NEW PHOTOMETRY FOR THE INTERMEDIATE-AGE LARGE MAGELLANIC CLOUD GLOBULAR CLUSTER NGC 2121 AND THE NATURE OF THE LMC AGE GAP¹

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ABSTRACT

We report new photometry for the cluster NGC 2121 in the Large Magellanic Cloud, which shows a prominent hydrogen core exhaustion gap at the turnoff and a descending subgiant branch reminiscent of Galactic open clusters. We achieve an excellent fit using the Girardi isochrones, finding an age of $3.2 \pm 0.5$ Gyr, with $[\text{Fe/H}] = -0.6 \pm 0.2$. The isochrones fit the color and shape of the turnoff and subgiant branch so precisely that we can constrain the metallicity, as well as the age. The same isochrones also fit SL 663 and NGC 2155, although our photometry for these clusters has much larger errors. We find these clusters to be 0.8 Gyr younger and 0.4 dex more metal-rich than recently reported in the literature. Consequently, we argue that NGC 2121, NGC 2155, and SL 663 are not properly assigned to the age gap in the LMC, but instead are among the first clusters to be have formed in the relatively metal-rich, younger group of LMC clusters. We propose a new definition of the LMC age gap as extending from 3.2 to 13 Gyr, with ESO 121-SC03 still the only remaining candidate for membership in the age gap.

Key words: color-magnitude diagrams — galaxies: star clusters — Magellanic Clouds — stars: evolution

1. INTRODUCTION

In the course of reducing data from our snapshot survey of Magellanic globular clusters (principal investigator [PI], M. Shara, grant GO-5475), we noticed three clusters in the LMC with peculiar color-magnitude diagrams. They appeared to have two turnoff points, complete with subgiant branches. Without improved photometry, it was not possible (in our opinion) to determine an age for these clusters. The double turnoffs and subgiant branches appeared so evident to us that exotic explanations (cluster mergers, multiple bursts of star formation with in a cluster) would have to be considered, if the effect were real. The clusters might be 1–3 Gyr old metal-rich clusters, or they could be older than 4 Gyr, perhaps lying in the 4–12 Gyr “age gap” of LMC clusters (Jensen, Mould, & Reid 1988; Da Costa 1991; van den Bergh 1991).

After our LMC snapshot data became public, Sarajedini (1998) argued that NGC 2121, NGC 2155, and SL 6633 are old LMC clusters with $[\text{Fe/H}] \approx -1$ that should properly be assigned to the age gap. Motivated by the peculiar results of our own reductions, we sought to obtain much longer integrations of these clusters using HST, and we were granted observations of one target, NGC 2121.

The formation history of clusters in the LMC is known to be sporadic. Jensen et al. (1988) were unable to find any LMC clusters (other than ESO 121-SC03) with ages between 4 and 10 Gyr; they proposed the existence of a gap in the cluster age distribution. In considering the ages and metallicities of LMC clusters, Olszewski et al. (1991) show that a gap is present in both age and metallicity between those younger clusters with ages in the range 1–3 Gyr and very old globular clusters similar to those found in the Milky Way. The recent photometry of Olsen et al. (1998) and Johnson et al. (1999) strengthens further the existence of the age and metallicity gap: The oldest LMC clusters are indeed excellent matches for old Milky Way halo globular clusters, such as M3 and M5. The younger LMC clusters have $[\text{Fe/H}] < -1$; it is interesting that ground-based photometry of NGC 1754 resulted in an erroneous (young) age for this metal-poor cluster; Olszewski et al. (1991) suspected that it might be old, and new HST photometry now clearly places it in the very old group of clusters. Although less prominently discussed in the literature, the metallicity gap is just as evident as the age gap. While clusters of intermediate metallicity of approximately $-1.4$ dex are known in the SMC (Da Costa & Hatzidimitriou 1988), they have never been found in the LMC, even using the modern Ca triplet method employed by Olszewski et al. (1991). No further results have been found to challenge the gap in metallicity between the younger group of clusters at $\sim 0.7 \pm 0.3$ dex and the oldest LMC globular clusters at $\sim 2$ dex. Only ESO 121-SC03 remains a strong candidate for a cluster lying firmly in the age/metallicity gap, at 10 Gyr old (Mateo, Hodge, & Schommer 1986) and $[\text{Fe/H}] = -0.91 \pm 0.16$ from high-resolution spectroscopy (Hill et al. 2000). The reality of the age gap has been most securely established by recent photometric surveys of large numbers of clusters (see, e.g., Geisler et al. 1997, 1999; Bica et al. 1998). These studies find virtually no new candidate clusters that might lie in the gap.

