Three Populous Clusters Discovered to be in the LMC Age Gap

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ABSTRACT

In the process of searching the Hubble Space Telescope archive, we have serendipitously discovered three populous Large Magellanic Cloud (LMC) clusters with ages that place them in the LMC ‘age gap.’ These clusters - NGC 2155, SL663, and NGC 2121 - turn out to have $[Fe/H] \sim -1.0$ and ages of $\sim 4$ Gyr. This puts them in the age gap between the intermediate-age LMC clusters, the oldest of which are $\sim 2.5$ Gyr old, and ESO121-SC03, which has an age of $\sim 9$ Gyr. The addition of these three clusters to the LMC age - metallicity relation has reduced the discrepancy between the age distribution of the LMC clusters and the field stars. Furthermore, it indicates that searches to find more clusters older than $\sim 2.5$ Gyr in the LMC are crucial to a better understanding of its global star formation history.

Subject headings: galaxies: Magellanic Clouds, clusters, dwarf, formation, evolution

1. Introduction

The chemical enrichment/star formation history (SFH) is an identifying feature of every self-gravitating stellar system. One manifestation of this is the relation between age and metallicity among the star clusters in a given galaxy. Empirical information on how cluster age and metal abundance correlate provides an important clue that will eventually allow us to understand how star formation (and hence chemical enrichment) proceeds under a variety of potentially influential

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1Based on observations made with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555.

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3Guest User, Canadian Astronomy Data Centre, which is operated by the Dominion Astrophysical Observatory for the National Research Council of Canada’s Herzberg Institute of Astrophysics.
circumstances. It is for this reason that we strive to better define the age-metallicity relations of the cluster and field populations in galaxies. Nearby galaxies are no exception, especially the Large and Small Magellanic Clouds (L/SMC) which have provided numerous puzzles and challenges for theorists. One of the most persistent of these has been the ‘age gap’ seen between the intermediate-age clusters ($t \lesssim 2.5$ Gyr; see Sec. 4.1 for a justification of this limit) and the old clusters ($t \gtrsim 13$ Gyr) in the LMC (Geisler et al. [1997]). The LMC age gap is also a metallicity gap in the sense that the intermediate-age clusters have $\langle [\text{Fe/H}] \rangle \sim -0.5$, while the old clusters are closer to $\langle [\text{Fe/H}] \rangle \sim -2$. There is only one cluster that is known to lie in the gap - ESO121-SC03 with an age of $\sim 9$ Gyr and $[\text{Fe/H}] \sim -1$. In contrast, recent studies based on Hubble Space Telescope (HST) data of the LMC field stars tell a significantly different story (see Geha et al. [1998] for a review). While there are variations that depend on position in the LMC (Vallenari et al. [1996]), the global star formation rate has been fairly constant for most of the LMC’s history. However, sometime between 2 and 4 Gyr ago, a burst of star formation occurred producing the present population of young to intermediate age field stars and clusters (Bertelli et al. [1992]; Vallenari et al. [1996]; Gallagher et al. [1996]; Holtzman et al. [1997]). Furthermore, the models produced by Geha et al. [1998] suggest that roughly half of the LMC field stars are older than 4 Gyr. What this implies is that there should be many star clusters with ages between $\sim 2.5$ Gyr and $\sim 13$ Gyr, which were formed contemporaneously with the field stars. The obvious question of course is: where are these ‘age gap’ clusters?

A number of investigators have undertaken surveys to find clusters in the LMC age gap (Da Costa [1991]; Geisler et al. [1997], and references therein). The overwhelming conclusion has been that the LMC contains only one cluster with an age between 2.5 Gyr and 13 Gyr (i.e. ESO121-SC03). There is the possibility that some clusters did exist in the age gap sometime in the past, and that these have either dissolved into the LMC field or been stripped off (Olszewski [1993]). However, it is difficult to see how this process can preferentially affect only clusters formed during a given epoch, unless the mass spectrum of density fluctuations producing the gap clusters was somehow different from that which produced the other clusters in the LMC. The possible reasons for this are not obvious.

