COLOR-MAGNITUDE DIAGRAMS AND LUMINOSITY FUNCTIONS DOWN TO THE HYDROGEN-BURNING LIMIT. III. A PRELIMINARY HUBBLE SPACE TELESCOPE STUDY OF NGC 6791

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Received 2005 March 15; accepted 2005 April 22

ABSTRACT

Using Hubble Space Telescope Advanced Camera for Surveys Wide Field Channel images, we derive the color-magnitude diagram of the old, metal-rich open cluster NGC 6791 to nearly 29th magnitude in V, which is the neighborhood of the hydrogen-burning limit. Comparison with isochrones leads to a discussion of the distance modulus, the reddening, and the age of the cluster. By making a statistical correction for field stars, we derive a preliminary luminosity function and a very tentative mass function. The white dwarf sequence is clearly shown and has been discussed in a separate paper.

Key words: Hertzsprung-Russell diagram — open clusters and associations: individual (NGC 6791) — stars: low-mass, brown dwarfs

Online material: color figures

1. INTRODUCTION

NGC 6791 is unique among open clusters. Not only is it one of the richest of them (in sky surveys it is easily mistaken for a globular cluster), it also has both an unusual metallicity [Fe/H] = +0.3 (Stetson et al. 2003, hereafter S03; Worthey & Jowett 2003) and an anomalously old age of 8–12 Gyr (S03; Chaboyer et al. 1999). Its apparent distance modulus (m – M)V = 13.13.5 (see discussion in § 3.3) allows us to measure stars down to the neighborhood of the hydrogen-burning limit. We have therefore undertaken a Hubble Space Telescope (HST) study of this cluster (GO 9815) in which images made with the Advanced Camera for Surveys (ACS) take us down to V ≈ 29. This study is part of a more extended investigation aimed at studying stars in a low-mass regime that has never been accessible before and will serve as an important guide for theories of the structure of low-mass stars. Our color-magnitude diagrams (CMDs) check the luminosity-radius relation, while the faint end of the luminosity function (LF) can be used to check the mass-luminosity relation. Our target objects (NGC 6397, M4, ω Cen, 47 Tuc, and NGC 6791) allow us to cover most of the globular cluster (GC) metallicity regime, with an extension to suprasolar metallicities thanks to NGC 6791.

Our earlier results showed that while models are able to reproduce the observed main sequence (MS) almost down to the hydrogen-burning limit for metal-poor clusters (see our study of NGC 6397 in King et al. 1998, hereafter Paper I), theory fails to reproduce the CMD of a moderate-metallicity GC such as M4 (Bedin et al. 2001, hereafter Paper II). This inability of stellar models to reproduce the luminosity-color relation, and the implausible bends at the low-mass end of the mass functions (MFs) that we derive from our LFs, cast doubt on the reliability of the adopted theoretical framework. However, as discussed by Baraffe et al. (1998) and Cassisi et al. (2000), this occurrence must be related to current uncertainties in the relations between color and effective temperature that are adopted for transferring stellar models from the theoretical [log (L/L⊙), log T⊙] diagram to the various observational planes. These uncertainties, which are due mainly to the poorly known contribution of different chemical species to the opacities of the stellar atmospheres, become more serious at higher metallicities.

Because NGC 6791 lies in a rich Galactic field (at l = 70°, b = +11°), our program includes a second epoch of observation, to be carried out in mid-2005, to derive proper motions that we can use to separate out field stars. The first-epoch images have yielded so much interesting information, however, that we feel they merit the report that is given here. In fact, we are already able to present the deepest CMD of NGC 6791, with a MS that extends down to the hydrogen-burning limit and, for the first time, the white dwarf (WD) cooling sequence, possibly down to the faintest WDs in NGC 6791. This paper concentrates on the presentation of the data set, the data reduction, and the MS stars. The WD cooling sequence has been discussed in a separate paper (Bedin et al. 2005b).

