WHITE DWARFS IN NGC 6791: AVOIDING THE HELIUM FLASH

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ABSTRACT

We propose that the anomalously bright white dwarf luminosity function observed in NGC 6791 (Bedin et al.) is the consequence of the formation of 0.5 M⊙ white dwarfs with helium cores instead of carbon cores. This may happen if mass loss during the ascent of the red giant branch is strong enough to prevent a star from reaching the helium flash. Such a model can explain the slower white dwarf cooling (relative to standard models) and fits naturally with scenarios advanced to explain extreme horizontal branch stars, a population of which are also found in this cluster.

Subject headings: open clusters and associations: individual (NGC 6791) — stars: evolution — stars: horizontal-branch — stars: luminosity function, mass function — stars: mass loss — white dwarfs

1. INTRODUCTION

The open cluster NGC 6791 is an interesting object for several reasons. It is among the richest of the Galactic disk clusters, possibly the oldest, and possesses a significantly supersolar metallicity. These attributes have made it the target of several detailed studies. Nevertheless, there is still some uncertainty as to its true age. Stetson et al. (2003) give an estimate ~12 Gyr, while studies such as that of Carney et al. (2005) or King et al. (2005) yield estimates closer to ~8 Gyr. The age uncertainties are covariant with uncertainties in the cluster metallicity ([Fe/H] ~ 0.25–0.5) and distance.

The above estimates are all arrived at by measurements of the main-sequence turnoff and giant sequences. The detection of a significant white dwarf population in NGC 6791 (Bedin et al.) is thus of considerable interest, since it offers the potential to measure cluster parameters by entirely independent means. However, fitting standard white dwarf models to the observed luminosity function yields a cluster age of ~3 Gyr. In this paper we examine some nonstandard white dwarf models and propose an explanation for this puzzling discrepancy.

In § 2 we review the results of Bedin et al. (2005) and summarize the various possible explanations they were able to rule out. Thereafter we describe two additional possibilities not considered in that paper (residual nuclear burning and the production of massive white dwarfs with helium cores). In § 3 we compare these models to the data and demonstrate that the latter may indeed provide an explanation for the NGC 6791 luminosity function. In § 4 we examine some of the consequences of this model and possible predictions.

2. THE WHITE DWARF LUMINOSITY FUNCTION

The luminosity function derived by Bedin et al. (2005) has the characteristic shape expected for the white dwarf population drawn from a burst of star formation: strongly peaked near a limiting value, followed by a sharp drop at lower luminosities. The problem is that the location of the peak is far brighter than anticipated. The expected absolute magnitude for a 0.5 M⊙ white dwarf of age 8 Gyr is $M_{\odot} = 13.44$, which, combined with a distance modulus of $\mu = 13.44$, yields an expected peak location of $F_{606W} = 29.5$. Yet the luminosity function of Bedin et al. (2005) peaks at approximately $F_{606W} = 27.5$. They present compelling evidence that the peak lies well above their completeness limit, so that one is forced to consider ways to generate a peak in the luminosity function at much brighter magnitudes than expected.

Bedin et al. (2005) reviewed several possible explanations for their luminosity function. Simply decreasing the distance or extinction is not viable, as it would drive the age derived from the main-sequence turnoff to unacceptably large values. Small changes in the white dwarf models, such as changing the hydrogen layer thickness or the ratio of carbon and oxygen in the core, do not produce a large enough effect. White dwarfs produced by truncated stellar evolution in binaries (Kippenhahn et al. 1967) do cool more slowly, but generally have a range of masses ~0.3–0.4 M⊙ and so would be redder than the observed white dwarf cooling track. Indeed, any explanation involving binary stars needs to account for the narrow mass range and the lack of bright (relative to a white dwarf) companions at the present time.