While understanding the SFH of the LMC is extremely important, this was not our original aim when we began this study. Initially, we were searching the Hubble Space Telescope (HST) archive looking for intermediate age clusters that display the red giant branch (RGB) Bump in their color-magnitude diagrams (CMD). We did find one such cluster (NGC 411; see Alves & Sarajedini [1998]). However, more importantly for the present work, we discovered three clusters whose CMDs exhibit significant numbers of stars in the Hertzsprung gap, indicative of ages older than $\sim 2.5$ Gyr. These clusters are NGC 2155, NGC 2121, and SL663, and the next section describes the observations of these clusters and the data reduction. Section 3 presents the CMDs while Section 4 discusses the ages yielded by these CMDs. The implications of these results are detailed in Section 5.
2. Observations and Reductions

The observations used in the present study were taken with the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) during the period 1994 January 30 to February 2. For each cluster, one 230s exposure and one 120s exposure were obtained in the F450W (∼B) and F555W (∼V) filters, respectively, with the gain value set at 14 e/ADU. The telescope was not moved between these observations. The images were recalibrated at the Canadian Astronomy Data Centre using the ‘recommended’ calibration frames. The frames were then multiplied by the geometric distortion correction frame (Biretta [1995]). Before beginning the photometric reduction process, the bad pixel masks were applied to the program frames thereby flagging pixels known to be defective. We note in passing that the identification of one of the clusters, SL 663, appears to be incorrect in the image header. The position of the target (αJ2000 = 5h 42m 30s, δJ2000 = −65° 21′ 49″) is coincident with the cluster SL 663 in the Kontizas et al. (1990) catalogue not SL 633 as suggested by the image header (which is the 30 Doradus cluster). Table 1 gives the Journal of the observations.

Aperture photometry was performed using the routines in DAOPHOT II (Stetson [1994]). A nominal aperture radius of 2 pixels was used with aperture corrections providing the offset to total magnitudes inside of a 0.5 arcsec radius. The typical errors in the aperture corrections were ±0.05 mag. After matching the instrumental magnitudes to form colors, the following equations were used to transform our data to the standard system defined by Holtzman et al. (1995):

\[ B = b + a_B + b_B(B - V) + c_B(B - V)^2 \]
\[ V = v + a_V + b_V(B - V) + c_V(B - V)^2, \]

where \( b \) and \( v \) refer to the instrumental magnitudes (i.e. aperture magnitude + aperture correction + 2.5Log(t) − 25.0), and \( B \), \( V \), and \( (B - V) \) are the standard system values. The coefficients for F450W and F555W are taken from Table 10 and 7 of Holtzman et al. (1995), respectively. A 12% CTE correction in the y-axis direction was also included (Holtzman et al. [1995]) because these data were taken at an operating temperature of −76° C before WFPC2 was cooled to −88° C.

3. Color-Magnitude Diagrams

We first seek to investigate the integrity of our data reduction method. To accomplish this, we have chosen the LMC cluster NGC 2193, which Geisler et al. (1997) claim has an age of 2.3 Gyr, one of the oldest among the intermediate age clusters (IACs). Figure 1 shows the \( B - V \) color-magnitude diagram (CMD) of NGC 2193 from archival HST observations made in the F450W and F555W passbands. Only the Planetary Camera data are plotted. In the same figure, we have included the ground-based photometry of NGC 2193 from the work of Da Costa et al. (1987). These latter data were originally observed in \( B - R \) and have been transformed to \( B - V \).
using the well-determined relation published by Mighell et al. (1998a). The agreement between these datasets is striking. All of the CMD features appear to coincide between these two datasets. This agreement lends credence to our reduction methods and lays the foundation for the remainder of the paper.

The lower panel of Fig. 1 compares the CMD of NGC 2193 to that of the cluster SL 556 (Hodge 4), to which Geisler et al. (1997) assign an age of ∼3 Gyr. This is the oldest cluster among the IAC according to Geisler et al. (1997), even older than NGC 2193 based on their analysis. However, the clear correspondence of the HST data for NGC 2193 and Hodge 4 indicates that in fact these two clusters are more likely to be the same age. We return to this issue in the next section.

Figures 2 through 4 illustrate the CMDs for the program clusters in this study - NGC 2155, SL 663, and NGC 2121, respectively - the clusters that appear to lie in the LMC age gap (see below). In each figure, CMDs for the four WFPC2 CCD chips (PC1, WF2, WF3, and WF4) are shown. The clusters were centered on the PC1 aperture so that this CMD exhibits the cluster principal sequences most clearly. The strongest case is that of NGC 2155 which displays a blue hook near the main sequence turnoff (MSTO) and a well-developed subgiant branch indicative of an older population. The CMD of SL 663 also displays these features, but because SL 663 is not as populous as NGC 2155, the features are not as obvious. The morphology of the NGC 2121 main sequence turnoff is similar to that of NGC 2155, but its subgiant branch is not as well developed.

