THE ASTRONOMICAL JOURNAL, 115:1778–1790, 1998 May

DEEP *HUBBLE SPACE TELESCOPE* OBSERVATIONS OF STAR CLUSTERS IN NGC 1275[1]

MATTHEW N. CARLSON,[2] JON A. HOLTZMAN,[2] ALAN M. WATSON,[3] CARL J. GRILLMAIR,[4] JEREMY R. MOULD,[5] GILDA E. BALLESTER,[6] CHRISTOPHER J. BURROWS,[7] JOHN T. CLARKE,[6] DAVID CRISP,[4] ROBIN W. EVANS,[4] JOHN S. GALLAGHER III,[8] RICHARD E. GRIFFITHS,[9] J. JEFF HESTER,[10] JOHN G. HOESSEL,[8] PAUL A. SCOWEN,[10] KARL R. STAPELFELDT,[4] JOHN T. TRAUGER,[4] AND JAMES A. WESTPHAL[11]

Received 1997 November 17; revised 1998 January 22

ABSTRACT

We present an analysis of compact star clusters in deep *Hubble Space Telescope* Wide Field Planetary Camera 2 images of NGC 1275. *B*- and *R*-band photometry of roughly 3000 clusters shows a bimodality in the $B-R$ colors, suggesting that distinct old and young cluster populations are present. The small spread in the colors of the blue clusters is consistent with the hypothesis that they are a single-age population, with an inferred age of 0.1 to 1 Gyr. The luminosity function shows increasing numbers of blue clusters to the limit of our photometry, which reaches several magnitudes past the turnover predicted if the cluster population is identical to current Galactic globular clusters seen at a younger age. The blue clusters have a spatial distribution that is more centrally peaked than that of the red clusters. The individual clusters are slightly resolved, with core radii $\lesssim 0.75$ pc if they have modified Hubble profiles. We estimate the specific frequencies of the old and young populations and discuss the uncertainties in these estimates. We find that the specific frequency of the young population in NGC 1275 is currently larger than that of the old population and will remain so as the young population evolves, even if the majority of the low-mass clusters are eventually destroyed. If the young population formed during a previous merger, this suggests that mergers can increase the specific frequency of globular clusters in a galaxy. However, the presently observed young population likely contains too few clusters to have a significant impact on the overall specific frequency as it will be observed in the future.

Key words: galaxies: active — galaxies: star clusters

1. INTRODUCTION

Early *Hubble Space Telescope* (*HST*) observations of NGC 1275, the central galaxy in the Perseus Cluster, revealed a population of about 60 blue ($V-R \sim 0.3$) star clusters surrounding the nucleus (Holtzman et al. 1992). The color of these clusters suggests an age of roughly 300 million years based on the models of Charlot & Bruzual (1991). Spectra of the brightest object (Zepf et al. 1995) also suggest an age of 0.1 to 0.9 Gyr, based on a comparison of the observed line widths with those predicted by the models of Bruzual & Charlot (1993). None of the clusters seem to have Hα emission, with the exception of one object found by Shields & Filippenko (1990), which appears to be a much younger object. The blue clusters in the original Wide-Field/Planetary Camera 1 (WF/PC-1) images appear unresolved, suggesting sizes of less than 15 pc. The brightest object has $V = 18.9$, which corresponds to $M_V = -15.8$ for $H_0 = 75$ km s^{-1} Mpc^{-1} and $cz = 5264$ km s^{-1} (Strauss et al. 1992). The brightnesses of the blue clusters suggest masses of between 2×10^4 and 1×10^8 $M_\odot$, depending on the assumed age and distance, if one assumes that the objects are star clusters with a Salpeter initial mass function (IMF). The observed sizes, luminosities, and the estimated masses suggest that these objects may be young analogs of globular clusters.

In the past several years, massive young clusters have been observed in a variety of other galaxies. Lutz (1991) detected young globular cluster candidates in a ground-based study of the merger remnant NGC 3597, and these have been confirmed to be compact by *HST* observations (Holtzman et al. 1996). Candidate young globular clusters have also been found in other interacting systems, including NGC 7252 (Whitmore et al. 1993), NGC 4038/4039 (Whitmore & Schweizer 1995), and NGC 3921 (Schweizer et al. 1996), among others. A few massive clusters are seen in the starburst galaxy NGC 253 (Watson et al. 1996), while others have been detected in the ring galaxies NGC 1097 and NGC 6951 (Barth et al. 1995) and the dwarf galaxies

[1] Based on observations 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, Inc., under NASA contract NAS 5-26555.

[2] Department of Astronomy, New Mexico State University, Department 4500, P.O. Box 30001, Las Cruces, NM 88003; mcarlson@nmsu.edu, holtz@nmsu.edu.

[3] Instituto de Astronomía, Universidad Nacional Autónoma de México, J. J. Tablada 1006, Col. Lomas de Santa Maria, 58090 Morelia, Michoacán, Mexico; alan@astrosmo.unam.mx.

[4] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; carl@wfpc2-mail.jpl.nasa.gov, dc@crispy.jpl.nasa.gov, rwe@wfpc2-mail.jpl.nasa.gov, krs@wfpc2-mail.jpl.nasa.gov, jtt@wfpc2-mail.jpl.nasa.gov.

[5] Mount Stromlo and Siding Spring Observatories, Australian National University, Private Bag, Weston Creek, ACT 2611, Australia; jrm@mso.anu.edu.au.

[6] Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, 2455 Hayward Street, Ann Arbor, MI 48109; gilda@sunshine.sprl.umich.edu, clarke@sunshine.sprl.umich.edu.

[7] Astrophysics Division, Space Science Department, European Space Agency; and Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; burrows@stsci.edu.

[8] Department of Astronomy, University of Wisconsin at Madison, 475 North Charter Street, Madison, WI 53706; jsg@tiger.astro.wisc.edu, hoessel@jth. astro.wisc.edu.

