The Astrophysical Journal, 679: L29–L32, 2008 May 20

THE PUZZLING WHITE DWARF COOLING SEQUENCE IN NGC 6791: A SIMPLE SOLUTION[1]

L. R. Bedin,[2] M. Salaris,[3] G. Piotto,[4] S. Cassisi,[5] A. P. Milone,[4] J. Anderson,[2] and I. R. King[6]
Received 2008 February 18; accepted 2008 April 9; published 2008 April 24

ABSTRACT

In this Letter we demonstrate that the puzzling bright peak in the luminosity function of the white dwarf (WD) cooling sequence of NGC 6791 can be naturally accounted for if ∼34% of the observed WDs are WD+WD binary systems.

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

1. INTRODUCTION

NGC 6791 is a peculiar open cluster. It is one of the richest open clusters, unusually old (8–9 Gyr; Stetson et al. 2003; King et al. 2005), and extremely metal rich ([Fe/H] ∼ +0.4; Gratton et al. 2006; Carraro et al. 2006; Origlia et al. 2006). NGC 6791 is close enough that *HST*/ACS imaging can reach very faint luminosities. Because of this, it has been one of our targets for the study of the bottom of the main sequence (MS; proposals GO-9815 and GO-10471; PI: King). In previous papers we studied the color-magnitude diagram (CMD), mass function (King et al. 2005), and the white dwarf (WD) cooling sequence (CS). The latter investigation (Bedin et al. 2005, hereafter Paper I, and Bedin et al. 2008, hereafter Paper II) provided us with additional exciting and unexpected results.

The most important results are as follows: (1) The WD luminosity function (LF) shows a peak at a magnitude (F606W = 27.45 ± 0.05) that would imply a CO-core WD cooling age inconsistent by a factor >2 with the age obtained from the MS turnoff (TO; Paper I). (2) With second-epoch *HST* observations, in Paper II we identified a second, fainter peak in the WD LF, as richly populated as the brighter peak, but at a magnitude (F606W = 28.15 ± 0.05) still slightly brighter than expected from the TO age. (3) In addition, in Paper II we found that at the magnitude level of each of the two LF peaks, the WD cooling sequence describes a sort of blue hook. (4) The WD CS ends at F606W ∼ 28.35.

As discussed in Paper II, the fainter peak in the WD LF may be consistent with the expected position of the bottom of the CS for a cluster with the TO age of NGC 6791 if we account for the effect of ^{22}Ne diffusion in the liquid phase (e.g., Deloye & Bildsten 2002; García-Berro et al. 2008), plus smaller contributions from ^{22}Ne separation during the crystallization phase (Segretain 1996), plus uncertainties in the core CO profile due to the ^{12}C(α, γ)^{16}O reaction rate.

However, for the brighter peak in the WD LF, neither could we find any convincing explanation nor, even 3 yr after the publication of Paper I, has a plausible scenario to explain this anomaly appeared in the literature. Hansen (2005) and Kalirai et al. (2007) speculated that the two peaks in the CS LF could be accounted for by assuming that the cluster has two different types of WDs. In addition to the usual CO-core WDs, they claim that NGC 6791 also hosts an anomalously high number of very massive He-core WDs (masses of at least 0.5 $M_\odot$), which produce the observed bright peak in the LF. The presence of some He-core WDs cannot of course be excluded, and indeed Kalirai et al. (2007) have identified in the upper part of the CS of NGC 6791 a few very bright WDs whose masses (below the value of the electron-degenerate core mass at the He flash) are consistent with "normal" He-core WDs. The massive He-core WD scenario, by contrast, is severely challenged by theoretical evidence, as we exhaustively discussed in Paper II. The main problem—apart from the need for extremely efficient mass loss along the red giant branch even for masses well above 1 $M_\odot$—is that the mass of these He-core WDs needs to be sizably larger than the core mass at the He flash in metal-rich, low-mass red giant branch stars, which sets the maximum allowed mass for He-core WDs. It is also not clear how to explain the blue hook of the CS at the magnitude of the bright peak, unless the He-core WDs reach masses much larger than the already high value of 0.5 $M_\odot$. In this Letter we will show that no sizable population of massive He-core WDs is needed to explain the WD CS in NGC 6791, which may turn out to be less perplexing than originally thought.

