EVIDENCE FOR EXTENDED STAR FORMATION IN THE OLD, METAL-RICH OPEN CLUSTER, NGC 6791?

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ABSTRACT

NGC 6791 is an old, metal-rich star cluster normally considered to be a disk open cluster. Its red giant branch is broad in color yet, to date, there is no evidence for a metallicity spread among its stars. The turnoff region of the main sequence is also wider than expected from broadband photometric errors. Analysis of the color–magnitude diagram reveals a color gradient between the core of the cluster and its periphery; we evaluate the potential explanations for this trend. While binarity and photometric errors appear unlikely, reddening variations across the face of the cluster cannot be excluded. We argue that a viable alternative explanation for this color trend is an age spread resulting from a protracted formation time for the cluster; the stars of the inner region of NGC 6791 appear to be older by ∼1 Gyr on average than those of the outer region.

Key words: open clusters and associations: general – open clusters and associations: individual (NGC 6791)

1. INTRODUCTION

Star clusters have long been promoted as ideal tests of stellar evolution because of the homogeneity in age and chemical composition displayed by their stars; ω Cen is invariably cited as the iconic exception that proves this rule. However, the last three decades have witnessed an increasingly rapid reversal of this rule thanks to improved and expanded spectroscopic and photometric databases supplying definitive evidence for mixed and sometimes discrete sub-populations in abundance, age, or both within the same cluster (Piotto 2009). Since this evidence has been compiled for either Milky Way globular clusters or the rich, intermediate-age open clusters of the Magellanic Clouds, it suggests that cluster environment—high total mass or stellar density—is a crucial factor in creating and retaining a mixed population. It would also imply that most Milky Way open clusters should display a high degree of chemical and age homogeneity.

If the environmental scenario is valid, support might exist among the Milky Way open clusters that most resemble those of the Magellanic Clouds in mass. Two obvious candidates at intermediate age are NGC 7789 and NGC 2158. For these clusters, the modest evidence to date provides little support for an internal spread in age or composition (see, e.g., Martell & Smith 2009), with the color spread in the color–magnitude diagram (CMD) of NGC 2158 being a possible byproduct of variable reddening (Carraro et al. 2002).

A somewhat less obvious candidate is the open cluster NGC 6791. This cluster is unique in the Milky Way, being the most massive old open cluster at an age of ∼ 8 Gyr and extremely metal-rich ([Fe/H] ∼ +0.40; Carraro et al. 2006; Origlia et al. 2006; Anthony-Twarog et al. 2007; Boesgaard et al. 2009). Moreover, its extended survival on an orbit which carries it well within the solar circle suggests a system of significantly higher mass at the time of its formation (Carraro et al. 2006). Since the CMD-based age spread estimated for populous clusters is usually less than the 0.7 Gyr found for NGC 419 by Rubele et al. (2010), the CMD of NGC 6791 may have resembled that of the Magellanic Cloud clusters 7 Gyr ago.

While the red giant branch of NGC 6791 is broad in color (Janes 1984; Stetson et al. 2003), as with NGC 7789 and NGC 2158, no statistically significant evidence for a metallicity spread within the cluster has been reported so far. Although never explicitly mentioned, the upper main sequence (MS) and the turnoff (TO) region of its CMD are broad as well, an observation in most clusters usually attributed to photometric errors, variable reddening, and/or binaries. We show in this Letter that a highly plausible, though not exclusive, explanation for the MS/TO broadening is an age spread between the inner and the outer regions of the cluster, implying possible detection of prolonged, if not discrete, star formation activity in NGC 6791.