There is one potential explanation in the literature that actually predates the Bedin et al. (2005) observation. Bildsten & Hall (2001) and Deloye & Bildsten (2002) discuss the retardation of white dwarf cooling that is made possible by the sedimentation of $^{22}$Ne during the cooling process. Although the contribution is small for most white dwarfs, it gets larger if there is more $^{22}$Ne, which is expected from more metal-rich systems. Thus, Deloye & Bildsten in fact predicted that the effects of sedimentation would be largest in such a system as NGC 6791. At first glance, the NGC 6791 white dwarfs might appear to be a stunning confirmation of the prediction of "sedimentars," but the size of the predicted effect is somewhat smaller than that needed to explain the Bedin et al. result. Figures 12 and 13 of Deloye & Bildsten can be converted into a prediction that the bulk of the white dwarfs should be found between $F_{606W} = 28$ and 29, depending on the value of the assumed diffusion coefficient (the brightest value being found for a rate 10 times faster than the nominal but uncertain value). Nevertheless, the agreement may be improved by further calculations in progress (L. Bildsten 2005, private communication).

At present, however, the observations still require an explanation; thus we wish to reexamine two issues touched on by Bedin et al. (2005), but not explored to the fullest.

2.1. Thick Hydrogen Layers and Nuclear Burning

Bedin et al. (2005) did examine the effects of changing the hydrogen layer mass on the cooling, but as far as can be told from

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the paper, they considered only the effect it has on heat transport from the core to the surface. For a large enough hydrogen layer, the pressure and temperature at the base are high enough to maintain some level of residual nuclear burning by the pp process, i.e., an additional heat source. This mechanism has been invoked in previous instances of anomalously young white dwarfs with low mass (e.g., Alberts et al. 1996; Driebe et al. 1998). Could residual nuclear burning be the explanation for the bright white dwarfs in NGC 6791? Unfortunately, this seems unlikely. The effects of nuclear burning are only significant for masses \( M < 0.25 \, M_\odot \) (Driebe et al. 1999; Althaus et al. 2001; Hansen et al. 2003).

To confirm this, we calculate several new white dwarf cooling sequences using the code described in Hansen (1999). The helium layer is taken to be \( q_{\text{He}} = 10^{-2} \). All models have total mass \( 0.5 \, M_\odot \). We use the same C/O profile as in the previous models, but consider a variety of hydrogen layer thicknesses, ranging from \( q_H = 10^{-4} \) to \( q_H = 5 \times 10^{-3} \). The lower end of the range is the canonical value expected for most white dwarfs, but larger values are possible given the uncertain nature of the mass-loss history of evolved stars.

In the initial stages (central temperatures \( >10^8 \) K) of the approach to the cooling sequence, the evolution is driven by neutrino cooling in the core and the cooling is similar for all models. However, as the star shrinks toward a more compact, degenerate configuration, the pressure and temperature at the base of the hydrogen layer increase, and nuclear burning is possible for some range of hydrogen layer masses. For even the most massive layers considered, the models remain brighter than the fiducial \( (q_H = 10^{-4}) \) models only for \( \sim 2 \) Gyr. This is because, if one increases the mass of the hydrogen layer, the pressure and density at the base of the envelope are higher, and so the rate of burning is higher. In the end, the effect of a larger reservoir is balanced by a higher rate of consumption, limiting the delay one can achieve. After 2 Gyr, no model has a hydrogen layer larger than \( q_H \sim 5 \times 10^{-4} \). Thus, after \( \sim 8 \) Gyr, the white dwarf will have approximately the same luminosity regardless of the initial hydrogen mass. This is demonstrated in Figure 1. The white dwarf cooling time (neglecting the main-sequence lifetime of the progenitor for now) for white dwarfs at \( M_{\odot} = 1.7 \text{ Gyr} \) is 1.6 Gyr for a standard C/O model. Even the thickest hydrogen envelope considered \( (q_H \sim 5 \times 10^{-3}) \) only lengthens the cooling time to this luminosity by 0.6 Gyr.

### 2.2. Helium Cores

The notion that the NGC 6791 white dwarfs have cores composed of helium, rather than carbon or oxygen, was touched on briefly by Bedin et al. (2005). However, they ruled this out as helium core white dwarfs are believed to result from binary evolution, and the majority have masses that range \( 0.3 \text{–} 0.4 \, M_\odot \) and would thus be too red to fit the observations.

We believe this to be an overly conservative restriction. In this section we examine models for white dwarfs of mass \( 0.45 \text{–} 0.55 \, M_\odot \) (models with this mass are consistent with the color and magnitude of the upper cooling sequence), which nevertheless possess cores composed purely of helium. We leave issues of provenance to § 3.