2. BINARIES IN NGC 6791

A conspicuous feature of the CMD of NGC 6791 is the large number of photometric binaries visible on the red side of the MS (Fig. 1). In order to derive the fraction of MS+MS binaries with mass ratio $q > 0.5$, we applied the recipes of Milone et al. (2008). First, the CMD was cleaned of field stars using the proper motions of Bedin et al. (2006). We then divided the CMD in two parts: a region A containing all the single stars and the binaries with a primary with $17.5 < m_{\rm F814W} < 21.0$ (shadowed region in Fig. 1) and a region B (darker region in Fig. 1) that is the portion of A populated by binaries with $q > 0.5$. The bluest line is the MS fiducial line moved by 3 σ to the blue, where σ is the photometric error coming from the artificial-star tests (Bedin et al. 2008). The reddest line is the locus of $q = 1$ binaries, moved 3 σ to the red. The locus in the CMD of the binaries with a given mass ratio q was found using the mass-luminosity relation of Pietrinferni et al. (2004).

The fraction of binaries with $q > 0.5$ is calculated as $f_{\rm bin}^{q>0.5} = N_{\rm OBS}^{\rm B}/N_{\rm OBS}^{\rm A} - N_{\rm ART}^{\rm B}/N_{\rm ART}^{\rm A}$, where $N_{\rm OBS}^{\rm A(B)}$ is the number of stars (corrected for completeness) observed in region A (B); $N_{\rm ART}^{\rm A(B)}$ is the corresponding value of artificial stars. (The derivation of the equation is straightforward but too long to include

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

[2] Space Telescope Science Institute, 3800 San Martin Drive, Baltimore, MD 21218; bedin@stsci.edu, jayander@stsci.edu.

[3] Astrophysics Research Institute, Liverpool John Moores University, 12 Quays House, Birkenhead CH41 1LD, UK; ms@astro.livjm.ac.uk.

[4] Dipartimento di Astronomia, Università di Padova, Vicolo dell' Osservatorio 2, I-35122 Padova, Italy; giampaolo.piotto@unipd.it.

[5] INAF-Osservatorio Astronomico di Collurania, via M. Maggini, 64100 Teramo, Italy; cassisi@oa-teramo.inaf.it.

[6] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580; king@astro.washington.edu.

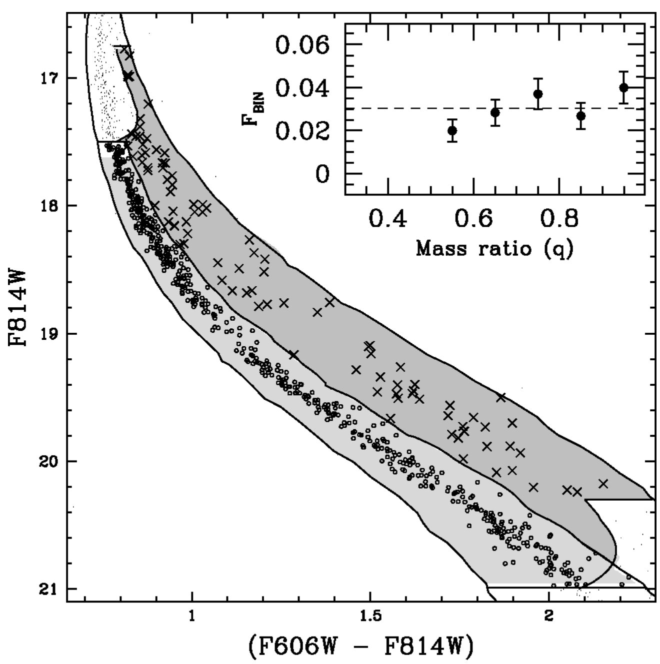

FIG. 1.—The main sequence of NGC 6791 with the binaries with mass fraction $q > 0.5$ plotted as crosses. In the inset, the distribution of the binary fraction for $q > 0.5$ is shown. Note that we used proper-motion membership (Bedin et al. 2006) to remove field stars from the CMD. See text for the definitions of the shadowed regions.