1.1. Observations

We imaged NGC 2121 on 2000 January 28 using WFPC2 for 1600 s in each of the filters F555W and F814W and for 800 s in the filter F336W. The frames were reduced using the standard pipeline procedures. Photometry was obtained using DAOPHOT/ALLFRAME (Stetson 1994) and was calibrated using the new transformation equations

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and corrections of Dolphin (2000). These transformations and corrections account for the charge transfer efficiency and the pre– and/or post–cool down differences. Application of the Dolphin corrections accounts for minor differences between our photometry of the snapshot clusters and that of Sarajedini (1998). For NGC 2121, of course, our improved color-magnitude diagram is due to our longer integration time.

Several clusters of interest (NGC 2121, 2155, 2193, SL 556, and 663) were observed in 1994, as part of our snapshot survey (PI, M. Shara). The exposure times and dates of observations for these clusters are given in Table 1. All the snapshot data were reduced as described above, but because the snapshot data have only one frame in each color, the signal-to-noise ratio (S/N) is smaller and the cosmic-ray and hot-pixel contamination is larger for those data.

2. COLOR–MAGNITUDE DIAGRAMS

Figure 1 shows the color-magnitude diagram (CMD) of NGC 2121 based on our new data. We illustrate statistically subtracted data, as well as the CMD formed from the “field” population constructed from the outer portions of the wide-field chips (half the total area of WFPC2). Although the cluster is likely still present in this field population, it serves as a clear upper limit to the field contamination. The true nature of the apparent doubled turnoff is now obvious: there is a wide hydrogen core exhaustion gap.

| Cluster | Filter | Total Exposure Time (s) | No. of Exposures | Date       |
|---------|--------|-------------------------|------------------|------------|
| NGC 2121... | F450W  | 230.0                   | 1                | 1994 Feb 2 |
|         | F555W  | 120.0                   | 1                | 1994 Feb 2 |
|         | F555W  | 1600.0                  | 4                | 2000 Jan 28|
|         | F814W  | 1600.0                  | 4                | 2000 Jan 28|
|         | F336W  | 800.0                   | 2                | 2000 Jan 28|
| NGC 2193... | F450W  | 230.0                   | 1                | 1994 Jan 30|
|         | F555W  | 120.0                   | 1                | 1994 Jan 30|
| NGC 2155... | F450W  | 230.0                   | 1                | 1994 Feb 1 |
|         | F555W  | 120.0                   | 1                | 1994 Feb 1 |
| SL 556 ...... | F450W  | 230.0                   | 1                | 1994 Feb 1 |
|         | F555W  | 120.0                   | 1                | 1994 Feb 1 |
| SL 663 ...... | F450W  | 230.0                   | 1                | 1994 Feb 1 |
|         | F555W  | 120.0                   | 1                | 1994 Feb 1 |

Fig. 1.—Globular cluster NGC 2121 fills the entire field of WFPC2. We have isolated a field population from a field covering half the area of the WFPC2 at the greatest distance from the cluster center in the planetary camera (PC) chip (right). This field CMD has been statistically subtracted from the complete data set to yield our best effort at representing the true cluster CMD (left).
The redward arc of the turnoff point with the blue hook leading to the subgiant branch is indicative of hydrogen core exhaustion in intermediate-mass stars. The descending subgiant branch is indicative of high metallicity. We overlay the Girardi et al. (2000) isochrones, forcing the fit to the red clump stars. Right: NGC 2121, complete data (including the field main sequence). We overlay the log \( t = 9.5 \) isochrones but vary the metallicity. Note that [Fe/H] = —0.68 is a superior fit to the data.