4. Cluster Ages

4.1. Comparison With Theoretical Isochrones

One method we can utilize to estimate the cluster ages is simply to overplot isochrones on the CMDs of the clusters presented herein. We will make use of the tracks published by Bertelli et al. (1994), which are given for Z=0.001 ([Fe/H] = −1.3) and Z=0.004 ([Fe/H] = −0.7) and include the effects of convective core overshooting for stars more massive than one solar mass. Before, we proceed with the isochrone comparisons, we need an estimate for the metallicity of each cluster. In the case of NGC 2193 and Hodge 4, we look to the metallicity values derived from published CMD photometric studies. In particular, Mateo & Hodge (1986) derive [Fe/H] = −0.7 ± 0.3 for Hodge 4 and Da Costa et al. (1987) find [Fe/H] = −0.5 ± 0.3 for NGC 2193. For the sake of convenience in the isochrone comparison, we adopt [Fe/H] = −0.7 for both of these clusters.

Our preferred metallicity indicator for NGC 2155, SL 633, and NGC 2121 is the slope of the RGB because it is independent of reddening and uncertainties in the photometric zeropoint. The latter could be significant given the fact that the data have been derived from HST WFPC2 observations taken before the cooldown to −88°C. In addition, Mighell et al. (1998b) have shown that, for clusters as young as 4 Gyr, the RGB slope metallicities are only 0.11 ± 0.06 dex more
metal-poor as compared with metal abundances estimated from the Calcium triplet (Da Costa & Hatzidimitriou 1998). We note in passing that this method is not applicable to NGC 2193 and Hodge 4 because these clusters are younger than ~4 Gyr, whereas we show below that the program clusters are ~4 Gyr old. To facilitate the measurement of the RGB slope, we begin by fitting a polynomial to the RGB stars using the iterative 2σ rejection procedure described by Sarajedini & Norris (1994) applied to the combined photometry from all four WFPC2 CCDs for each cluster. These fits are shown in Fig. 5. Utilizing the relation published by Mighell et al. (1998b) for the RGB slope measured 2 magnitudes above the HB, we find \([Fe/H] = -1.08 \pm 0.12\) for NGC 2155, \([Fe/H] = -1.05 \pm 0.16\) for SL 663, and \([Fe/H] = -1.04 \pm 0.13\) for NGC 2121. Thus, all three of these clusters share approximately the same metallicity, which we take to be \([Fe/H] = -1.0\) for the isochrone comparison. These low metallicities are also a fairly strong indicator of relatively old age (see the age-metallicity relation of Olszewski et al. 1991), although there are some IACs with comparably low metallicities (Bica et al. 1998).

Figures 6 through 9 show our Planetary Camera photometry for the 5 LMC clusters of this paper and the theoretical isochrones of Bertelli et al. (1994). For the sake of completeness, Fig. 10 displays the isochrone fit to the CCD photometry of ESO121-SC03 from Mateo et al. (1996). In each figure, the isochrones have been shifted vertically by matching the magnitude of the red HB clump and horizontally by matching the location of the unevolved main sequence below the turnoff. This approach eliminates the need to rely on the integrity of the photometric zeropoints, the reddening, and the distance to the LMC as well as reducing the influence of various theoretical uncertainties in the models (e.g. mixing length parameter, helium diffusion, opacities, etc.)