2. OBSERVATIONAL DATA AND REDUCTIONS

Our observations, made with the Wide Field Channel (WFC) of the ACS, were of a field centered 1.5 northeast of the cluster center. They were taken on 2003 July 16 and 17 through the F606W and F814W filters; in each filter the exposure times were 3 × 30 = 2 × 1142 s and 4 × 1185 s. The images in each color were dithered by fractional pixels for better photometry and astrometry.

We made our first measurements on the _FLT images, which are a pipeline output that includes corrections for bias and flat field. We corrected pixel values for geometric distortion according to the recipe given by Anderson (2002).

Then, in order to reach as faint a magnitude as possible, we created a stacked image in each color as follows. We first measured magnitudes and positions in each image using the effective
point-spread function (ePSF) method described by Anderson & King (2000), and we corrected these positions for geometric distortion using the Anderson (2002) prescription. We then chose one of the images as a reference frame and found the best linear transformation between each of the other images and this frame.

Since ACS WFC images are undersampled, we made a stack in which the original 50 mas pixels are subsampled by a factor of 2 in each direction. We accomplished this as follows. For each pixel of the supersampled image, we calculated the position to which it corresponds in each of the distortion-corrected images and chose a pixel value derived from bilinear interpolation in that image. (There is no need to allow for the fact that the new pixels are smaller, since the magnitude zero point is calibrated only at a later stage.) We calculated the mean of these six values using residuals to eliminate outliers by $\sigma$-clipping at the 3 $\sigma$ level.

We refer to the resulting stacks as superstacks. For all but the brightest stars our final photometry was performed on the two superstacks, using DAOPHOT (Stetson 1987) and ALLSTAR (described in the DAOPHOT User’s Manual), with a PSF based on a Moffat function and a quadratic spatial variation.

In attempting to push photometry to a faint limit, there is always a problem with false detections at the faint end. We used three criteria to eliminate false objects. First, we did the FIND operation with a threshold of 3.5 times the $\sigma$ of the background in order to minimize the background noise effects. Then we eliminated as many false objects as possible by requiring that the absolute value of the SHA parameter of DAOPHOT be less than 0.2 and that the positions of the star in each of the two superstacks agree within a distance of 0.5 pixels. Before choosing the numerical criteria just quoted, we carried out photometry using a number of other values of the parameters and examining the resulting CMDs; we adopted the values that appeared to give the best compromise between accepting false stars and losing real ones.

Because stars brighter than $m_{F606W} \simeq 20.5$ are saturated in long exposures, for them we used photometry by the method of Anderson & King (2000) on short-exposure images. The superstack magnitudes were put on the zero point of the short-exposure images by comparing the magnitudes of a large number of well-measured, nonsaturated stars that were common to both sets. The zero points were set by the procedures described in Bedin et al. (2005a).

Our final step was a determination of completeness as a function of magnitude. We did this by adding artificial stars (constructed from our PSF, with a realistic amount of noise added). In the artificial star tests 38,000 stars, on a grid with a spacing of 42 pixels, were added to each of the superstacks. The grid was displaced by a random number of pixels in each coordinate, the number ranging from 0 to 1 less than the separation. The same displacement was used for each color.

The artificial stars had random $m_{F606W}$ magnitudes over a range of 7 mag ($23.5 \leq m_{F606W} \leq 30.5$). Two separate experiments were carried out. In one, the $m_{F814W}$ magnitude was chosen so as to place the star on the ridgeline of the WD sequence; in the other, the stars were on the ridgeline of the MS. The superstacks containing the artificial stars were processed in exactly the same way as the real superstacks had been. The results of the artificial star tests on the MS are shown in Figure 1. The left panel shows, in a CMD, the input (solid line) and output $m_{F806W} - m_{F814W}$.
Figure 1 (right) shows that our MS star counts are >50% complete for all magnitudes $m_{F606W} < 28.35$.