TABLE 2

| Cluster  | [Fe/H] | Age (Gyr) | log (age) |
|----------|--------|-----------|-----------|
| NGC 2121 | —0.68  | 3.2       | 9.5       |
| NGC 2155 | —0.68  | 3.2       | 9.5       |
| NGC 2193 | —0.68  | 2.2       | 9.35      |
| SL 556   | —0.68  | 2.2       | 9.35      |
| SL 633   | —0.68  | 3.2       | 9.5       |

at the main-sequence turnoff point. This gap occurs when the completely convective core suddenly exhausts hydrogen, requiring a structural readjustment of the star, which has the effect of causing the bluward hook in the evolutionary tracks. The strong descending subgiant branch (due to the high metallicity) caused some confusion in the lower S/N data. The turnoff morphology we observe is typical of Galactic open clusters of approximately this age (e.g., M67; Montgomery, Marschall, & Janes 1993). Roxburgh (1978) criterion. A detailed fit of our data to such models will be deferred to a later paper; in this paper, we focus on the question of whether NGC 2121 and similar clusters actually fall well within the age and/or metallicity gap.

We achieve an excellent fit of the Girardi et al. (2000) isochrones to the data (Fig. 2) for an age of 3.2 Gyr and [Fe/H] = —0.68. These isochrones are based on models with a moderate amount of convective overshooting. We make the fit by tying the isochrone red clump to the observed red clump (as in Rich et al. 2000), which removes uncertainties, such as the spatial depth of the LMC cluster system. The goodness of the fit, including the accurate reproduction of the subgiant branch, is remarkable. Figure 3 shows that the fit is equally good using our new \( U, V, \) photometry. Figure 2 proves that the fit strongly depends on metallicity, and while Olszewski et al.'s (1991) spectroscopy gives \(-0.6 \pm 0.1 \) dex, the isochrone fit also requires this metallicity.

The excellent isochrone fit to the new CMD of NGC 2121 gives a foundation on which to approach the snapshot data, which have much larger photometric errors. We find that the same isochrones (log \( t = 9.5, [\text{Fe/H}] = —0.68 \)) that fit NGC 2121 also appear to fit NGC 2155 and SL 663 as well. Figure 4 shows isochrones overlaid on the snapshot...
oldest LMC clusters are all very metal-poor, approximately \([\text{Fe/H}] \sim -2\) to \(-0.5\) without leaving behind long-lived star clusters. It is clear that the formation of star clusters may accompany chemical enrichment, but it is not a requirement for enrichment to occur.

Can we defend our claim that the metallicity of NGC 2121 is high based on the isochrones alone? All published spectroscopic metallicity measurements in NGC 2121 give metallicities higher than \(-1\) dex. Cohen (1982) derives \([\text{Fe/H}] = -0.95\) from Fe, Ca, Na, and Mg line widths at low resolution for two stars. Bica et al. (1998) find \([\text{Fe/H}] = -0.75\) from integrated DDO photometry of the cluster, but such a method can be affected by field contamination, a concern also for the integrated light spectral indexes of de Freitas Pacheco, Barbuy, & Iddiart (1998). We consider the measurement of \([\text{Fe/H}] = -0.61\) by Olszewski et al. (1991; based on Ca triplet spectra of two stars) to be the most reliable because the Ca triplet method is well calibrated, and the composition is scaled solar for metal-rich stars. Furthermore, Olszewski et al. (1991) confirm radial velocity membership of the two stars in NGC 2121 and use calibrating clusters with higher metallicity. Olszewski et al. (1991) also measure the Ca triplet in NGC 2155, finding \([\text{Fe/H}] = -0.55\). It is interesting to note that Olszewski et al. (1991) find \([\text{Fe/H}] = -0.93\) for ESO 121-SC03 using the low-resolution Ca triplet method, while Hill et al. (2000) find \([\text{Fe/H}] = -0.91\) using high-resolution VLT spectroscopy of stars in the cluster. We believe that the Ca triplet metallicities are more accurate than abundance measurements derived from fits to the red giant branch slope.