here.) We found $f_{\rm bin}^{q>0.5} = 0.16 \pm 0.02$. We repeated the same procedure for the fractions of binaries with $q > 0.6$, 0.7, 0.8, and 0.9. Then we derived the fractions of binaries in five intervals of size $\Delta q = 0.1$ in the range $0.5 < q \leq 1$. [For example, we calculated the fraction of binaries with $0.5 < q \leq 0.6$: $f_{\rm bin}^{0.5<q<0.6} = (f_{\rm bin}^{q>0.5} - f_{\rm bin}^{q>0.6})$, and similarly for the other bins.] The results are plotted in the inset of Figure 1. The distribution of the binary fraction as a function of q is flat. Extrapolating this flat distribution to lower mass ratios ($q < 0.5$), we estimate that the total MS+MS binary fraction in the core of NGC 6791 is $f_{\rm bin}^{\rm tot} \simeq 32\% \pm 3\%$.

We have also calculated the global fraction of binaries using other methods described in the literature and found similar results. In particular, we also estimated the binary fraction using the procedure described by Sollima et al. (2007; see their § 5). The only differences from what is described in that paper are that we used the mass-luminosity relation of Pietrinferni et al. (2004) and that we removed the field stars using proper motions (and not a Galactic model, as in Sollima et al.) The Sollima et al. (2007) method is based on simulations of the photometric binary population assuming different mass-ratio distributions, followed by a comparison between the observed and simulated CMDs (see their paper for further details). If we assume the binary fraction to be the function of the mass ratio that Fisher et al. (2005) found for the solar-neighborhood distribution, we find for NGC 6791 $f_{\rm bin}^{\rm tot} = 25\%$; if we get our distribution by randomly coupling stars from the De Marchi et al. (2005) initial mass function, we get $f_{\rm bin}^{\rm tot} = 37\%$.

Photometric binaries are not the only evidence for a large binary population in NGC 6791. In a recent large survey of stellar variability in a field of $\sim 30 \times 30$ arcmin^2 centered on the center of NGC 6791, De Marchi et al. (2007) have identified a large number of variable stars whose variability is associated with their binary nature. In particular, De Marchi et al. brought to three the number of known cataclysmic variables (CV) in NGC 6791, showing that on the basis of their proper motions they are all high-probability cluster members. In addition, De Marchi et al. found 29 contact binaries and 61 eclipsing systems.

A precise determination of the total number of binaries in NGC 6791 is beyond the purpose of the present Letter. However, it is clear that this cluster hosts a large binary population (surely >25%–30%), as it is clear that photometric binaries are only one of the kinds of binary present. It is also evident from the many CVs that white dwarfs are commonly found in binaries, as well. Moreover, we note that in the cluster core, where the ACS field of Papers I and II is centered, the fraction of binaries with massive components (of interest for the discussion in the following section) must be higher than the average fraction in the cluster, because of mass segregation effects.

3. THE EFFECT OF BINARIES ON THE WD CS

In the previous section we have shown that NGC 6791 hosts a sizable fraction of stars in binary systems. Consequently, we can expect a high fraction of NGC 6791 WDs to be in binaries, and part of them must be WD+WD binary systems. Prompted by this reasoning, we investigated the effect of double WD binaries on the WD CS.

To this purpose, we simulated the WD cooling sequence of NGC 6791 using the same WD isochrones described in Paper II, for a progenitor metallicity [Fe/H] $= +0.4$. Each isochrone provides the magnitudes of a single-age, single-metallicity CS in the ACS/WFC Vega-mag system, together with the mass of the evolving WD at each point along the CS and the corresponding progenitor mass. We used an apparent distance modulus $(m - M)_{\rm F606W} = 13.44$ and $E({\rm F606W} - {\rm F814W}) = 0.14$, consistent with Papers I and II. We adopted as theoretical counterpart of the single WDs in the observed CS the 6 Gyr old isochrone that matches the fainter peak of the LF. This age is younger than the TO age. As briefly outlined in § 1 and discussed in detail in Paper II, this discrepancy may be removed if some new developments in the physics of WD cooling (which will slow down the cooling process) are implemented in CO-core WD modeling.