The two panels of Fig. 6 illustrate the isochrone comparisons to the photometry of NGC 2193 and Hodge 4. These clusters are believed to be among the oldest IAC; as such, knowledge of their precise ages is important in setting the upper age limit of the IAC. From the appearance of Fig. 6, we derive an age of 2.0 ± 0.2 Gyr for NGC 2193 and Hodge 4. The quoted error is our best estimate of the 1σ uncertainty inherent in this age determination. The result that both NGC 2193 and Hodge 4 have similar ages is not surprising given the comparison shown in the lower panel of Fig. 1. In contrast to these results, the work of Geisler et al. (1997) indicates that their oldest IAC (Hodge 4) has an age of ~3 Gyr, while NGC 2193 is given an age of 2.3 Gyr. The higher-quality HST data presented herein has allowed us to revise these ages downward somewhat. Our upper age limit for the IAC agrees with that of Bomans et al. (1995), who performed isochrone fits to 17 such clusters. They find that the oldest cluster in their sample is NGC 1978 with an age of 2.2 Gyr. Hodge 4 and NGC 2193 are assigned ages of 2.0 Gyr and 1.6 Gyr, respectively. Taken together, the evidence suggests that 2.2 Gyr is a good estimate for the age of the oldest IAC. However, to be conservative and keeping in mind the uncertainty in these ages, we adopt 2.5 Gyr as the boundary between the age of the oldest IAC and the onset of the age gap.

The two panels of Figs. 7, 8, and 9 show the isochrone comparisons to NGC 2155, SL 633, and NGC 2121, respectively. In all cases, the Z=0.001 isochrones are displayed in the upper panel, while the Z=0.004 isochrones are included in the lower panel. Recall that our metallicity
determination indicated that $[Fe/H] \sim -1.0$ for these clusters. As a result, we show comparisons to both metallicities with the intention of interpolating between them. Based on the position of the main sequence turnoff (MSTO) and the subgiant branch, we infer an age of 4.5 Gyr from the $Z=0.001$ isochrones and 3.5 Gyr from the $Z=0.004$ isochrones. Taking the mean of these values, we conclude that NGC 2155, SL 633, and NGC 2121 all have ages of $4.0 \pm 0.3$, where, again we have attempted to estimate the 1\(\sigma\) uncertainty. As a result, it appears as though these three clusters have ages which are older than the oldest known IAC; this places them squarely in the LMC age gap. We point out however that if the metal abundances of these clusters are in reality higher than we have estimated herein, their ages will be correspondingly younger, as evidenced by the $Z=0.004$ isochrone fits. We return to the implications of this possibility in Sec. 5.

We now seek to establish the age of ESO121-SC03 based on the same techniques utilized above for the other clusters. From the slope of the cluster RGB measured from the RGB fit calculated by Sarajedini et al. (1995), we find $[Fe/H] = -1.01 \pm 0.15$. This is in good agreement with $[Fe/H] = -0.93 \pm 0.1$ determined by Olszewski et al. (1991) from Calcium triplet spectroscopy of 3 stars. Thus, we compare the photometry of ESO121-SC03 to isochrones with abundances that bracket this value and interpolate between them to estimate the cluster age. Figure 10 shows such a comparison; from the appearance of this figure, we infer an age of 11 Gyr from the $Z=0.001$ isochrones and 8 Gyr from the $Z=0.004$ isochrones. Taking the mean of these values results in an age of $9.5 \pm 0.5$ Gyr (estimated 1\(\sigma\) error). This is in excellent agreement with the results of several previous investigators (e.g. Geisler et al. 1997; Mateo et al. 1986).

4.2. $\delta V$ Ages

Another method at our disposal is to estimate the cluster ages via morphological indicators in the CMD as formulated by Phelps et al. (1994). They define the ‘MSTO’ magnitude as the point midway between the bluest point of the actual MSTO and the base of the RGB. The difference in magnitude between this point and the red HB clump is designated by $\delta V$. They also define the difference in color ($\delta(B-V)1$) between the MSTO and the point on the lower RGB located one magnitude above the MSTO. Using an empirically derived equation ($\delta V = 3.77 - 3.75 \times \delta(B-V)1$), they convert the measured $\delta(B-V)1$ values to $\delta V$. The resulting quantity is combined with $\delta V$ to create a mean morphological age indicator designated by $\langle \delta V \rangle$.