The isochrone fits at the turnoff (clear descending subgiant branch) also confirm the high metallicity of NGC 2121 and the other clusters in this group. For these clusters, we now assign \([\text{Fe/H}] = -0.6, 0.4\) dex higher than that derived from the red giant branch slope by Sarajedini (1998). The descending subgiant branch is also seen in intermediate-age, relatively metal-rich Galactic clusters and is caused by an increase in blanketing, in which the star's atmosphere expands and cools in the approach to the red giant branch. The concurrence of abundance inferred from the CMDs and the Ca triplet spectroscopy compels us to favor the higher abundance scale for NGC 2121, NGC 2155, and SL 663. We are convinced that these clusters are more metal-rich than ESO 121-SC03, and by metallicity, as well as age, belong on the young side of the age gap.

The core of our argument associating these clusters with the younger group (rather than the age gap) rests on both a 0.4 dex increase in metallicity and a 0.2 dex decrease in age relative to Sarajedini's (1998) values. However, our new values are supported by the data, and a combination of \(\log t = 9.5\) and \([\text{Fe/H}] = -1\) simply does not fit the CMD of NGC 2121. Plotted in linear space, the gap between our age of 3.2 Gyr and the 13 Gyr ages for the oldest LMC clusters (or even the 10 Gyr age of ESO 121-SC03) is still very large. We propose the former—the interval from 3.2 to 13 Gyr—as the new boundaries for the LMC age gap, verified by high-resolution WFPC2 photometry. We conclude that the age gap in the LMC remains real and unexplained.
Figs. 4.—CMDs for NGC 2121, NGC 2155, and SL 663 from the short snapshot survey exposures. These data are typically 120–230 s exposures with no cosmic-ray cleaning. The best-fit isochrones (log \( t = 9.5 \), \([\text{Fe/H}] = -0.68\)) from the high-quality CMD of NGC 2121 are overlaid on these much noisier CMDs. We conclude that there is no evidence for any clusters in this group being older than NGC 2121.

Figs. 5.—CMDs for two additional candidate old LMC clusters in our sample, NGC 2193 and SL 556, also fitted using the best-fit Girardi et al. (2000) isochrones (log \( t = 9.3–9.7 \), in steps of 0.1) with \([\text{Fe/H}] = -0.68\). We find an age of 2.2 ± 0.5 Gyr for these clusters (see Table 2). These clusters are likely to be younger than NGC 2121.
Fig. 6.—Plot of age as a function of metallicity for LMC clusters, based on the data in Dirsch et al. (2000). Our new data (given in Table 2) are indicated by a cross (our best fit to NGC 2121, which we apply to NGC 2155 and SL 663) and a plus sign (our ages for NGC 2193 and SL 556). Ages and metallicities for the clusters are given in Table 2. We estimate an error of $\pm 0.05$ in log age from our fit of the isochrones. We adopt the metallicity scale of Olszewski et al. (1991) for our clusters (see text). We also adopt the metallicity of Hill et al. (2000) for ESO 121-SC03, and we presume an age of 13 Gyr for the oldest group of LMC globular clusters, based on recent WFPC2 photometry. Note that the age gap extends from 3.3 to 13 Gyr.

Fig. 7.—Same as Fig. 6, but using a logarithmic age scale. We have modified the Dirsch et al. (2000) data as discussed in Fig. 6. The gap remains very clear, with the WFPC2 data confirming the findings of recent ground-based surveys that the age gap is real.
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