2. CMD: STRUCTURE AND ANALYSIS

We make use of the *BVI* photometric database compiled by Stetson et al. (2003, ST03), complemented by a proper-motion analysis of NGC 6791 supplied by Dr. Kyle Cudworth (2008, private communication). Based upon over 1700 CCD frames and covering ∼19 arcmin squared, the photometry of ST03 is of exceptionally high precision to more than 4 mag below the TO. Merger of the two data sets generated a catalog of 1093 stars with membership probability above 80% and photometric errors below 0.050 mag in *B* and 0.020 mag in *V* and *I*. The observational data are shown in the CMD's on the left of Figure 1. For comparison on the right are synthetic CMD's based upon the isochrones of Girardi et al.(2005) and Marigo et al. (2008) for an age of 8.5 Gyr and [Fe/H] = 0.4, with a binary percentage of 30%. The synthetic CMD has been blurred based upon the quoted photometric errors from ST03. Qualitatively, it is apparent that the observed CMD exhibits greater scatter than predicted by the synthetic diagrams. A more quantitative illustration is provided by the inset histograms as a function of color for stars between $V = 17.6$ and 18.0; a small color shift has been applied to the histograms with increasing V to account for the mild slope of the TO. The primary peak from single stars has approximately twice the full width at half-maximum (FWHM) in $B - I$ as the synthetic CMD and is separated in color from the binary contribution by an amount that precludes composite stars as the source of the scatter.
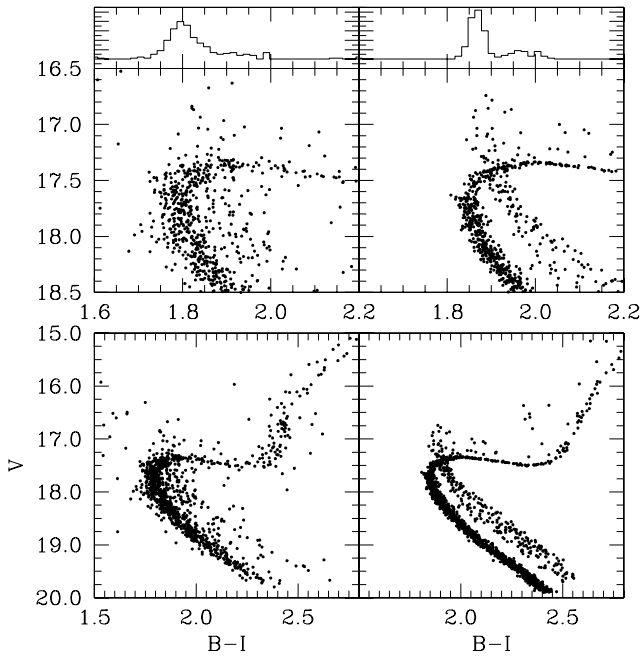
Figure 1. Lower left panel: CMD based upon ST03 photometry for stars with proper-motion membership above 80%. Lower right: synthetic CMD for an age of 8.5 Gyr, with 30% binaries and observational errors included. Upper panels: expanded TO view of the two lower panels.

Figure 2. Left panel: inner (red) and outer (green) region CMD. Middle panel: isochrone fit (solid line) to the inner cluster CMD. Right panel: fit defined by the inner cluster (middle panel) superposed upon the CMD for the outer region.

Binaries and photometric errors aside, scatter in CMD's can have multiple origins—reddening, age, and metallicity, to name a few. However, a key element for NGC 6791 emerged as a byproduct of a discussion of its distance based upon MS-fitting to nearby field stars (Twarog et al. 2009). Figure 2 illustrates the point. The cluster sample, centered on ST03 8075, was divided radially into an inner core of radius 150 pixels on the WEBDA scale ($\sim 2'$) containing 381 stars and an outer region with the remaining 712 stars. The CMD of Figure 1 is replotted at left with the core stars in red and the outer region in green. It is evident that the two regions generate slightly different CMD's. To emphasize this, the middle panel shows a fit of the core CMD with an isochrone (Girardi et al. 2005; Marigo et al. 2008) of age 8.5 Gyr and [Fe/H] = 0.4, shifted by $E(B - I) = 0.30$ and $(m - M) = 13.40$. In a differential context the exact parameters are not important but the isochrone is clearly an excellent match to the data; if anything, the isochrone delineates the bluer edge of the vertical TO region.