Following the methods described by Phelps et al. (1994), we have computed $\langle \delta V \rangle$ for the 6 LMC clusters in this paper. The results are shown in Table 2. Janes & Phelps (1994) discuss the use of this $\langle \delta V \rangle$ parameter to estimate ages. They combine $\langle \delta V \rangle$ values for 26 open clusters and 39 Galactic globular clusters to parameterize age as a function of $\langle \delta V \rangle$ ($\text{Age} = 0.73 \times 10^{(0.256\langle \delta V \rangle+0.0662\langle \delta V \rangle^2)}$. We have applied this relationship to our $\langle \delta V \rangle$ values to arrive at the ages listed in column 4 of Table 3. Janes & Phelps (1994) caution that their formulation is most reliable when used in a relative sense and should not be trusted to yield precise absolute ages. Thus, it is of interest to investigate the offset between the $\langle \delta V \rangle$ ages and those estimated...
from isochrone fitting. Column 5 of Table 2 lists these age differences. The mean of the differences is $1.05 \pm 0.09$ Gyr. The small error associated with this value suggests that the relative ages as derived from the two methods are highly robust. Therefore, because the $\langle \delta V \rangle$ ages have an uncertainty in their zeropoint, for the remainder of this paper, we adopt the cluster ages as given by the isochrone comparisons.

### 4.3. Comparison With Previous Results

We begin by noting that there is very little previous work on the properties of the cluster SL663. Elson & Fall (1988) quote an age of $2.2 \pm 0.4$ Gyr based on an unpublished CMD from Mario Mateo. Aside from its position on the sky, no other information exists in the literature for SL663.

The situation is marginally better for the cluster NGC 2155. Searle et al. (1980) classify it as an SWB type VI cluster based on its location in the integrated light $Q(ugr)$ vs $Q(vgr)$ diagram. Elson & Fall (1988), again quoting an unpublished CMD from Mario Mateo, list an age of $2.5 \pm 0.6$ Gyr. Olszewski et al. (1996) prefer an age of 3.5 Gyr for NGC 2155. The sole published CMD for NGC 2155 is that of Hesser et al. (1976) which is based on photographic plates and is not transformed to magnitudes on a standard photometric system. As a result, the current utility of this diagram is questionable. Metallicity measurements for NGC 2155 range from $[Fe/H] = -0.55$ (Olszewski et al. 1991) to $[Fe/H] = -1.2 \pm 0.2$ (Bica et al. 1986), although the former has generally been preferred in previous work since it is based on Calcium triplet spectroscopy of individual stars (albeit only 3) whereas the latter is based on integrated DDO photometry. We return to this point below.

Lastly, NGC 2121 has received considerable attention in previous studies. Like NGC 2155, Searle et al. (1980) classified NGC 2121 as an SWB type VI cluster. The photographic CMD presented by Flower et al. (1983) reveals a cluster with an age of 2.0 Gyr (Geisler et al. 1997). Metallicity measurements for NGC 2121 include $[Fe/H] = -0.95 \pm 0.4$ (Cohen 1982; Fe, Ca, Na, and Mg line widths for two stars), $[Fe/H] = -0.75 \pm 0.25$ (Bica et al. 1986; integrated DDO photometry), $[Fe/H] = -0.61$ (Olszewski et al. 1991; Calcium triplet spectra for two stars), and $[Fe/H] = -0.10 \pm 0.21$ (de Freitas Pacheco et al. 1998; integrated-light spectral indices).

The Calcium triplet metallicities published by Olszewski et al. (1991) have received general acceptance in the literature. They are thought to be relatively reliable. However, Bica et al. (1998) have found that the metallicities published by Olszewski et al. (1991) for IACs of similar age to their sample are more metal-rich by $\sim 0.25$ dex. The nature of this difference is unknown and could be due to a metallicity gradient in the LMC disk (since the Bica et al. clusters are generally further out) or to a difference in the metallicity values themselves. Adding support to the latter possibility is the fact that for NGC 2155 and NGC 2121, our RGB slope analysis yields metallicities that are $\sim 0.4$ dex more metal-poor than those values quoted by Olszewski et al.
It is clear from the above discussion that the published values for the ages and metallicities of SL663, NGC 2155, and NGC 2121 span a large range. In the present paper, we have combined HST/WFPC2 photometry for 5 clusters along with ground-based CCD photometry for another to establish a robust relative age and abundance ranking for these clusters. Because these ages are based on the location of the main sequence turnoff, they should be considered the most reliable yet determined for these clusters. In addition, even though our metallicity measurements are not based on spectra for a large number of individual stars in each cluster, they are also likely to be the most reliable to date because our method has been tested previously on SMC clusters (Mighell et al. 1998b).

