochrone of WDs of all masses, due to their finite cooling age. If one uses a power-law IMF ($dn/dm \propto m^{-(1+x)}$), the exact value of the exponent x ($x = 1.35$ for Salpeter IMF) does not affect the position of the LF peak. The position of the peak of the observed WDCS can be reproduced only by assuming an age below 3 Gyr, in clear disagreement with the estimated TO age of about 8–9 Gyr (~1.5 mag fainter). A subpopulation of stars with age of ~3 Gyr can be excluded by the fact that we do not observe the corresponding TO.

Further evidence that we are facing a serious problem is given in Figure 3 (*middle and bottom panels*), which compares the WD LF of the solar metallicity open cluster M67 (Richer et al. 1998) with our NGC 6791 WD LF. The NGC 6791 WD data have been transformed into the Johnson-Cousins system from the ACS one, using the transformations by Sirianni et al. (2005), which should be accurate to a few hundredths of a magnitude. The distance moduli have been subtracted from both LFs (we used values in Percival & Salaris 2003), and the NGC 6791 LF has been rebinned in order to match the M67 binning. The M67 LF also shows a peak, which most probably denotes the bottom of the DA WD sequence. Surprisingly enough, the peaks in the two clusters are at the same absolute magnitude. But the TO age of M67 is only ~4 Gyr (see, e.g., Salaris et al. 2004), i.e., about half the NGC 6791 age. With our WD isochrones, using lifetimes for solar metallicity progenitors, we can reproduce the observed peak in the M67 WD LF adopting an age of 3.5 Gyr, consistent with its TO age. The same result is obtained by Richer et al. (1998, 2000) with their own WD isochrones. The fact that the TO and WD ages agree for M67 makes the disagreement in NGC 6791 even more puzzling.

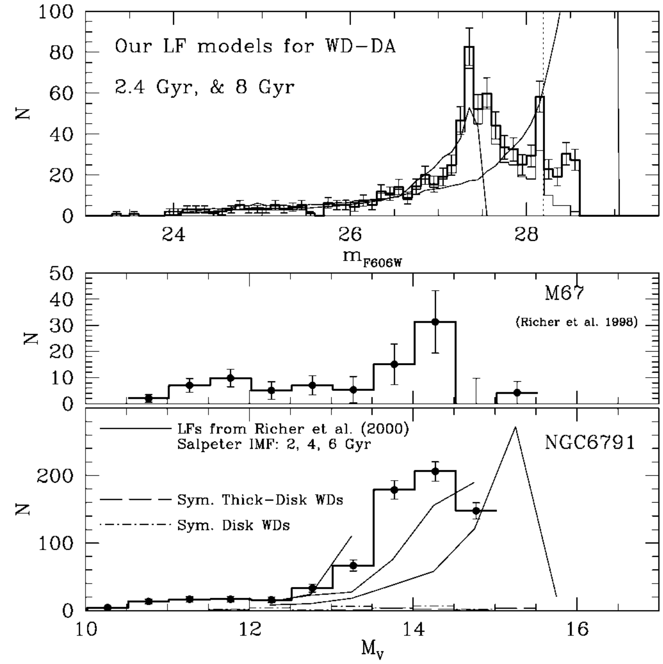

FIG. 3.—*Top*: Completeness-corrected LF, with the theoretical LFs for 2.4 and 8 Gyr overplotted. The vertical dotted line is the 50% completeness level. The WD LF of M67 (*middle*) and that of NGC 6791 (*bottom*) have peaks at the same absolute magnitude, corresponding to an age younger than 4 Gyr.

4. DISCUSSION

As shown in the previous paragraph, the nature of the WD LF peak at $m_{\rm F606W} \simeq 27.4$ is enigmatic. We are faced with two possibilities: either (1) the peak represents the bottom of the WDCS, and in this case we need to understand why the WD cooling age is in sharp contrast with the age inferred from the MS TO; or (2) the peak is not due to the classical DA WDs. In this section we further discuss the consequences of these two hypotheses.

Let us first examine the possibility that the observed peak indeed represents the bottom of the WDCS of NGC 6791. A wrong cooling age could simply come from having adopted a wrong distance modulus, but an apparent distance modulus smaller by 1.5 mag would imply a TO age well above 20 Gyr. On the other hand, we cannot exclude that the TO age could be wrong because the adopted metallicity is wrong, although the most likely metallicity interval (Taylor 2001) cannot solve the discrepancy.