By contrast, the same isochrone superposed upon the CMD of the outer region (right panel) demonstrates that between $V = 18.3$ and the base of the giant branch, the outer region has a bluer TO and brighter subgiant branch, indicative of a younger age, all other parameters being equal. The color histograms for each region, derived in the same manner as in Figure 1, confirm that the MS broadening is a result of the superposition of two narrower but offset distributions.

Two key points should be emphasized. First, for stars fainter than the vertical TO, the color offset disappears and the unevolved MSs are indistinguishable. Second, while we have used the $V, B - I$ diagram to illustrate the separation to optimal effect, the color separation is apparent with either the $V, B - V$ CMD or the $V, V - I$ CMD, with the $B - I$ trend being the sum of the two offsets. Given these constraints, we can now evaluate the likelihood that the offsets are caused by photometric errors, reddening, and/or age.
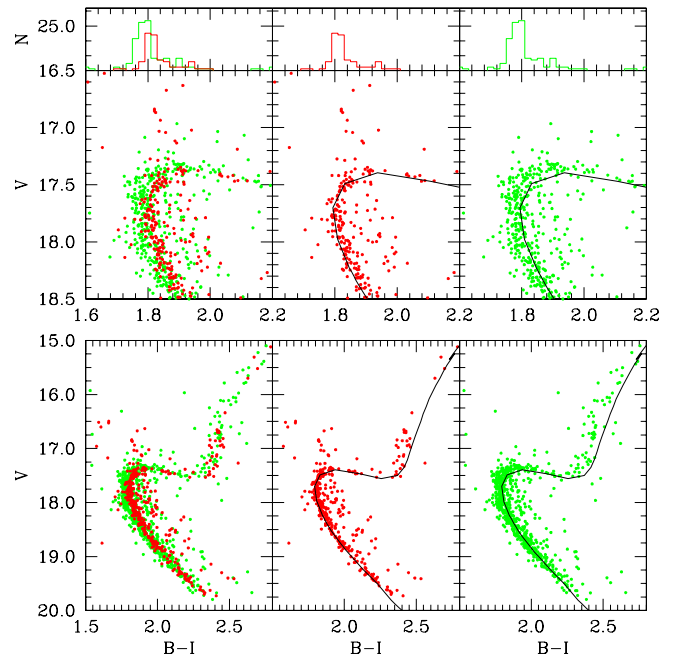
The internal precision of the ST03 photometry is exceptional but this does not preclude the possibility of radially dependent, systematic shifts in color. To test this, we compared the BV photometry of ST03 with that of Kaluzny & Rucinski (1995), the next most accurate photometric database covering approximately the same area, derived using a reduction and calibration procedure independent of ST03. $B - V$ was adopted as the color index due the lack of I photometry in the Kaluzny & Rucinski (1995) survey.

Figure 3 shows the residuals in $B - V$, in the sense (ST03–KR95), for all stars brighter than $V = 20.0$ as a function of radial position in pixels on the coordinate scale of ST03. Stars with absolute residuals larger than 0.15 mag have been excluded from the analysis. The vertical bar illustrates the breakpoint defining inner versus outer region in Figure 2. The filled circles show the mean residuals with standard deviations in annuli 100 pixels wide. While there is evidence that the $B - V$ photometry of ST03 for the inner region is slightly redder than the outer, compared to the system of Kaluzny & Rucinski (1995), the difference ($+0.0070 \pm 0.0015$ mag) is too small to produce the color shift as defined by the $V, B - V$ CMD. Even more important, because the magnitudes are independently calibrated in each filter, a color gradient would only arise if there is a radially dependent offset in each of the individual calibrations which coincidentally combined to produce color offsets which mimicked coherent color/temperature changes in $B - V$, $V - I$, and $B - I$, but only for stars from the subgiant branch to the TO region. While it cannot be excluded, this seems somewhat implausible.