[9] Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213.

[10] Department of Physics and Astronomy, Arizona State University, Tyler Mall, Tempe, AZ 85287; jjh@cosmos.la.asu.edu, scowen@tycho.la.asu.edu.

[11] Division of Geological and Planetary Sciences, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125; jaw@sol1.gps.caltech.edu.

NGC 1569, NGC 1705 (O'Connell, Gallagher, & Hunter 1994), and He 2-10 (Conti & Vacca 1994). While no generally accepted picture has emerged as to what conditions lead to the formation of young clusters, galaxy interactions appear to be an important component.

It is particularly difficult to determine the precise mechanism responsible for the presence of these objects in NGC 1275 because of the myriad peculiarities of this galaxy, including the presence of a significant amount of dust, streamers of Hα emission, an active nucleus, and the location of the galaxy at the center of a cooling flow in the Perseus Cluster. Two hypotheses have been offered for the origin of these clusters, namely, that they were formed from the substantial mass deposition of the Perseus Cluster cooling flow (200 $M_\odot$ yr^{-1}), or that the cluster formation was triggered by a galaxy-galaxy interaction. Holtzman et al. (1992) preferred the latter hypothesis, based on the observed lack of spread in the WF/PC-1 colors (which implies a common age for the objects) and the appearance of a ripple in the galaxy light that suggests that a previous interaction may have occurred. Richer et al. (1993) found larger color spreads in high-resolution CFHT images and preferred the cooling-flow hypothesis. However, Holtzman et al. (1996) did not detect young clusters in three of a sample of four other cooling-flow galaxies; the central cluster galaxy in Abell 1795 may have a few clusters, but it also has a peculiar morphology that suggests a previous interaction.

The merger hypothesis is particularly interesting in light of the theory that elliptical galaxies form through mergers and the observation that ellipticals have higher specific frequencies of globular clusters than spirals, where the specific frequency is a measure of the number of globular clusters per unit luminosity of the host galaxy. Ashman & Zepf (1992) investigated the proposition that clusters might form during mergers and suggest that, in such an event, cluster formation would occur in a brief burst, resulting in a set of newly formed clusters with a common age and color. This would lead to a cluster system with a bimodal distribution of cluster colors reflecting the difference in metallicity or age (or both) between the original and the newly formed clusters. They predict that the spatial distribution of the younger clusters would be more sharply peaked toward the center of the galaxy than that of the old cluster system, because the old globular cluster populations of the two progenitor galaxies would remain spatially extended and would probably be dynamically heated during the merger, while the new clusters would be formed out of gas that becomes more centrally concentrated during a merger. However, as Harris, Pritchet, & McClure (1995) note, an increase in specific frequency as a result of a merger requires not only that globular clusters form during such an event, but that they form *preferentially* over noncluster stars, as compared with the ratio of clusters to background stars in the progenitor galaxies.

Few estimates of the specific frequency of these young cluster systems exist. Watson et al. (1996) suggest that the four young clusters in NGC 253 most likely have formed with a large specific frequency. In the merger remnant NGC 3921, Schweizer et al. (1996) find that the blue clusters will increase the overall number of clusters enough that the galaxy will come to have the specific frequency of an elliptical within 7 Gyr. Miller et al. (1997) find that the specific frequency of globular clusters in the merger remnant NGC 7252 will rise over the next 15 Gyr as the background population fades to resemble that of an elliptical. These results all suggest that interactions can increase the specific frequency in a galaxy.

Luminosity functions of old globular cluster systems have been well studied and used as a part of the extragalactic distance scale because of their uniformity from galaxy to galaxy; they are roughly Gaussian in shape with a peak near $M_V = -7.3$ (Harris 1996). The luminosity functions of most of the recently discovered young cluster systems are poorly determined, because of either small number statistics (few young clusters in the galaxy) or incompleteness. A notable exception is the young cluster system in NGC 4038/4039, which shows no turnover to 2 mag fainter than the turnover predicted for a typical old cluster system, even after allowing for the expected fading of the clusters based on stellar population models. Based on this, van den Bergh (1995) argued that this cluster system may be intrinsically different from old globular cluster systems. However, Mateo (1993) notes that, at least in the LMC, the observed increasing cluster luminosity function is well modeled by a combination of globular and open clusters. Also, several authors have recently suggested that substantial numbers of clusters may be destroyed over a Hubble time (Gnedin & Ostriker 1997; Elmegreen & Efremov 1997); mechanisms include evaporation and tidal disruption by galactic bulges and disks.

We have obtained Wide Field Planetary Camera 2 (WFPC2) images of NGC 1275 that go about 4 mag deeper (in the red) than the WF/PC-1 observations of Holtzman et al. (1992). These observations provide more accurate colors than previous observations and probe the cluster population to approximately 2.5 mag fainter than the turnover expected if this population is identical to the Galactic globular cluster system seen at a younger age.

Section 2 briefly summarizes the observations and the reductions. Section 3 discusses our analysis and potential sources of error. In § 4, we present our results, including the photometry, luminosity function of the clusters, surface density distribution, an estimate of the specific frequency, and analysis of the sizes of the objects.

2. OBSERVATIONS AND DATA REDUCTION

Observations of NGC 1275 were made with the WFPC2 on 1995 November 16 in the F450W and F702W filters. Exposure times in F450W were 200, 1000, and 3 × 1300 s. In F702W the exposures were 200, 900, 1000, and 2 × 1300 s. The F450W and F702W filters are roughly similar to broadband *B* and *R* filters.

The data were reduced using the procedures discussed by Holtzman et al. (1995b). The individual exposures were all taken with a common pointing, and the frames in each color were combined. Cosmic rays were rejected in the averaging based on the expected variance from photon statistics and readout noise; an extra term that was proportional to the signal in the pixel was included in the expected variance to allow for small pointing differences between frames.