Theoretical cooling sequences that include a fraction of unresolved noninteracting WD+WD binaries have been computed by means of a Monte Carlo (MC) simulation. A value of the progenitor mass for a generic single WD along the CS is extracted randomly according to a Salpeter initial mass function (IMF). The mass and the F606W and F814W magnitudes of the WD are then determined by quadratic interpolation along the isochrone points. To assign a companion to this WD, we extract randomly a value of q according to the adopted statistical distribution (see below), and the corresponding WD mass and magnitudes are calculated using the isochrone. The fluxes of the two components in the F606W and F814W filters are added, and the total magnitudes and colors of the composite system are computed. We then added the distance modulus to these magnitudes and perturbed them randomly by using a Gaussian photometric error with the σ from the artificial-star tests. A theoretical LF was then computed for this synthetic population and compared with the observed one.

Figures 2 (panels *a* and *b*) and 3 show the CMDs and the LF of a synthetic cooling sequence computed assuming a fraction of binary systems of 54% and a mass ratio q with a flat distribution between 0.5 and 1.0, as obtained for the MS+MS binaries (Fig. 1, *inset*). (The effect of a different distribution for $q < 0.5$ will be briefly discussed below.) The 54% overall

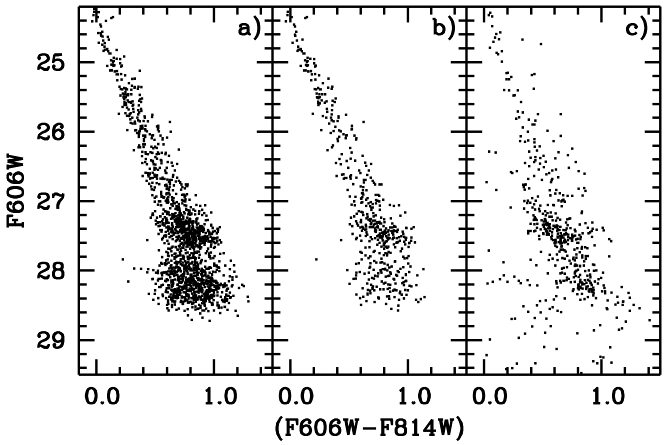

FIG. 2.—Comparison between observed (panel *c*) and simulated (panels *a* and *b*) CMDs of the WD CS. Panel *a* shows the results of one MC simulation. Panel *b* shows the same simulation as in *a*, but with stars randomly removed in order to account for the incompleteness, as obtained from artificial-star tests (see Paper II). The resulting number of objects along the CS is approximately the same as in the observed diagram (panel *c*). The synthetic CMDs contain 34% of WD+WD binary systems. The faint objects at F606W < 28.4 are mostly background galaxies, as shown in Fig. 9 of Bedin et al. (2008). At that magnitude level we could not use proper motion to select cluster members.

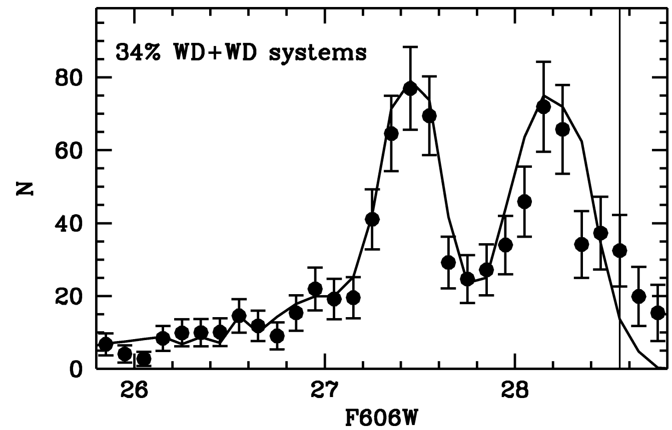

FIG. 3.—Comparison between observed (points with error bars) and simulated, completeness-corrected WD LF assuming a fraction of WD+WD binary systems equal to 34%. A vertical line shows the limit of reliability of our completeness correction.

fraction leads to ∼34% of WD+WD binaries on the CS. This lower number is a consequence of the fact that the companion of a star that has become a WD may have a mass too low to have evolved to the WD stage at the present age of the cluster.

The simulation of the LF includes a factor of 10 more WDs than the observed ones—in order to minimize the effect of random fluctuations in a given magnitude bin—and has been rescaled to match the number (allowing for the completeness correction) of objects in the magnitude interval 26.0 < F606W < 26.8. A comparison with the observed CMD (Fig. 2, *right panel*) and the F606W LF (Fig. 3) shows an astonishing overall agreement. The WD+WD pairs produce a secondary, brighter peak in the LF that agrees in magnitude, width, and height with the observed one. The explanation for this additional peak that matches the observations so well can be found by examining the corresponding CMD.