Finally, it should be recognized that for area coverage, filter coverage, and especially internal precision, no published photometry for NGC 6791 even comes close to Stetson et al. (2003). Attempts to prove or disprove the form of CMD structure illustrated in Figure 2 using any other published source at best will lead to marginal differences, as exemplified by Figure 3, with no means of determining which data set defines
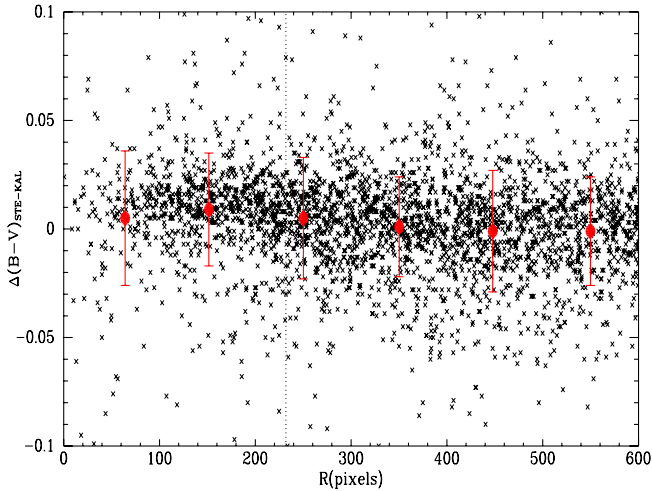
Figure 3. Residuals in $B - V$ between ST03 photometry and Kaluzny & Rucinski (1995) as a function of radial position. The vertical band defines the boundary between the inner and outer clusters. Filled points show the mean residuals with standard deviations in annuli 100 pixels wide.

Figure 4. Same as Figure 1 with the NGC 6791 CMD compared to a synthetic CMD constructed with an extended period of star formation lasting 1 Gyr.

the "correct" system. For example, a similar comparison was attempted using the $B - I$ data of Montgomery et al. (1994), producing no evidence for a radial gradient, but the photometric scatter in the latter data set severely reduced the statistical significance of the null result.

For an alternative independent check of the reality of the color gradient, the stars defining the central peak distributions in a ± 0.02 mag range in the histograms of Figure 2 were identified and compiled using the data of ST03 and the intermediate-band photometry of Anthony-Twarog et al. (2007). The mean color difference in $B - I$ for $V = 17.6$ to 18.0 between the inner and outer regions is 0.0196 ± 0.0023 (sem). (It should be noted that this estimate is a lower bound on the shift required to optimally align the inner and outer region CMD's. The CMD for stars above $V = 17.6$ exhibits the greatest differential between the inner and outer zones, but the effect is a combined offset in both color and magnitude due to the curvature of the TO and thus more difficult to quantify than a simple color shift using the approximately vertical zone at the TO.) For the intermediate-band color index, $b - y$, the mean difference for the same stars is 0.0137 ± 0.0038 (sem), consistent with a true color difference between the two samples but barely a 3.5σ effect. The intriguing result is that the differentials in m_1 and hk, the metallicity indicators, both imply that the core region is more metal-poor than the outer region by between 0.2 and 0.3 dex, though the statistical significance of this differential is even weaker than that of $b - y$ and supplies further evidence of the challenge in trying to identify the origin of the color change. Note that the color shift implied by this potential metallicity difference, all things being equal, should make the core bluer than the outer region.