3. ANALYSIS

Combined color images of NGC 1275 in the PC and in the WFPC2 fields are shown in Figures 1*a* and 1*b*, respectively. The nucleus is in the center of the PC, and the other

FIG. 1*a*

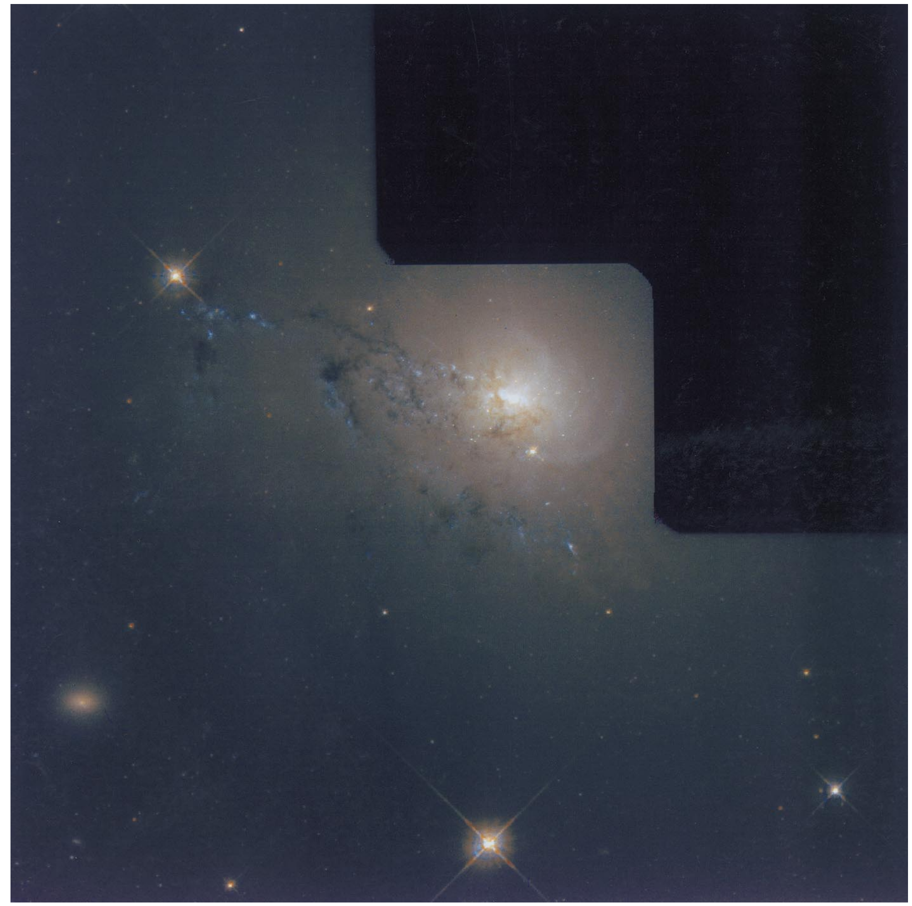

FIG. 1*b*

FIG. 1.—(*a*) PC image of NGC 1275; (*b*) WFPC2 image of NGC 1275

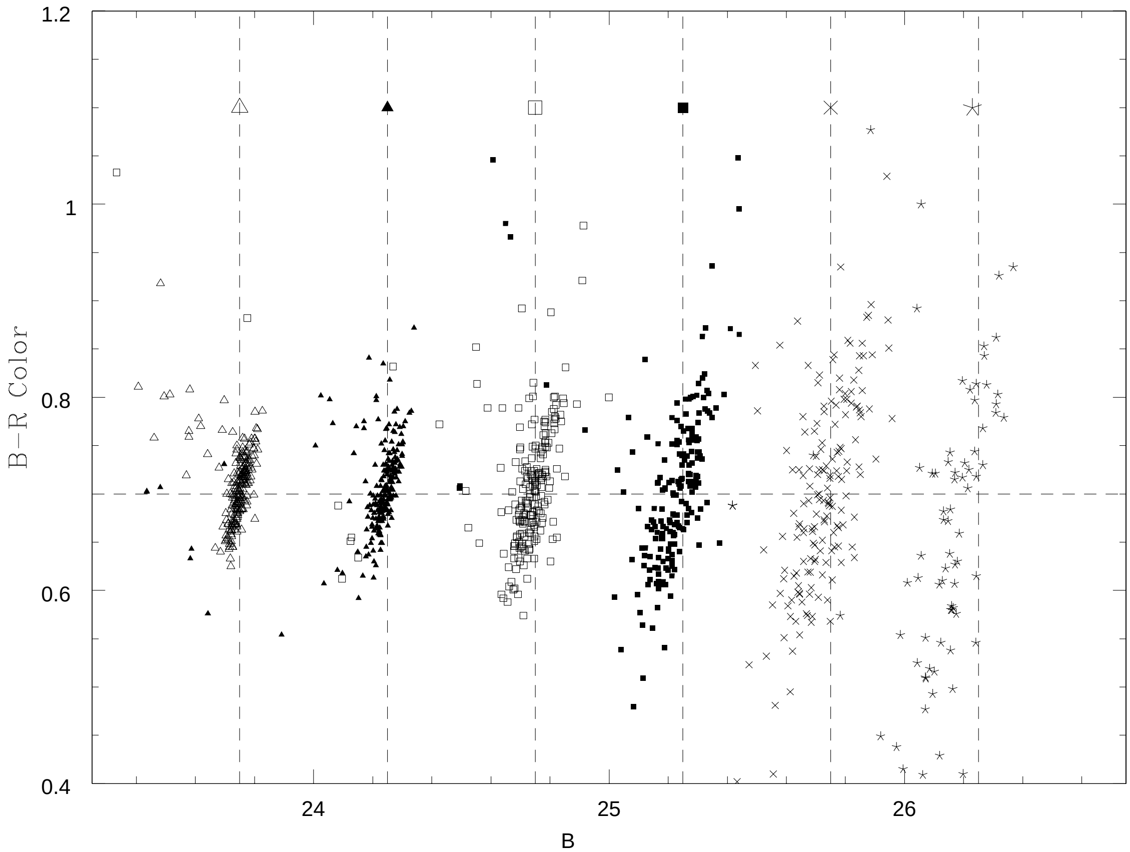

FIG. 2.—Scatter in measured magnitudes of artificial stars. The simulated stars were given a $B-R$ of 0.7. Vertical dashed lines represent the input magnitudes for all artificial clusters of a given point type. Only clusters in the southwest corner of the image with errors less than 0.15 mag in B and R are shown, to simplify comparison with Fig. 4*b*.