The synthetic CMD displays a clump of stars at approximately constant F606W brightness, extended toward the blue, at the bottom of the sequence, corresponding to the end of the single WD CS. In the case of a single WD population, this clump contains the overwhelming majority of WDs.

The WD masses that populate the clump range from ∼0.6 to ∼1 $M_{\odot}$, and the corresponding progenitor masses are between ∼1.8–2.0 and ∼5–6 $M_{\odot}$. For comparison, the progenitor mass at the top of the CS is ∼1.3 $M_{\odot}$, and the corresponding WD mass is ∼0.56 $M_{\odot}$. Given that the WDs in the clump at the bottom of the CS span almost the full range of progenitor masses, the most probable outcome for a WD+WD system is obtained by combining the flux of two WDs randomly selected from this clump. As the F606W magnitude is approximately constant along the clump, we will have a similar feature in the CMD, but ∼0.75 mag brighter. This naturally explains the appearance of an additional brighter clump in the CMD, why it turns to the blue, and also the bright peak in the LF, at exactly the location observed.

The prediction of a secondary bright peak (and its magnitude location) in the LF produced by binary WD+WD systems is robust against reasonable trends of the mass ratio *q* of their progenitors. We made simulations using a flat *q* distribution from zero to unity. We also tested the possibility that the *q* distributions are single-valued, and we experimented with different values of *q*, between 0.5 and 1.0. The only major effect is that the total fraction of binaries must be changed for varying *q* distributions, in order to match the height of the observed bright peak in the LF. On the other hand, the fraction of WD+WD systems needed to match the height of the peak is only marginally affected.

A few WD+WD systems with progenitors below 1.6–1.8 $M_{\odot}$ must be present also in the upper CS (above the brighter peak). Their presence makes the CS wider in color at fixed F606W, compared to the case of single WDs. To further test our binary scenario—as suggested by the referee—we have considered the upper part (F606W ≤ 26.5) of the theoretical and observed sequences in panels *b* and *c* of Figure 2. We subtracted from the F606W − F814W colors of the individual objects the corresponding color of the fiducial WD CS obtained from a linear fit to the CMD of the simulated and observed CSs, respectively. In this way, both sequences are made vertical in the CMD, with intrinsic color widths that can now be easily compared. For F606W ≤ 26.5, the rectified synthetic sequence has a color rms of 0.07 mag in F606W − F814W, smaller than the rms of 0.13 mag of the observed CS. Similar results are found for 25.2 < F606W < 25.8 (0.06 and 0.11 mag) and for 26.0 < F606W < 26.5 (0.09 and 0.17 mag). In summary, simulated WD+WD binaries do not produce a CS that is wider in color than observed. The broader observed CS is very likely due to the presence of some low-mass He-core WDs, which must be redder than the CO-core WDs (see Paper I and Paper II).

Another clear evidence of the binary nature of the brighter peak would be its concentration to the center of the cluster. Frustratingly, however, this is out of our reach, because our field lies completely within the core of the cluster, where the density should be roughly constant. (An unpublished star count by one of us [I. R. K.] gives a core radius of about 2.5′—a little more than the distance from the center of our field to its corner.)

4. CONCLUSIONS

In this Letter we have demonstrated that the anomalously bright peak in the luminosity function of the white dwarf cooling sequence of NGC 6791 discovered by Bedin et al. (2005)

can be naturally accounted for if ∼34% of the observed WDs are actually WD+WD binary systems. This population of double WDs requires that about 50% of the objects in NGC 6791 be binaries. Such a fraction of binaries is totally plausible for an open cluster like NGC 6791. We demonstrated that NGC 6791 has a fraction of MS+MS binaries of the order of 25%–35%, similar to the fraction of photometric binaries found in M67, another old, massive open cluster (Montgomery et al. 1993). As shown by Hurley et al. (2005), a model that takes into full account the dynamical properties of M67 and the properties of its stellar population requires a fraction of the order of 60% for the present-day binaries (starting from a primordial binary fraction of 50%), values very similar to those required to explain the WD CS of NGC 6791. The WD LF down to the bottom of the CS in M67 has been studied by Richer et al. (1998). Unfortunately, the large photometric errors, the small number of measured WDs, and the consequently large LF bin size (0.5 mag) do not allow investigation of the effect of the large binary population of M67 on the WD CS.