Another possibility is an IFMR radically different from the one we used. However, as we have verified with various numerical tests, none of the proposed IFMR in Figure 11 of Hansen et al. (2004) helps solve the problem. As noted by the referee (H. Richer), the WD LF shows an apparent gap (of low statistical significance, however) at $M_{\rm F606W} \simeq 12.2$, which could correspond to a similar feature identified in M4 at $M_{\rm F606W} \simeq 13.2$ (Hansen et al. 2004)—a full magnitude fainter. Is this further evidence that the cooling models specific for NGC 6791 fail? In the magnitude range covered by the bottom of the observed WD sequence, all modern WD cooling models—including the Salaris et al. (2000) models that we have adopted here—provide very similar cooling times (see, e.g., Prada-Moroni & Straniero 2002).

Another possibility for explaining this age mismatch is to invoke a wrong CO chemical stratification in the WD core of the models (that underestimates the energy available during the cooling and the crystallization process) and/or a wrong atmospheric H-layer thickness. However, the most recent determination of the $C^{12}(\alpha, \gamma)O^{16}$ reaction rate would not solve the problem, nor would the largest possible value of $\Delta m_{\rm H}$ for the H layer.

The CMD of Figure 1 clearly shows that NGC 6791 has a large population of binaries. It might be that the LF peak is made of DA WDs whose progenitors were produced by merging (or stripping) in binaries, possibly during their MS phase. If these mergers occur about 2–3 Gyr after the birth of the cluster and the resulting objects have masses of ∼1.5 $M_{\odot}$, their WD progeny would populate the region of the LF peak for a cluster age of about 8 Gyr. The counterpart of these merged progenitors might be the blue stragglers (BSs). Davies et al. (2004), based on observational evidence by Piotto et al. (2004), show that the number of BSs coming from evolving binaries should have been much larger in the first few gigayears of the life of the cluster. We also note that the horizontal branch (HB) of NGC 6791 has an anomalous morphology (Yong et al. 2000). The origin of this anomaly is not at all clear, and it is even less clear how it propagates into the WD regime.

Let us now explore the case that the LF peak is not due to DA WDs. WDs with a degenerate He-core and masses of 0.3–0.4 $M_{\odot}$, from progenitors of ∼1.3–1.5 $M_{\odot}$, can populate the region of the observed peak if we adopt a cluster age of ∼8 Gyr, according to the He-core WD models by Serenelli et al. (2001). However, a substantial contamination by He-core WDs can be excluded because, due to their lower mass, they are much redder than the bulk of the WDCS that we observe. We explicitly verified this point by transforming into the ACS Vega magnitude photometric system the He-core WD models by Serenelli et al. (2001) for masses of 0.32 and 0.41 $M_{\odot}$ (see Fig. 2). Moreover, using as a normalizing factor the number of stars on the MS and adopting a Salpeter IMF, we estimated that the total number of CO WDs in our field should be ∼430, which compares reasonably well with the ∼600 objects observed. Although ignorance of the IMF at higher masses, as well as mass segregation effects, make this number extremely uncertain, there seems to be little room for a substantial population of He-core objects. For DA WD luminosities around $\log(L/L_{\odot}) \sim -4.0$, non-DA objects are slightly fainter than DAs (∼0.5 mag, but the exact value depends on the WD mass), and the difference increases quickly with decreasing luminosity. These objects may contribute to the possible second peak around ∼28.2 but, again, only for ages around 3 Gyr. Also, the possibility that the peak comes from a cluster of far, unresolved blue galaxies can be excluded, as the spatial distribution of the observed WDs is not significantly different from that of the cluster MS stars.

We also note that the WD LF of Figure 1*b* never drops to zero. This fact could indicate that we have not reached the end of the WDCS. In this case the presence of a peak in the WDCS may also indicate the onset of an unknown energy release at this specific age and metallicity (sedimentation/separation of CO, pycnonuclear reaction, or whatever can cause a temporary slowdown in the cooling).

Finally, it is worth remarking that NGC 6791 is a cluster with several peculiarities (high binary fraction, anomalous HB, very metal rich, dynamically old, etc.) that may have altered the stellar populations in the cluster, and hence it is too early to call for major revisions in the WD formation and evolution models. It is surely of great interest to extend the present investigation at least down to the magnitude where we expect to see the peak of a 8–9 Gyr WDCS.

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Note added in proof.—An interesting possible solution to the WD cooling-age problem was offered by C. J. Deloye & L. Bildsten (ApJ, 580, 1077 [2002]), who suggested that at metallicities higher than solar the diffusion of Ne^{22} nuclei in the liquid interior could slow down the cooling appreciably. Although their prediction would agree with our observations only if the diffusion coefficient of Ne^{22} were an order of magnitude larger than is supposed, it is not out of the question that a corrected diffusion coefficient could be that large.