For white dwarfs hot enough to be far from the strongly coupled regime in the core, the heat content (and thus the cooling time) of the star is inversely proportional to the mass number of the core constituent. Thus, if we consider two \( 0.5 \, M_\odot \) white dwarfs, one composed of carbon and the other of helium, both with an age of 8 Gyr, then the latter will be considerably brighter. In fact, it will have approximately the same luminosity as the carbon core model has at an age \( \sim 8/3 \text{–} 2.7 \) Gyr. This is approximately the age inferred by Bedin et al. (2005). Figure 1 shows that the helium core model fares considerably better than the C/O models, yielding a cooling time of \( \sim 4 \) Gyr to \( M_F \sim 27.3 \). While this is still somewhat below the 8 Gyr age of the cluster, we must recall that the cluster age is the sum of the time spent on both the cooling sequence and on the main sequence. Thus, the difference between the cluster age and the helium core cooling time indicates the mass of the main-sequence progenitors of this anomalous population.

We use the analytic stellar evolution formulae encoded in the SSE package (Hurley et al. 2000) to calculate the main-sequence lifetimes of stars with \( Z = 0.035 \). For the low end of the cluster age range \( (\sim 8 \text{ Gyr}) \), the progenitor mass for helium core white dwarfs at the observed cutoff is \( \sim 1.45 \, M_\odot \), while for the high end of the age range \( (\sim 12 \text{ Gyr}) \), the progenitor mass is \( \sim 1.17 \, M_\odot \). Exploring the range of applicable white dwarf masses \( (0.45 \text{–} 0.55 \, M_\odot) \) does not change the conclusions significantly.

Next we try to model the luminosity function. Before doing this we need to consider in more detail the possible origins of such a population.

### 3. AVOIDING THE HELIUM FLASH IN NGC 6791

There are good reasons to believe that most white dwarfs have C/O cores. Upon reaching the tip of the red giant branch (RGB), a star ignites core helium burning (under degenerate conditions for lower mass progenitors, which leads to a thermonuclear runaway aka the helium flash), and the star moves onto the horizontal branch. It undergoes extended core helium burning followed by shell burning on the asymptotic giant branch before becoming a
Stars in binaries sometimes manage this feat by losing their envelope on the ascent of the RGB due to Roche lobe overflow, i.e., mass transfer to a companion. However, this leads to a range of masses, most of which are considerably lower than the \( \sim 0.5 \, M_\odot \) needed to fit the NGC 6791 cooling sequence. Bedin et al. (2005) have already considered and rejected this possibility. In order for our model to work, we have to hypothesize that many single stars in NGC 6791 have managed to lose their envelopes before reaching the helium flash, so that they move directly from the RGB to the white dwarf cooling sequence.

In fact, this hypothesis dovetails quite naturally with several theories for the origins and nature of extreme horizontal branch (EHB) stars. This term is used to describe a class of stars, found both in the field and in clusters, that appear to be related to traditional horizontal branch stars but are hotter/bluer. It has been suggested (Faulkner 1972; Sweigart et al. 1974) that such stars are core helium-burning stars with particularly thin hydrogen envelopes, possibly as a result of extreme mass loss on the RGB. Subsequent work has developed this picture even further. Castellani & Castellani (1993) and Castellani et al. (1994) report the formation of what they call “red giant stragglers” in models for globular cluster evolution. In some cases, the stars make it to the white dwarf cooling sequence before igniting helium. D’Cruz et al. (1996) considered models with a range of mass-loss rates on the RGB and found that, in addition to the formation of EHB stars, they formed so-called flash-maque stars, which lose so much mass that they never ignite helium and simply go directly to helium core white dwarfs. In fact, given the large amount of mass loss required to form EHB stars, especially the very bluest “blue hook stars” (Brown et al. 2001; Cassisi et al. 2003; Moehler et al. 2004), it would require extreme fine tuning to produce EHB stars without also producing some helium core white dwarfs. This is important because NGC 6791 possesses a significant population of such EHB stars (Kuluzny & Udalski 1992; Liebert et al. 1994). Thus, if one takes the above models at face value, a substantial population of helium core white dwarfs is expected wherever EHB stars are found and thus should be found in NGC 6791.