We can anticipate that a secondary peak, about 0.75 mag brighter than the clump at the bottom of the CS, is also present in the WD CS of M4 (L. R. Bedin et al., in preparation). The presence of WD+WD binaries in M4 has also been noticed by Hansen et al. (2004), who showed that a binary fraction up to 10% does not affect the M4 age inferred from the WD CS.

As a final note, we want to emphasize that a large fraction of binaries implies also the presence of many interacting binaries. The three CVs and the many contact binaries discovered by De Marchi et al. (2007) provide observational support to this fact. We suspect that this high binary fraction may be related to the other peculiarity of this cluster, the presence of a blue horizontal branch (Kaluzny & Udalski 1992; Stetson et al. 2003), despite its supersolar metallicity. Interestingly enough, the presence of close or interacting binaries with the consequent mass-loss enhancement can also explain the presence of some He-core WDs, such as those spectroscopically identified by Kalirai et al. (2007) in the upper part of the CS.

J. A. and I. R. K. acknowledge support from STScI grants GO-9815 and GO-10471. G. P. and A. P. M. acknowledge partial support from the Agenzia Spaziale Italiana under contract ASI/088/06/0.

REFERENCES

Bedin, L. R., King, I. R., Anderson, J., Piotto, G., Salaris, M., Cassisi, S., & Serenelli, A. 2008, ApJ, 678, 1279 (Paper II)
Bedin, L. R., Piotto, G., Carraro, G., King, I. R., & Anderson, J. 2006, A&A, 460, L27
Bedin, L. R., Salaris, M., Piotto, G., King, I. R., Anderson, J., Cassisi, S., & Momany, Y. 2005, ApJ, 624, L45 (Paper I)
Carraro, G., Villanova, S., Demarque, P., McSwain, M. V., Piotto, G., & Bedin, L. R. 2006, ApJ, 643, 1151
Deloye, C. J., & Bildsten, L. 2002, ApJ, 580, 1077
De Marchi, F., et al. 2007, A&A, 471, 515
De Marchi, G., Paresce, F., & Portegies Zwart, S. 2005, in The Initial Mass Function 50 Years Later, ed. E. Corbelli, F. Palle, & H. Zinnecker (Dordrecht: Springer), 77
Fisher, J., Schröder, K., & Smith, R. C. 2005, MNRAS, 361, 495
García-Berro, E., Althaus, L. G., Corsico, A. H., & Isern, J. 2008, ApJ, 677, 473
Gratton, R., Bragaglia, A., Carretta, E., & Tosi, M. 2006, ApJ, 642, 462
Hansen, B. M. S. 2005, ApJ, 635, 522
Hansen, B. M. S., et al. 2004, ApJS, 155, 551
Hurley, J. R., Pols, O. R., Aarseth, S. J., & Tout, C. A. 2005, MNRAS, 363, 293
Kalirai, J. K., Bergeron, P., Hansen, B. M. S., Kelson, D. D., Reitzel, D. B., Rich, R. M., & Richer, H. B. 2007, ApJ, 671, 748
Kaluzny, J., & Udalski, A. 1992, Acta Astron., 42, 29
King, I. R., Bedin, L. R., Piotto, G., Cassisi, S., & Anderson, J. 2005, AJ, 130, 626
Milone, A., Piotto, G., Bedin, L. R., & Sarajedini, A. 2008, Mem. Soc. Astron. Italiana, in press (arXiv:0801.3177)
Montgomery, K. A., Marschall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Origlia, L., Valenti, E., Rich, R. M., & Ferraro, F. R. 2006, ApJ, 646, 499
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Richer, H. B., Fahlman, G. G., Rosvick, J., & Ibata, R. 1998, ApJ, 504, L91
Segretain, L. 1996, A&A, 310, 485
Sollima, A., Ferraro, F. R., Fusi Pecci, F., & Sarajedini, A. 2007, MNRAS, 380, 781
Stetson, P. B., Bruntt, H., & Grundahl, F. 2003, PASP, 115, 413