5. Discussion and Conclusions

The resulting relation between age and metallicity for the LMC star clusters is shown in Fig. 11. The open symbols are the ages and abundances from the work of Geisler et al. (1997) supplemented by additional clusters from Bica et al. (1998) and the values for NGC 2193, Hodge 4, and ESO121-SC03 from this paper. The filled square represents the location of our three ‘age gap’ clusters. Clearly, the clusters NGC 2155, NGC 2121, and SL 663 do indeed fall in the age gap between $\sim 2.5$ Gyr and $\sim 13$ Gyr. The reader should keep in mind, however, that if the metallicities of these clusters are higher than the values we have adopted herein, their ages will be correspondingly younger (see Sec. 4.1). As such, they may eventually be considered as belonging to the old-age tail of the IAC distribution. Future spectroscopic abundance measurements will shed more light on this.

In any event, the addition of these three clusters to the age-metallicity relation of the LMC has not eliminated the discrepancy between the cluster age distribution and that of the field stars. If there are no more clusters to be discovered in the gap, then we will require some explanation for why the clusters and the field stars exhibit such differing SFHs. However, what is more likely is that there are as yet unstudied clusters in the LMC that will further fill in the age gap. Future ground-based and HST photometric surveys may reveal more such clusters.

For the present paper, we have utilized archival HST/WFPC2 images of LMC populous clusters to show that there are at least three clusters in the LMC age gap - NGC 2155, SL663, and NGC 2121. These clusters have $[Fe/H] \sim -1.0$ and ages of $\sim 4$ Gyr. The addition of these three clusters to the LMC age-metallicity relation is the first step in reducing the significant difference between the inferred SFHs of the LMC clusters and the field stars. This strongly indicates that searches to find more clusters older than $\sim 2.5$ Gyr in the LMC are crucial to a better understanding of its global SFH.

We acknowledge fruitful conversations with Eva Grebel, Doug Geisler, and Pierre Demarque.
We are grateful to Eva Grebel and Gary Da Costa for a careful reading of this manuscript as well as the referee, Doug Geisler, whose comments greatly improved the quality of this work. Ata Sarajedini would like to express his gratitude to UCO/Lick Obs. for kind hospitality during his visit. Ata Sarajedini was supported by the National Aeronautics and Space Administration (NASA) grant number HF-01077.01-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Alves, D., & Sarajedini, A. 1998, in preparation

Biretta, J. 1995, in Calibrating Hubble Space Telescope: Post Servicing Mission, Edited by A. Koratkar & C. Leitherer (STScI:Baltimore) p. 257

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275

Bertelli, G., Mateo, M., Chiosi, C., & Bressan. A. 1992, ApJ, 388, 400

Bica, E., Dottori, H., & Pastoriza, M. 1986, A&A, 156, 261

Bica, E., Geisler, D., Dottori, H, Clariá, J. J., Piatti, A. E., & Santos, Jr., J. F. C. 1998, astro-ph/9803167

Bomans, D., Vallenari, A., & de Boer, K. S. 1994, A&A, 298, 427

Burstein, D. & Heiles, C. 1982, AJ, 87, 1165

Cohen, J. G. 1982, ApJ, 258, 143

Da Costa, G. S. 1991, in The Magellanic Clouds, eds. R. Haynes & D. Milne (Dordrecht:Reidel), 183

Da Costa, G. S. 1997, in Stellar Astrophysics for the Local Group: A First Step to the Universe, edited by A. Aparicio & A. Herrero (Cambridge University Press: Cambridge), in press

Da Costa, G. S., & Hatzidimitriou, D. 1998, in press

Da Costa, G. S., King, C. R., & Mould, J. R. 1987, ApJ, 321, 735

Elson, R. A. W., & Fall, S. M. 1988, AJ, 96, 1383

de Freitas Pacheco, J. A., Barbuy, B., & Idiart, T. 1998, A&A, 332, 19

Flower, P., Geisler, D., Hodge, P., Olszewski, E., & Schommer, R. 1983, ApJ, 265, 15

Gallagher, J. S. et al. 1996, ApJ, 466, 732
Geha, M. C. et al. 1998, AJ, 115, 1045

Geisler, D., Bica, E., Dottori, H., Clariá, J. J., Piatti, A. E., & Santos, J. F. C. 1997, AJ, 114, 1920

Grebel, E. 1997, in Review of Modern Astronomy, edited by R. E. Schielicke, in press