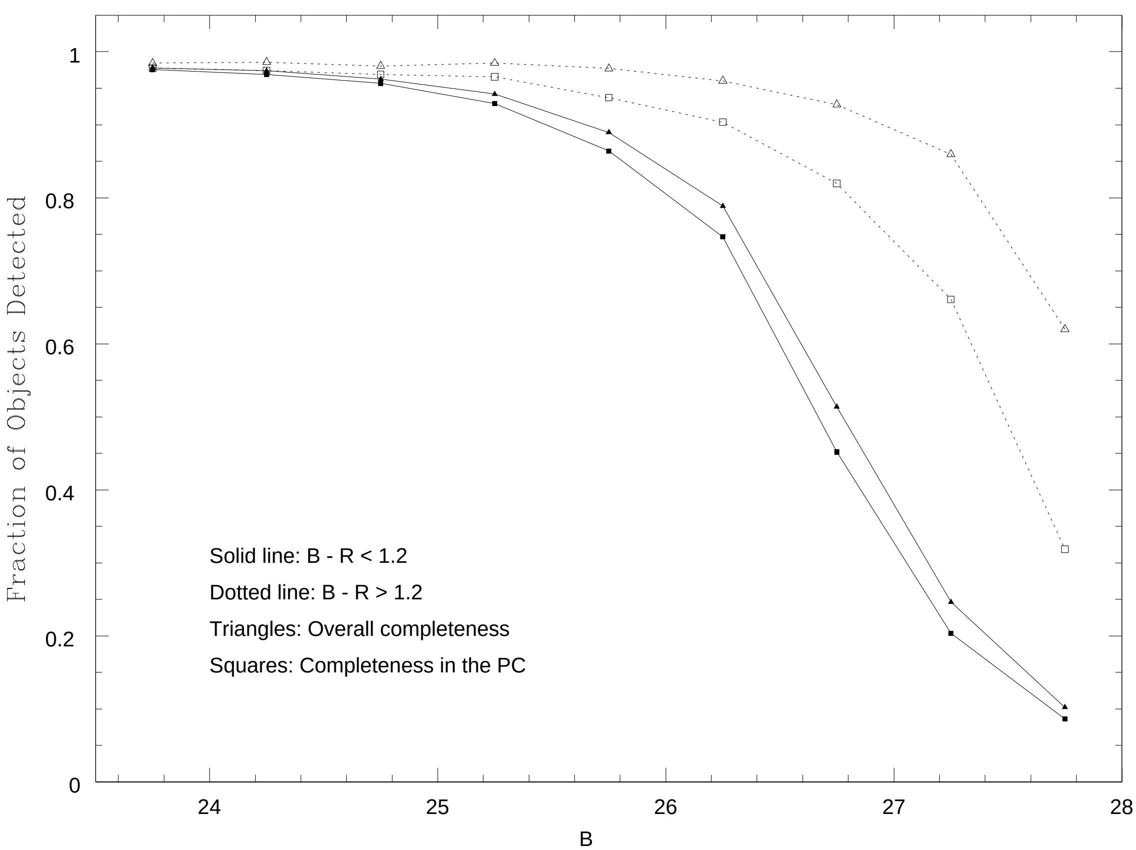

FIG. 3.—Completeness as a function of B magnitude for the clusters in the PC frame and in the whole image (weighted by the distribution of clusters). Blue and red clusters are shown separately.

bright point source in the PC is a foreground F star (Hughes & Robson 1991). Almost all of the remaining point sources are candidate star clusters in NGC 1275.

To detect the compact clusters, we summed the two colors and subtracted a 5×5 boxcar–smoothed version of this image. We divided this by the square root of the smoothed image to provide an image whose units were proportional to the local noise (assuming the noise is dominated by the background, as is the case here). We then used IRAF's DAOFIND to detect objects on the resulting image, in order to provide a uniform detection threshold in signal-to-noise ratio across the image. The choice of detection threshold was determined by minimizing the number of spurious detections and maximizing the number of faint objects detected, judging from a visual inspection. Objects were filtered by shape, based on roundness and sharpness criteria computed by DAOFIND; we required roundness between -1 and 1 and sharpness between 0.2 and 1. Several areas of the frame were masked out, including the galaxy nucleus, the bright saturated star in the PC, and a few bright stars and galaxies in the WFs.

Aperture photometry was performed using a 1 pixel–radius aperture in both the PC and the WFs. The small aperture was used to reduce background-related errors, which are large in the central region of the galaxy. Sky values were determined by taking an estimate of the mode in a background annulus; in the PC, the annulus was 2 pixels wide with an inner radius of 12 pixels, while in each WF the corresponding annulus was 3 pixels wide with an inner radius of 6 pixels. We chose to use small sky annuli because the galaxy background is variable on small scales.