3. THE COLOR-MAGNITUDE DIAGRAM

3.1. Our Results

Figure 2 shows our full CMD of NGC 6791 for the ~3200 stars that remain after the selection described in the preceding section. The CMD extends for 15 mag, from a couple of magnitudes above the turnoff (TO) down to $m_{F606W} \sim 29$, i.e., ~6 mag fainter than in S03.

The CMD shows a MS with a well-defined TO, as well as several magnitudes of a WD sequence. As expected from the relatively low Galactic latitude of the cluster ($b = +11^\circ$), the entire CMD is contaminated by field stars. As mentioned above, we will use our second-epoch images (2005 July) to remove the field stars by measuring the proper motions of all the stars. The field stars are not nearly so numerous, however, as to obscure the cluster CMD, which is clearly visible down to $m_{F606W} \sim 28$. According to the artificial star tests, the completeness of our photometry is 50% at $m_{F606W} = 28.34$ and reaches 90% at $m_{F606W} = 27.5$. Indeed, we still see numerous faint field stars, but the cluster sequence seems to be dwindling away.

In Figure 2 there is a clear indication of a well-populated binary sequence running parallel to the MS and of a possible WD-WD binary sequence running parallel to the WD cooling sequence. Both sequences indicate that the fraction of binaries in this cluster must be relatively high. A more quantitative analysis will be done when we have removed the field stars.

Figure 2 also contains two very blue stars that correspond to subdwarf candidates discussed by Kaluzny & Rucinski (1995) and S03 (11562 and 12652 in their catalog). These stars are likely cluster members (S03), and their presence in such a metal-rich cluster is noteworthy. They might correspond to very hot HB stars, implying some anomalously high mass loss along the red giant branch or an anomalous composition (e.g., strong helium enhancement, as found in Piotto et al. [2005] for a subsample of stars in ω Cen).

3.2. Comparison with the S03 CMD

Unfortunately, it is not possible to compare our CMD directly with that of S03, on account of differences in the color systems. The magnitudes of S03 are in standard $BVI$, whereas our magnitudes are constrained, by observational necessity, to be in the system defined by the F606W and F814W filters of the HST.

![Fig. 2.—The $m_{F814W}$ vs. $m_{F606W} - m_{F814W}$ and the $m_{F606W}$ vs. $m_{F606W} - m_{F814W}$ CMDs.](image-url)
for faint red stars of the metallicity of NGC 6791 no SEDs at all exist yet, so comparison of observation with theory will have to await the appearance of the theory.

The real value of a system such as UBVRI is that observers can intercompare their observations conveniently if they all agree to use that system. For the comparison of observation with theory, however, all systems are equally valid, because comparison depends only on the basic operation of integrating the SEDs of the theory over the passbands of the observing system.

3.3. Isochrone Fitting

One of the driving reasons for this entire project, and, in general, the main reason for studying the CMD of a cluster, is for comparison with the predictions of stellar evolution models. Such comparisons provide important information on the stellar structure and atmosphere and allow measuring of important cluster parameters, including the age and MF. The most appropriate way to perform such a comparison is to transform the theoretical tracks into the observational plane. These transformations become more and more uncertain for stars much cooler or much hotter than the Sun, and, as noted in the previous section, the problem becomes really severe for suprasolar metallicities, to the point that we expect our observations to provide important new inputs to the theoreticians working in this field.

Unfortunately, there is an additional problem that complicates our efforts: the (often large) uncertainties in the reddening and the distance modulus of the object observed. These uncertainties are particularly large in the case of NGC 6791, for which various studies in the last 20 years have found reddening values $0.09 < E(B - V) < 0.20$ and true distance moduli $12.6 < (m - M)_0 < 13.6$ (see S03 and references therein).