If photometric errors are not the solution, the next option is variable reddening. The value of this solution is that it helps explain the apparent lack of a color differential for the unevolved MS. With $\Delta E(B - I) = 0.030$, $\Delta E(B - V) = 0.013$, and $\Delta A_V = 0.040$. For a change of $B - I = +0.03$ on the unevolved MS, V changes by +0.09 mag. Thus, the impact of reddening on the scatter in the unevolved MS is cut almost in half to 0.017 mag. The full impact is visible at the vertical TO because the distribution of points is almost orthogonal
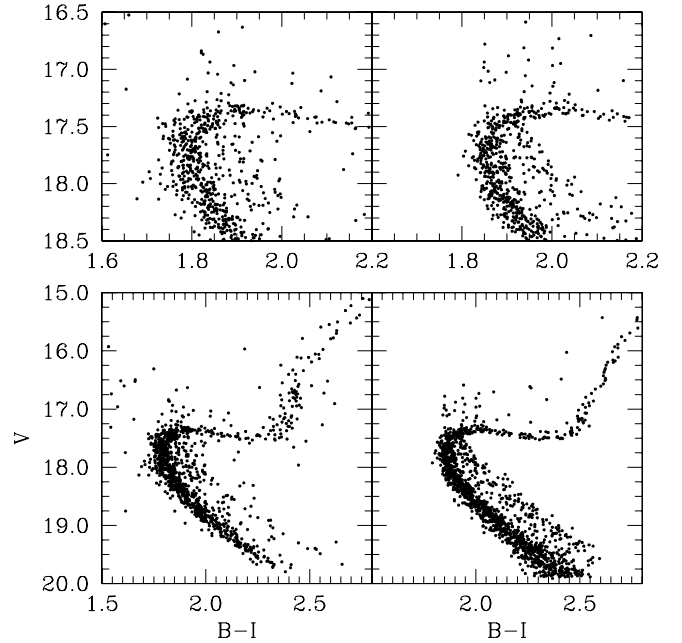
to the reddening vector. However, the second location in the CMD where the impact should be at least as noticeable is the vertical giant branch. The inner region giant branch does not appear to separate from the outer region as well as the TO, if at all, but the scatter in color for both regions is at the same level as the expected shift. The base of the vertical giant branch does extend redder for the inner core compared to the outer region. However, the morphology difference between the branches leads to a superposition of both sets as one moves up the giant branch to $V = 17.25$. Therefore, the evidence for excluding reddening remains inconclusive. If it is the cause of the offset, the implication is that the stars within the cluster core are reddened more than the outer region by $\Delta E(B - V)$ between 0.010 and 0.015 mag.

3. DISCUSSION AND CONCLUSIONS

We have argued that photometric error can be excluded as the source of the distributions seen in Figure 2; metallicity effects, if they exist at all, appear to work in the wrong direction. Having presented arguments questioning the exclusive role of variable reddening as the culprit, we now consider the viability of an age spread. The argument is demonstrated in Figure 4, identical to Figure 1 except that the synthetic CMD has been computed allowing for the inclusion of an age spread of 1 Gyr. Clearly an age spread of this size can almost completely account for the MS broadening. This solution has the added effect of removing any differential for stars on the unevolved MS since the age impact on the CMD will be increasingly apparent as one moves up the MS to the evolved stars in the TO region, with the maximum separation at the top of the TO. The color shift in the giant branches caused by this age offset would be less than half the size of the TO shift and impossible to detect within the scatter of the giant branch.

Should age be the predominant explanation for the broadened TO in the CMD of NGC 6791, it implies that the cluster formed during an extended star formation episode lasting ~ 1 Gyr, making it similar to several Magellanic Cloud clusters, except for

the long-standing anomaly of an extremely high metal content for this older cluster. Among open clusters, only NGC 6253, with less than half the age of NGC 6791, approaches the metallicity of NGC 6791 (Anthony-Twarog et al. 2010). This result, if correct, enhances the unique position of NGC 6791, as defined by the extreme combination of age, metallicty, and kinematics, among the Galactic open cluster population; we remind the reader that although NGC 6791 lies within the solar circle in the galactic disk, it has an unusually eccentric orbit (Carraro et al. 2006). Collectively, these properties might be an indication of an external origin for NGC 6791.

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