Corrections from 1 pixel aperture flux to flux within $0\farcs5$ were determined from the nine brightest sources. The average aperture corrections were 1.03 and 1.15 mag in the PC frame for F450W and F702W, respectively, and 0.63 and 0.71 mag in the WFs. These are slightly larger than the corrections for bright point sources measured by Holtzman et al. (1995b), but this is expected if these objects are slightly resolved. In the PC, measured aperture corrections varied on the order of 0.05 mag between different objects. Measured variations in the aperture corrections for the individual WFs were ~ 0.02 mag, so an average aperture correction was assumed for all three. If there is an intrinsic spread in cluster sizes, using a single-aperture correction for all objects would lead to systematic errors in the derived magnitudes. To first order, however, colors are unaffected by such a spread. The transformations from *HST* magnitudes (F450W, F702W) to Cousins magnitudes (B, R) were made using the transformations given by Holtzman et al. (1995a).

Foreground Galactic extinction in the direction of NGC 1275 was taken to be $A_B = 0.70$ (Burstein & Heiles 1984). We determined the extinction in the WFPC2 passbands by numerically integrating the product of an A star spectrum, the filter transmission, the system response, and an extinction curve from Cardelli, Clayton, & Mathis (1989), derived assuming $R_V = 3.1$. An A star was used because of its similarity to the observed spectrum of the bright clusters. This yielded $A_{\rm F450W} = 0.69$ and $A_{\rm F702W} = 0.40$. These estimates do not, however, include internal extinction, which may be important in NGC 1275, since patchy dust is evident; this is discussed further below.

Potential photometry errors include intrinsic Poisson error in the signal, error in the aperture correction, and error in the background level determination. Typical errors were estimated from the simulated clusters from our completeness tests and are shown in Figure 2. The dashed lines in color and magnitude indicate input magnitudes for the artificial clusters.

Completeness was estimated by generating simulated objects at each of nine different input magnitudes (23.75 to 27.75 in B). The simulated objects were given the same noise characteristics as real objects. In the PC, 1000 objects were placed randomly in each of three separate annuli to better model the variation of completeness with distance from the center of the galaxy. Each set of artificial clusters was given a spatial distribution that mimicked the distribution of the brightest ($B < 25$) blue and red clusters. In the WFs, the 1000 artificial objects were placed randomly in a uniform distribution. On each chip, a PSF of one of the isolated bright clusters was used to create the simulated objects (the use of other objects yielded comparable results). Two sets of artificial objects were placed to estimate the difference in detection efficiency for objects of two different colors; the two sets of simulated clusters were given $B-R = 0.7$ and $B-R = 1.6$, comparable to the colors of the observed cluster populations (see next section). The derived average completeness (weighted by the spatial distribution of the observed clusters) as a function of B magnitude is shown in Figure 3 for the whole image, as well as for the section that fell in the PC.

We estimated the number of foreground stars based on the models of Bahcall & Soneira (1980) and expect fewer than four objects with $B < 27$ in the PC. Since we expect such small numbers of foreground stars, we have neglected them.

4. RESULTS

4.1. *Photometry*

We present the photometry of all detected objects in NGC 1275 by plotting color against apparent magnitude in Figure 4*a*. Extinction-corrected absolute magnitudes and colors are shown as well, using a distance of 70.2 Mpc determined by assuming pure Hubble flow with $H_0 = 75$ km s^{-1} Mpc^{-1}. We find 1181 blue objects ($B-R < 1.1$) and 1855 red objects. Distinct red and blue populations are seen, although there is significant color scatter. Roughly 50% of the blue objects are seen in the PC, as compared with about 15% of the red objects.

These objects cannot be single stars, because they are marginally resolved and because they are too bright. With the exception of the Shields-Filippenko object, the objects lack Hα emission (Holtzman et al. 1992), which precludes their being emission-line objects. Consequently, they are probably star clusters, as supported by spectroscopy of the brightest object (Zepf et al. 1995). They are brighter and more compact than open clusters in the Galaxy; the brightest object is 250 times brighter than the brightest Galactic open cluster. Their closest analog seems to be globular clusters, although the inferred ages are much smaller (see below).

To test whether the observed color scatter is likely to be related to internal extinction within NGC 1275 and photometric errors from errors in background subtraction, we show in Figure 4*b* only clusters in the southwest half of the PC frame that have estimated photometric errors of less than 0.15 mag in both B and R. This region was chosen