Definitive measurements of the reddening, distance, and age of NGC 6791 are beyond the scope of the present paper. However, taking advantage of the shape of the MS around the TO, we can still extract some useful information from our data (information that was also used in the companion paper on the WD cooling sequence [Bedin et al. 2005b]). Figure 4 shows the same CMDs as in Figure 2, zoomed around the TO. In order to estimate the cluster age and distance modulus, we used the theoretical framework presented by Pietrinferni et al. (2004). We refer the interested reader to that paper for a detailed discussion of the stellar evolutionary models for both H- and He-burning phases. Here it is enough to note that these stellar models and isochrones are based on the most up-to-date physical scenario that is currently available.

The whole theoretical framework has been transferred from the theoretical plane to the observational Johnson-Cousins one by using the recipes described by Pietrinferni et al. (2004), while for the ACS system on board the HST we adopted the color-effective-temperature relations, bolometric-correction scale, and color transformations presented by Bedin et al. (2005a). In order to fit the CMD of NGC 6791, we have used the evolutionary models corresponding to the chemical composition $Z = 0.03$, $Y = 0.288$ (i.e., $[M/H] = 0.26$).

In Figure 4 we show the best fit we could get by eye. This would imply an age of $\sim 9$ Gyr, an $E(B - V) = 0.15$, and an apparent distance modulus $(m - M)_{F606W} = 13.5$, which would...
correspond to a true distance modulus \((m - M)_{0} = 13.0\), i.e., a distance of \(\sim 4\) kpc from us. Note that while the distance modulus differs by only 0.2 mag from the distance modulus found by S03, the reddening is significantly higher (by 0.06 mag). [We also note that Carney et al. (2005) recently found from an infrared study \(E(B - V) = 0.14 \pm 0.04\) and \((m - M)_{0} = 13.04 \pm 0.04\).] These differences in the estimated distance modulus and reddening are due in part to the combination of different assumptions adopted in computing the stellar models used in the present work and in the models used by S03 (for instance, the initial He content and physical inputs such as the equation of state; for a detailed discussion of a variety of stellar models, see VandenBerg et al. [2000] and Pietrinferni et al. [2004]) and in part to the different bolometric corrections used to transfer the various sets of stellar models from the theoretical plane to the observational ones. However, as shown in Figures 5 and 6, using our isochrones, properly transformed into the standard \(BVI\) system, with the data of S03, we obtain an age, distance, and reddening consistent with the values used in the fit of Figure 4. Only with a higher metallicity \((\frac{\text{M}}{\text{H}}) = 0.25\) would we obtain a smaller reddening \([E(B - V) = 0.12\), still above their 0.09\].

We also performed the same exercise as in Figure 22 of S03. Basically, we compared the color of the TO in a \(B - V\) versus \(V - I\) two-color diagram with theoretical TO colors for four different metallicities \((\frac{\text{M}}{\text{H}}) = -0.25, 0.05, 0.25, \text{and} 0.4\) and for ages in the interval 7–15 Gyr, at steps of 1 Gyr. adopting a reddening law \(E(V - I)/E(B - V) = 1.35\), we obtained a larger age (\(\sim 12–13\) Gyr) and a smaller reddening \([E(B - V) = 0.09]\) than those suggested by Figures 4–6 but very similar to the values suggested by S03. In this case one works only with differential numbers within the CMD; however, the results are based on the (uncertain) color of only one observational point, namely, the TO. We prefer the more traditional approach of isochrone fitting, as it also takes advantage of the shape of the MSTO and subgiant branch (SGB) regions. Indeed, Figures 4–6 indicate that the shape of the TO-SGB region is well reproduced by an isochrone at 9 Gyr, and that isochrones for ages >10 Gyr are too flat and have too short a distance between the TO and the bend in the SGB to be able to reproduce the observed sequence. In conclusion, according to our models, both our CMD on the \(HST\) ACS system and the S03 CMD suggest that NGC 6791 is a very old cluster, with an age greater than 8 Gyr, assuming a metallicity for it of \(0.2 < \frac{\text{M}}{\text{H}} < 0.4\).