We now try to model the observed luminosity function using this framework. We note that not all of the white dwarfs in NGC 6791 can have helium cores. The models discussed above that successfully avoid the helium flash do so with progenitors that begin their lives with masses slightly larger than 1 \( M_\odot \). Thus, in our models we impose a critical mass \( m_{\text{crit}} \), above which stars always produce standard C/O core white dwarfs. Furthermore, NGC 6791 does possess normal helium-burning stars (the EHB stars make up \( \sim 15\% \) of the helium-burning stars according to Liebert et al. [1994]) and even the EHB stars are helium burning, so that clearly some C/O white dwarfs are being produced. It seems likely that stellar evolution in this cluster explores all three post-RGB avenues discussed above. One may estimate the branching ratios as follows.

King et al. (2005) note that two of the EHB candidates from Kuluzny & Udalski (1992) lie within the Hubble Space Telescope field. Models suggest that this evolutionary stage lasts for \( \sim 10^8 \) yr. The offspring of EHB stars are C/O white dwarfs, and so, using the cooling time of C/O models (to F606W = 28), we estimate that \( \sim 2 \times 10^7/10^8 \times 2 = 40 \) of the white dwarfs in this field brighter than F606W = 28 should have come through this channel. In addition, C/O white dwarfs are also the end product of normal helium burning stars in the cluster. Although we do not have a strict count of HB stars in this field, Liebert et al. (1994) estimate that \( \sim 15\% \) of all NGC 6791 helium-burning stars are EHB stars. Thus, we estimate that the total number of C/O white dwarfs produced in this field with F606W < 28 is \( \sim 40/0.15 \sim 270 \). The total number of white dwarfs observed by Bedin et al. (2005) in the same field is \( \sim 600 \). The difference between these two numbers is the number of helium core dwarfs that went directly from RGB to cooling sequence. Thus, the ratio of C/O core white dwarfs to helium core dwarfs is estimated to be \( \sim 270/330 \sim 5.6 \). If we break this up further into EHB/normal HB/direct He core, we estimate ratios \( \sim 1:6:8 \). The principal uncertainty in this procedure is the degree to which internal cluster dynamical evolution violates the implicit closed-box assumption. Although EHB stars and white dwarfs should have very similar masses, the normal HB stars may have slightly higher masses and thus may be slightly underrepresented (since the field is away from the cluster core) in the census just described. In light of this uncertainty, we adopt a ratio of C/O to helium cores of 1:1 below.

Figure 2 shows the luminosity function of Bedin et al. (2005) (now binned in 0.5 mag bins) compared to sample 8 Gyr model luminosity functions. The best-fit value of \( m_{\text{crit}} = 1.6 \, M_\odot \) is slightly larger than the 1.45 \( M_\odot \) quoted in § 2.2 because the peak of the realized Monte Carlo number distribution lies slightly below the cutoff. The solid line shows a histogram for a model in which all stars with \( m < m_{\text{crit}} \) form helium core white dwarfs. The dotted line shows the C/O core luminosity function for the same parameters. The dashed line corresponds to a model in which 50% of the stars with \( m < m_{\text{crit}} \) form helium cores and the rest form C/O cores. We have included the effects of incompleteness, using the results from Bedin et al., kindly provided by Ivan King. The truncation of the C/O core luminosity function...
shows where this becomes important. The truncation of the helium core luminosity function occurs at significantly brighter magnitudes. The uncertain age of the cluster means that there is some flexibility in the choice of parameters. Figure 3 shows a fit using an age of 12 Gyr and $m_{\text{crit}} = 1.25 \, M_\odot$. The solid, dotted, and dashed lines once again indicate luminosity functions for helium core, C/O core, and a 1:1 combination, as in Figure 2.