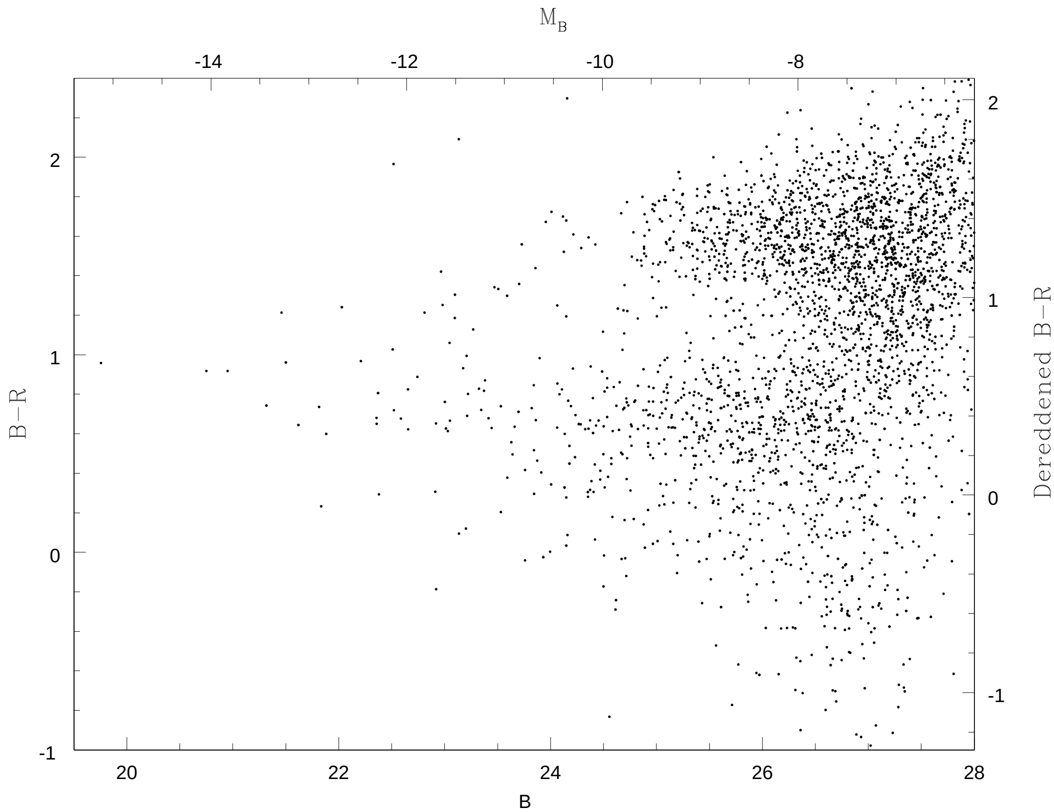

FIG. 4*a*

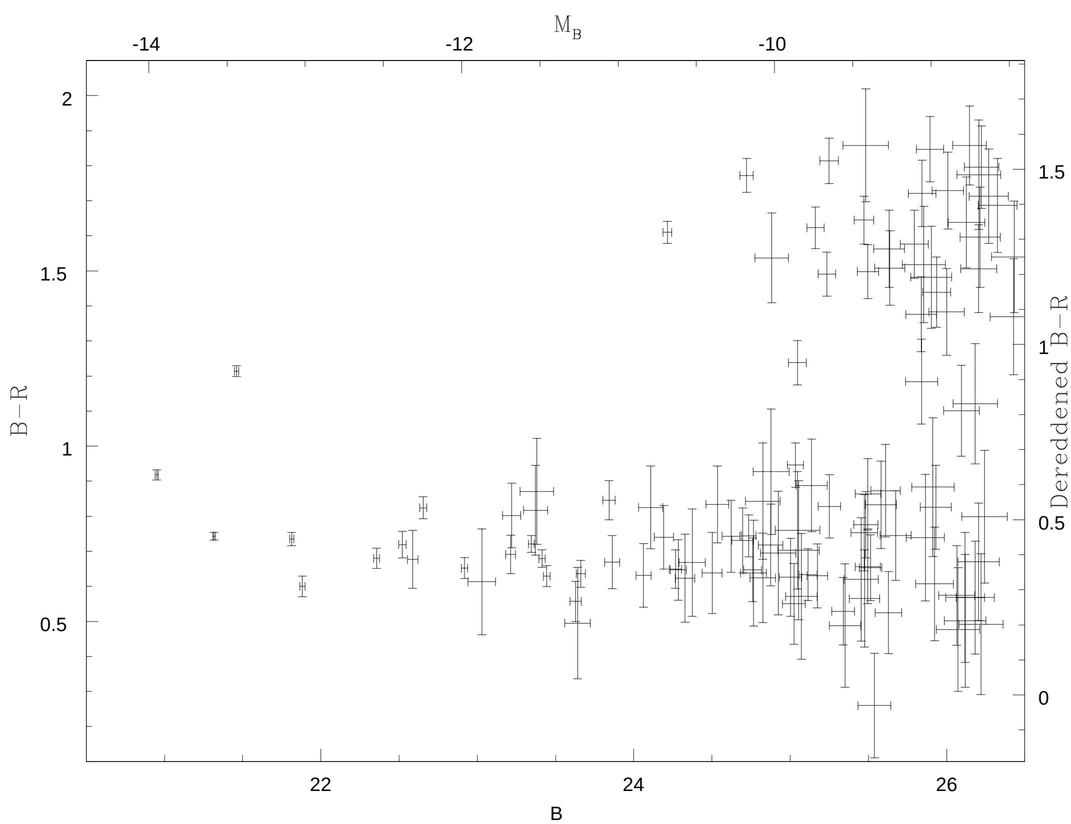

FIG. 4*b*

FIG. 4.—(*a*) $B-R$ color vs. B magnitude for all clusters in the PC and WFs; (*b*) $B-R$ color vs. B magnitude for clusters in the southwest portion of the PC frame with errors less than 0.15 mag in both B and R.

because it contains fewer obvious signatures of dust than the northeast region. In fact, we find that the spread in color among the blue objects in Figure 4*b* is consistent with that associated with photometric errors (see Fig. 2), supporting the conclusion that the observed color spread within the two populations is likely to be caused by the variation of internal extinction in the environment of the galaxy, rather than differences in age. We conclude that the blue clusters are a single-color, single-age population, with the spread in colors coming from Poisson errors and background subtraction errors. Figure 4*b* shows a distinct bimodality in the cluster population, consistent with the presence of two discrete populations.

The blue clusters have a typical dereddened $(B-R)_0 \sim 0.4$. This is much bluer than typical old globular clusters, which have $(B-R)_0 \sim 1.2$ (Harris 1996). The uniformity of the colors suggests that the clusters were formed in a single burst of relatively short duration rather than an ongoing or continuous process. Figure 5 shows the magnitude and color evolution of a single-burst population for a variety of metallicities, assuming a Salpeter IMF from 0.1 to 125 $M_\odot$ and a total mass of 1 $M_\odot$ (Bruzual & Charlot 1993). If we compare the measured colors of the blue clusters in the PC with the models, we infer ages of 10^7 to 10^9 yr, allowing for small possible systematic errors in the models and the data as well as the unknown metallicity of the objects. We note that the clusters are far too blue to be explained by a metallicity effect alone. Ages younger than 10^7 yr are ruled out by the absence of Hα emission from the clusters. Spectra of the clusters (Zepf et al. 1995) argue for a several hundred million year–old population dominated in the blue by A-type stars. It is also simply less probable that we that we should happen to observe these clusters at a younger age.