There are two important notes to add here. First of all, there is some inconsistency in the reddening obtained in the fits of Figures 5 and 6. This is in part related to the intrinsic

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**Fig. 4.—** Best fit of the Pietrinferni et al. (2004) isochrones to the observed CMD in the ACS observational plane. It implies an age of 9 Gyr, \(E(B - V) = 0.15\), and an apparent distance modulus \((m - M)_{\text{HSTACS}} = 13.5\). [See the electronic edition of the Journal for a color version of this figure.]
Fig. 5.—Same as Fig. 4, but with the isochrones fitted to the S03 data in the standard $BVI$ observational plane. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 6.—Same as Fig. 5, but for the $V$ vs. $B-I$ CMD (right). The same CMD is fitted with 8, 9, 10, and 12 Gyr isochrones for $[M/H] = 0.4$ (left). [See the electronic edition of the Journal for a color version of this figure.]
uncertainties of the isochrone fitting (because of the well-known degeneracy in age, distance, and reddening), but problems with the transformation of the models from the theoretical plane to the observational $BVI$ plane cannot be excluded.

More importantly, Figure 4 (which is in the ACS observational system) shows that the models are unable to reproduce the observed CMD for $m_{F606W} > 19.5$, being too blue compared with the observed sequences. The same procedure does give a good fit to the $BVI$ magnitudes of S03—clear evidence that the disagreement here is due to uncertainty in the color–effective-temperature relations. In this context we should note that our isochrones were transferred from the theoretical diagram to the standard Johnson system by using accurate tabulations of bolometric corrections and color–$T_e$ relations based on the updated model atmospheres by Castelli & Kurucz (2003). In the regime of low-mass MS stars, however (i.e., MS stars with $T_e \leq 4750$ K), the empirical color–$T_e$ relationships provided by Houdashelt et al. (2000) were adopted, since they provided a better fit of the MS locus of some selected open clusters (see Pietrinferni et al. 2004 for details). In the case of the ACS observational system, we rely fully on the theoretical color–$T_e$ transformations provided by Bedin et al. (2005a), since empirical calibration is lacking. This explains the apparent inconsistency—given that the theoretical stellar models are the same in all the figures—of the results obtained in Figures 4–6.

For the benefit of comparisons with theory, we quote the colors of the MS ridgeline (MSRL). For steps of 0.5 mag in $m_{F606W}$ from 18.5 to 28.5, the values of $m_{F606W} - m_{F814W}$ are 0.76, 0.84, 0.93, 1.05, 1.18, 1.36, 1.53, 1.72, 1.87, 2.03, 2.16, 2.28, 2.39, 2.47, 2.54, 2.62, 2.72, 2.82, 2.94, 3.14, and 3.38.

### 4. LUMINOSITY FUNCTION

One of the ultimate aims of this project is to derive an LF of NGC 6791, with the field stars cleanly removed by means of a proper-motion study. At the present time, even with only one epoch, we can derive a preliminary LF by making a statistical allowance for the field stars. In a CMD of the cluster, we mark out the MS, with its ridgeline marked by circles; the line through them is a quadratic smoothing. Middle: Verticalized MS at two scalings; cluster stars and field stars were counted between the heavy lines and the light ones, respectively. Right: LF, before and after completeness correction; the dotted line shows the correction that was made for field stars. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 7.—Left: MS, with its ridgeline marked by circles; the line through them is a quadratic smoothing. Middle: Verticalized MS at two scalings; cluster stars and field stars were counted between the heavy lines and the light ones, respectively. Right: LF, before and after completeness correction; the dotted line shows the correction that was made for field stars. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 7.—Left: MS, with its ridgeline marked by circles; the line through them is a quadratic smoothing. Middle: Verticalized MS at two scalings; cluster stars and field stars were counted between the heavy lines and the light ones, respectively. Right: LF, before and after completeness correction; the dotted line shows the correction that was made for field stars. [See the electronic edition of the Journal for a color version of this figure.]
twice as wide, because the Poisson error of the field-corrected MS counts is then $(N_{\text{clus}} + N_{\text{tid}}/4)^{1/2}$; the number of field stars then makes only a small contribution to the error.