Hesser, J. E., Hartwick, F. D. A., & Ugarte, P. 1976, ApJS, 32, 283

Holtzman, J. A. et al. 1995, PASP, 107, 1065

Holtzman, J. A., Mould, J. R., Gallagher, J. S., III, Watson, A. M., & Grillmair, C. J. 1997, AJ, 113, 656

Janes, K. A., & Phelps, R. L. 1994, AJ, 108, 1773

Kontizas, M., Morgan, D. H., Hatzidimitriou, D., & Kontizas, E. 1990, A&AS, 84, 527

Mateo, M., & Hodge, P. 1986, ApJS, 60, 893

Mateo, M., Hodge, P., Schommer, R. A. 1986, ApJ, 311, 113

Mighell, K. J., Sarajedini, A., & French, R. S. 1998a, ApJ, 494, L189

Mighell, K. J., Sarajedini, A., & French, R. S. 1998b, in preparation

Olszewski, E. W. 1993, in The Globular Cluster - Galaxy Connection, ASP Conf. Ser. No. 48, edited by G. H. Smith & J. P. Brodie (ASP:San Francisco), p. 351

Olszewski, E. W., Schommer, R. A., Suntzeff, N., & Harris, H. 1991, AJ, 101, 515

Olszewski, E. W., Suntzeff, N., & Mateo, M. 1996, ARA&A, 34, 511

Phelps, R. L., Janes, K. A., & Montgomery, K. A. 1994, AJ, 107, 1079

Sarajedini, A. & Norris, J. E. 1994, ApJS, 93, 161

Sarajedini, A., Lee, Y. -W., Lee, D. -H. 1995, ApJ, 450, 712

Searle, L., Wilkinson, A., & Bagnuolo, W. G. 1980, ApJ, 239, 803

Stetson, P. B. 1994, PASP, 106, 250

Vallenari, A., Chiosi, C., Bertelli, G., Aparicio, A., & Ortolani, S. 1996, A&A, 309, 367

Zinn, R. J. & West, M. J. 1984, ApJS, 55, 45
Fig. 1.— The upper panel shows the color-magnitude diagram for NGC 2193 from HST/WFPC2 from the present work (open circles) and the ground-based study of Da Costa et al. (1987; X’s). The latter have been converted from $B - R$ to $B - V$ using the equation derived by Mighell et al. (1998a). Note the good agreement between the two datasets. The lower panel compares the NGC 2193 photometry from the upper panel (open circles) with our HST/WFPC2 photometry for SL 556 (Hodge 4; X’s). The latter has been shifted by +0.05 in $B - V$ to match the location of the NGC 2193 red HB clump. Note that these two clusters are almost identical in age (main sequence turnoffs coincide) and metallicity (red giant branches coincide).

Fig. 2.— Color-magnitude diagrams for NGC 2155 for each individual WFPC2 CCD chip.

Fig. 3.— Color-magnitude diagrams for SL 663 for each individual WFPC2 CCD chip.

Fig. 4.— Color-magnitude diagrams for NGC 2121 for each individual WFPC2 CCD chip.

Fig. 5.— The red giant branch (RGB) polynomial fits used to estimate the slope of the RGB, which is then utilized to measure the cluster metallicity.

Fig. 6.— Comparison of theoretical isochrones with the Planetary Camera photometry for NGC 2193 and Hodge 4. We have adopted a metallicity of $[\text{Fe/H}] = -0.7$ for these clusters. The isochrones have been shifted vertically by matching the magnitude of the red HB clump and horizontally by matching the location of the unevolved main sequence below the turnoff. The isochrone fits yield an age of 2.0 Gyr for both of these clusters.

Fig. 7.— Same as Fig. 6 except that we plot the Planetary Camera photometry for NGC 2155 and include isochrones for two metallicity values that bracket the abundance of the cluster. A mean age of $4.0 \pm 0.3$ Gyr is indicated by these comparisons.

Fig. 8.— Same as Fig. 7 except that the Planetary Camera photometry for SL 663 is shown.

Fig. 9.— Same as Fig. 7 except that the Planetary Camera photometry for NGC 2121 is shown.

Fig. 10.— Same as Fig. 7 except that the ground-based CCD photometry for ESO121-SC03 (Mateo et al. 1986) is shown. A mean age of $9.5 \pm 0.5$ Gyr is indicated by these comparisons.