The LMC has a number of compact clusters with comparable colors (van den Bergh 1981). These objects are substantially fainter than the brightest objects in NGC 1275, implying that they are less massive. Still, observations of blue clusters in the LMC, where we can directly measure

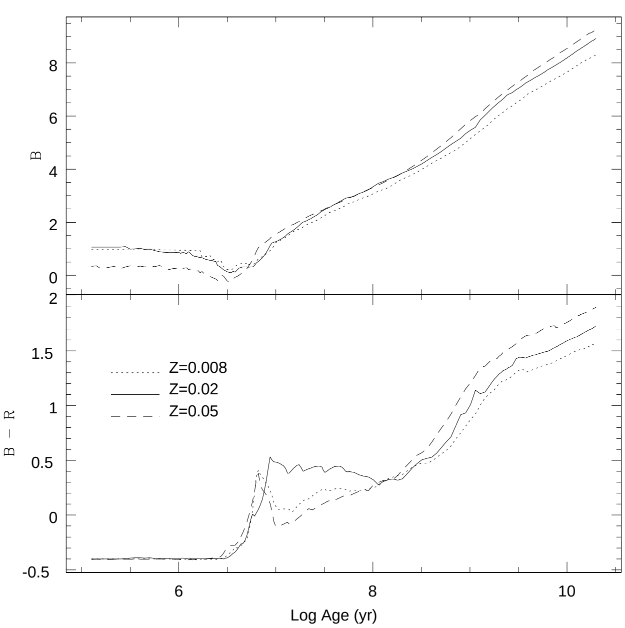

FIG. 5.—Luminosity and color evolution for a single-burst, simple stellar population from Charlot & Bruzual (1991). The luminosity is scaled to a 1 $M_\odot$ object. Evolution is shown for three different metallicities.

ages using the main-sequence turnoff in color-magnitude diagrams, provide a less model-dependent idea of the spread in colors that could be expected from a spread in ages. Figure 6 shows the distribution of $B-V$ versus age for LMC clusters; ages are from Elson & Fall (1988) and Hodge (1981, 1983), and colors from van den Bergh (1981). Between 10^8 and 10^9 yr, we see that the integrated colors of the clusters cover a range of 0.3 in $B-V$. This argues against a large spread in the ages for the NGC 1275 clusters, which show no such spread in colors. While our observations were in B and R, not B and V, the color spread in $B-R$ for the same age range would be 0.8 mag, assuming a $V-R$ versus $B-R$ relation from the population synthesis models.

Given ages, we can estimate masses for the clusters based on their luminosities. Age estimates of 10^8 and 10^9 yr yield mass estimates for the brightest object of 2×10^7 and 10^8 $M_\odot$, respectively. Blue clusters at our completeness limit of $B = 27$ have masses of 2×10^4 to 10^5 $M_\odot$. These masses are very comparable with those of Milky Way globular clusters, which typically have masses between 10^4 and 3×10^6 $M_\odot$, with a handful of clusters with $M < 10^4$ $M_\odot$ (Mandushev, Spassova, & Staneva 1991; Pryor & Meylan 1993). Our mass estimates depend on the assumption of a Salpeter IMF.

Two of the three brightest objects in the southwest half of the PC (Fig. 4*b*) have much redder colors than the rest of the blue clusters ($B-R$ of 0.95 and 1.23). While these objects are close to the nucleus, they are bright enough that errors in determining the galaxy background are not a large source of error. Possible explanations are reddening by dust, a younger age (slightly less than 10^7 yr old) when the integrated light is dominated by red supergiants (Leitherer & Heckman 1995), and the identification of these objects with late-type foreground stars. For the redder object, the last interpretation is supported by our measurement of sizes (§ 4.5), since it appears to be unresolved while almost all other objects appear marginally resolved.

We suggest that the objects with $B-R \sim 1.6$ (~ 1.3 dereddened) are the old population of globular clusters around NGC 1275. These are slightly redder than Galactic globular clusters that have an average $(B-R)_0 \sim 1.2$. The brightest ($M_B = -10.7$) has a magnitude similar to the brightest globulars seen in other central cluster galaxies.

4.2. *Luminosity Function*

Figure 7 shows the B luminosity function for the blue clusters ($B-R < 1.1$; *top*), and for the red clusters ($B-R > 1.1$; *bottom*). The dotted lines in each panel show the results after correction for incompleteness. The luminosity function of the blue clusters looks distinctly different from that expected for a typical old globular cluster population at a younger age. While the Galactic globular cluster luminosity function is Gaussian in shape with peak at $M_B \sim -6.6$ and $\sigma = 1.0$ mag (Harris 1996), the luminosity function for the clusters in NGC 1275 is more closely fitted by an exponential distribution. If we were to observe the current Galactic globular cluster system at an age of 500 Myr and at the distance of NGC 1275 (and the same Galactic extinction), we would observe a turnover in the luminosity function at $B \sim 24$ ($H_0 = 75$ km s^{-1} Mpc^{-1}). This prediction assumes 4 mag (13 Gyr) of fading, as suggested by the models of Bruzual & Charlot (1993). Our photometry is complete at the 50% level to 3 mag fainter than