Figure 7 shows the successive stages of this process. For clarity, the verticalized MS is shown at two different scales. At the far right is the LF, before and after correction for completeness, with error bars for the final values. The dotted histogram shows the size of the correction that was made for field stars.

The quantity of real interest, however, is the MF. Since the LF and the MF refer to the same stars, it is clear that

$$L(M_{F606W}) dM_{F606W} = -f(m) dm,$$

where the notation should be obvious; the minus sign is needed because $M_{F606W}$ and $m$ increase in opposite directions. Thus, we find the MF simply by multiplying the LF by $-dM_{F606W}/dm$. To do this, however, we need to know the mass-luminosity relation (MLR) at the metallicity of NGC 6791—which is lacking, because no appropriate set of color-$T_e$ transformations and bolometric corrections is available for very low mass stars with metallicity higher than solar. To alleviate this problem we use the following work-around. From our own set of stellar models we evaluate the difference in the $F606W$ magnitude between stellar models with the same mass and age ($\approx 10$ Gyr) but different metallicities: the solar one and the metallicity adopted for NGC 6791, $Z = 0.03$. We do this in the mass range 0.5–0.8 $M_\odot$; the mean value is $\Delta M_{F606W} \approx 0.24$ mag. We then apply this constant difference to a solar MLR extending to very low mass stars and use the resulting MLR for the conversion. It has to be emphasized that this is a crude approximation to the true MLR for high-metallicity stars. Nevertheless, we think that for lack of a more reliable MLR, this approach should give us a not-too-gross estimate of the MF of NGC 6791. The results are shown in Figure 8, in which successive panels show the LF, the MF in linear units, and the MF in logarithmic units. The MF is fairly flat, with irregularities that are probably due to nonoptimal field subtraction. We do not comment on it further, because of the crude way in which it was derived and because the second-epoch observations will lead to a more reliable MF.

One of the major purposes of this project was to study the MS in the neighborhood of the hydrogen-burning limit. The large error bars clearly make that impossible at the present stage. The faintest bin, for example, has only 9 ± 4.4 stars in it. But after we get our second-epoch observations, proper motions will identify the stars that are actual cluster members, and our study will be able to proceed. Our intention is to do as we did in the case of M4 (Paper II), using the much fainter limiting magnitude of the stars found in $m_{F814W}$ but not in $m_{F606W}$ to show that stars having the cluster motion drop nearly to zero well above the limit.

5. SUMMARY AND CONCLUSIONS

First-epoch HST observations of NGC 6791 have led to a color-magnitude diagram (CMD) in which the main sequence can be followed to magnitudes in the vicinity of the hydrogen-burning limit—about 6 mag fainter than the ground-based CMD of Stetson et al. (2003). In the region of overlap the agreement is good, except for color equations between our ($F606W, F814W$) system and their ($V, I$) system. At fainter magnitudes, uncertainties in the spectral energy distributions make it impossible for us to convert our magnitudes to ($V, I$).

Fits to theoretical isochrones, assuming [M/H] = +0.26, yield values $(m - M)_{F606W} = 13.5$ and $E(B - V)_{F606W} = 0.15$ at age 9 Gyr. For lack of the proper-motion separation of cluster stars from field stars that we will have at our second epoch, we make a statistical subtraction of field stars to get a preliminary luminosity function. Lacking also a reliable mass-luminosity relation (MLR) at this metallicity, we make a heuristic but reasonable offset from the solar-abundance MLR and derive a tentative mass function, which is rather flat.

L. R. B., S. C., and G. P. acknowledge financial support by MIUR (PRIN2002, PRIN2003). J. A. and I. R. K. acknowledge support by STSci grant GO 9815.

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