There are several points to note about these fits. We have not performed a detailed parameter scan in fitting the data because we do not possess a proper photometric uncertainty map for these data (which indicates the probabilistic relation between intrinsic and observed magnitude as a function of model magnitude; see Hansen et al. [2004] for a more detailed discussion of this question in the context of the globular cluster M4). The structure in the CMD in Figure 1 of Bedin et al. (2005) suggests that this is likely to be an important consideration in performing a true fit. We also need to assume something about the distribution of progenitor masses. We have assumed top-heavy mass functions, with a slope $x < -1$ (where Salpeter is $x = 1.35$). This is necessary to obtain luminosity functions as peaked as those seen here and is also broadly consistent with the main-sequence mass function observed by King et al. (2005) for this cluster (the number of main-sequence stars per magnitude bin increases with decreasing magnitude/increasing mass near the turnoff). For an open cluster as old as NGC 6791, there has likely been significant dynamical evolution, and so one should be cautious when interpreting this as a true mass function.

4. DISCUSSION

In this paper we propose a model to explain the origin of the peak in the NGC 6791 luminosity function at luminosities somewhat brighter than those expected on the basis of traditional white dwarf cooling models. Our proposal is that these are the result of the formation of helium core white dwarfs resulting from strong mass loss on the RGB, thereby avoiding an episode of core helium burning on the horizontal branch. In support of this model we point to the substantial population of EHB stars in NGC 6791, which are proposed to be stars that lost enough mass to almost make it to the white dwarf cooling track with their helium cores intact but finally ignited helium burning during the final contraction stage. In many models, EHB stars and helium core white dwarfs are expected to form together, as they are consequences of the same phenomenon: strong mass loss.

The scenario discussed here does make a definite prediction: that the white dwarf luminosity function for NGC 6791 should be bimodal, with a second peak at fainter magnitudes resulting from traditional C/O white dwarfs that did indeed pass through the horizontal branch phase. Figure 4 shows the expected luminosity function for our simple 8 Gyr model with $m_{\text{crit}} = 1.6 \, M_\odot$. The solid, dotted, and dashed histograms show the same luminosity functions as in Figure 2, but now we have not modeled the effects of incompleteness. We see that the second peak is expected to lie at magnitudes F606W $\sim 29$–30. The exact value will vary depending on the mass of the white dwarfs at the faint end. The value shown here is probably a little optimistic, since we used only 0.5 $M_\odot$ white dwarfs.

The narrowness of the white dwarf cooling sequence suggests that, however these helium core white dwarfs form, it must be by a process that strongly favors core masses $>0.4 \, M_\odot$. If heavy mass loss on the RGB is indeed the cause, this mass limit suggests that the progenitors must get within $\sim 1$ mag of the tip of the RGB before their evolution is truncated (based on metal-rich models using the formulae of Hurley et al. 2000). There is some observational support for this notion. Origlia et al. (2002) used the Infrared Space Observatory Camera (ISOCAM) to search for infrared excesses suggestive of mass loss in the cores of five globular clusters. They found evidence for significant mass loss only close to the RGB tip. Similarly, Ita et al. (2002) found many variable stars near the tip of the RGB in the Large Magellanic Cloud, possibly an indication of pulsation-driven mass loss. While these results are encouraging, they only indicate that most of the mass loss on the RGB is indeed likely to occur near the tip. There is clearly still much work required to verify that the amount of mass loss on the NGC 6791 RGB is sufficient to justify our hypothesis.

Finally, the referee has raised the question of whether the existence of this anomalous white dwarf population poses a problem.

Fig. 3.—Same as for Fig. 2, except that the cluster age is now assumed to be 12 Gyr, and the value of $m_{\text{crit}} = 1.25 \, M_\odot$.

Fig. 4.—Same as for Fig. 2, including the age and $m_{\text{crit}}$, except that now we make no correction for incompleteness. This shows the large number of white dwarfs that we expect to find at fainter magnitudes if this model is correct.
for the determination of population ages from the white dwarf cooling sequence (Fontaine et al. 2001; Hansen 2004 and references therein). Within the model proposed here, this is not the case, because the difference between the helium core and carbon core white dwarfs is discrete in nature, and any anomaly is readily apparent. Just as someone cannot be “a little bit pregnant,” a star must belong to one population or the other. If the model of Deloye & Bildsten (2002) is correct, however, then the anomaly is “tunable” via the abundance of $^{22}$Ne and thereby does indeed introduce an additional uncertainty to take into account. Thus, it is of considerable interest to distinguish between these two possibilities with a deeper observation of this cluster.

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