Fig. 11.— The relation between age and metallicity for LMC populous clusters. The open circles are data from Geisler et al. (1997) and Bica et al. (1998) supplemented by our determinations for NGC 2193, Hodge 4, and ESO121-SC03, while the filled square represents the location of the three ‘age gap’ clusters, NGC 2155, SL 663, and NGC 2121.
Figure 2 - Sarajedini
Figure 3 - Sarajedini
Figure 5 -
Sarajedini
NGC 2193
$Z = 0.004$
1.6, 2.0, 2.5 Gyr

SL556 (Hodge 4)
$Z = 0.004$
1.6, 2.0, 2.5 Gyr

Figure 6 - Sarajedini
NGC 2155  PC1
Z = 0.001
3.2, 4.0, 5.0 Gyr

NGC 2155  PC1
Z = 0.004
3.2, 4.0, 5.0 Gyr

Figure 7 - Sarajedini
SL 663 PC1
Z = 0.001
3.2, 4.0, 5.0 Gyr

Figure 8 - Sarajedini
Figure 9 - Sarajedini

NGC 2121 PC1
\[ Z = 0.001 \]
\[ 3.2, 4.0, 5.0 \text{ Gyr} \]

NGC 2121 PC1
\[ Z = 0.004 \]
\[ 3.2, 4.0, 5.0 \text{ Gyr} \]
Figure 10 -

Sarajedini

ESO121-SC03
$Z = 0.001$
8, 10, 12 Gyr

ESO121-SC03
$Z = 0.004$
6.3, 8, 10 Gyr
Figure 11 - Sarajedini

![Graph showing data points for NGC 2155, SL 663, and NGC 2121, with [Fe/H] on the y-axis and Log Age on the x-axis.]

NGC 2155
SL 663
NGC 2121
### Table 1. Journal of Observations

| Target       | Date        | Dataset     | α(J2000) | δ(J2000) | Filter  | Exp. Time |
|--------------|-------------|-------------|----------|----------|---------|-----------|
| NGC 2193     | 1994 Jan 30 | U26M0P01T   | 6° 06′ 17″ | -65° 05′ 57″ | F450W   | 230s      |
| NGC 2193     | 1994 Jan 30 | U26M0P02T   | 6° 06′ 17″ | -65° 05′ 57″ | F555W   | 120s      |
| SL556 (Hodge 4) | 1994 Feb 4 | U26M0O01T   | 5° 32′ 26″ | -64° 44′ 11″ | F450W   | 230s      |
| SL556 (Hodge 4) | 1994 Feb 4 | U26M0O02T   | 5° 32′ 26″ | -64° 44′ 11″ | F555W   | 120s      |
| NGC 2155     | 1994 Feb 1  | U26M0K01T   | 5° 58′ 33″ | -65° 28′ 45″ | F450W   | 230s      |
| NGC 2155     | 1994 Feb 1  | U26M0K02T   | 5° 58′ 33″ | -65° 28′ 45″ | F555W   | 120s      |
| SL 663       | 1994 Feb 1  | U26M0L01T   | 5° 42′ 30″ | -65° 21′ 49″ | F450W   | 230s      |
| SL 663       | 1994 Feb 1  | U26M0L02T   | 5° 42′ 30″ | -65° 21′ 49″ | F555W   | 120s      |
| NGC 2121     | 1994 Feb 2  | U26M0X01T   | 5° 48′ 13″ | -71° 28′ 46″ | F450W   | 230s      |
| NGC 2121     | 1994 Feb 2  | U26M0X02T   | 5° 48′ 13″ | -71° 28′ 46″ | F555W   | 120s      |

### Table 2. Cluster Ages

| Cluster       | Isochrone Age (Gyr) | ⟨δV⟩ | ⟨δV⟩ Age (Gyr) | Difference |
|---------------|---------------------|------|----------------|------------|
| NGC 2193      | 2.0                 | 1.66 | 3.0            | +1.0       |
| Hodge 4       | 2.0                 | 1.59 | 2.7            | +0.7       |
| NGC 2155      | 4.0                 | 2.12 | 5.1            | +1.1       |
| SL 633        | 4.0                 | 2.18 | 5.4            | +1.4       |
| NGC 2121      | 4.0                 | 2.11 | 5.0            | +1.0       |
| ESO121-SC03   | 9.5                 | 2.68 | 10.6           | +1.1       |