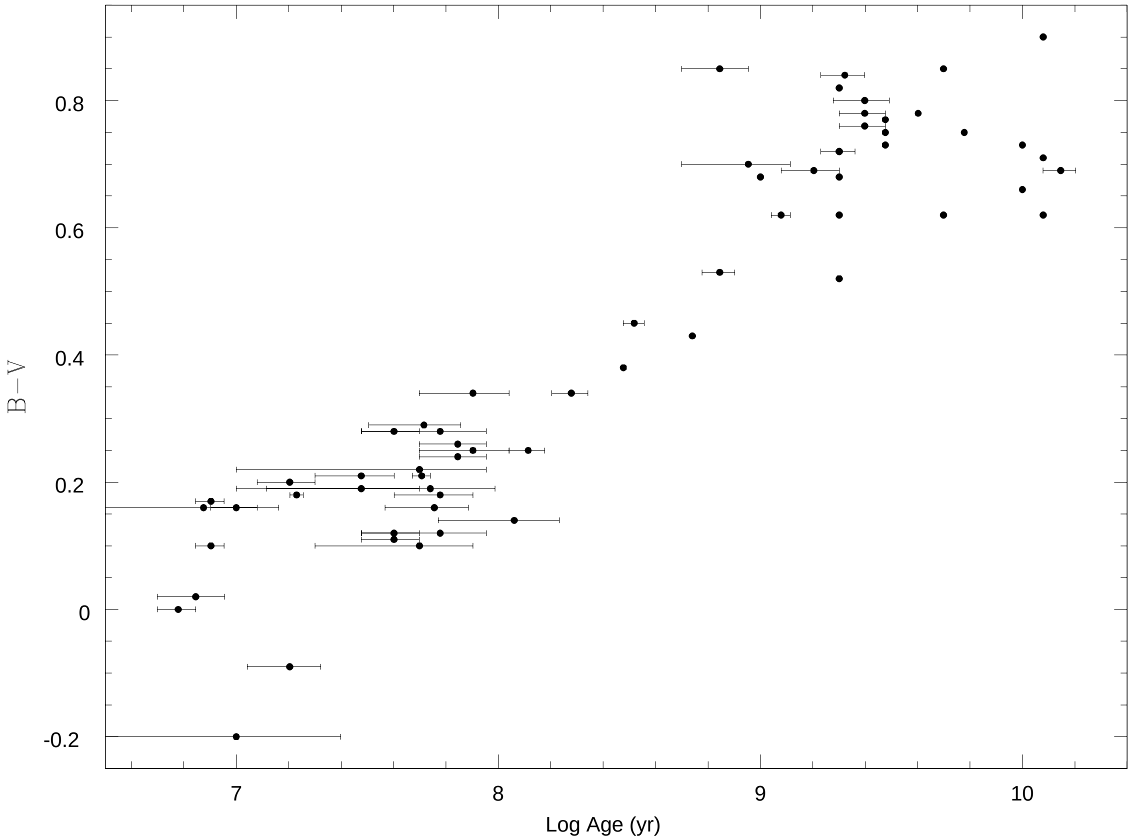

FIG. 6.—$B-V$ color vs. age for LMC clusters

this, yet there is no evidence of a turnover in the luminosity function of the clusters in NGC 1275.

The luminosity function of the blue clusters has the same trend as that of Galactic open clusters, namely, an increasing number of clusters at fainter magnitudes with no turnover (van den Bergh & Lafontaine 1984). However, the most luminous clusters in NGC 1275 are brighter than any observed Galactic open clusters, despite being older than the brightest of them. The compactness as inferred from the *HST* images is also different from that of open clusters (§ 4.5). Mateo (1993) found that an increasing luminosity function for clusters in the LMC can be produced by a mixed population of true globulars and open clusters. In NGC 1275, a similar explanation would require a large number of open clusters that are far more massive than any Galactic open clusters. Consequently, as a system, these clusters are different from any cluster system seen in Local Group galaxies. As individual objects, however, the physical properties appear most similar to globular clusters.

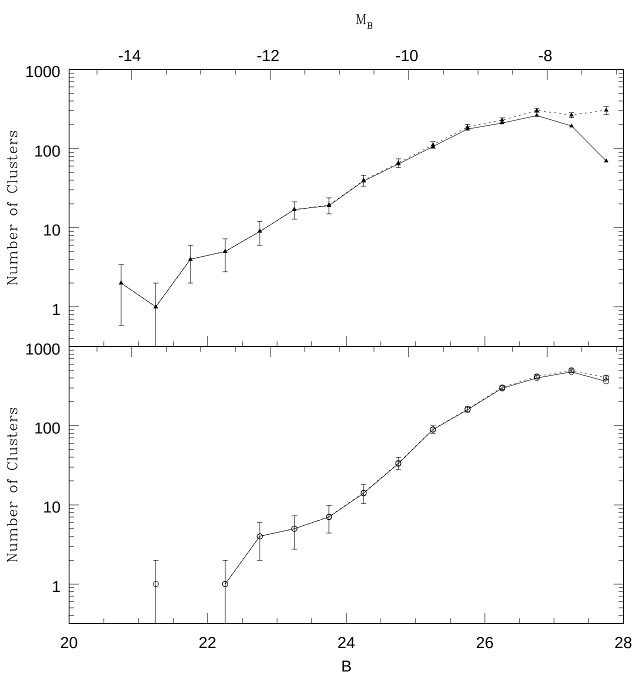

FIG. 7.—Luminosity functions for the clusters (*solid lines*) and with correction for completeness (*dotted lines*). *Top*, Blue clusters ($B-R < 1.1$); *bottom*, red clusters ($B-R > 1.1$).

In Figure 8, we compare the luminosity function of clusters in NGC 1275 with the luminosity functions in several of the other galaxies where reasonable numbers of blue clusters are found, as well as with the luminosity functions of Milky Way clusters. Dashed lines show rough completeness limits for the different observations, and dotted lines denote the location of the expected turnover, given the various age estimates of the clusters. There is no strong evidence in any of the young cluster systems for an intrinsic turnover in the luminosity function.

If these objects will evolve to look like the Galactic globular cluster system, some mechanism must preferentially destroy low-luminosity, low-mass clusters on time-scales of 13 Gyr. Two possibilities are tidal disruption and evaporation (Gnedin & Ostriker 1997; Elmegreen & Efremov 1997). For tidal disruption to preferentially destroy low-mass clusters, such clusters must have a lower mean density than more massive clusters. Evaporation

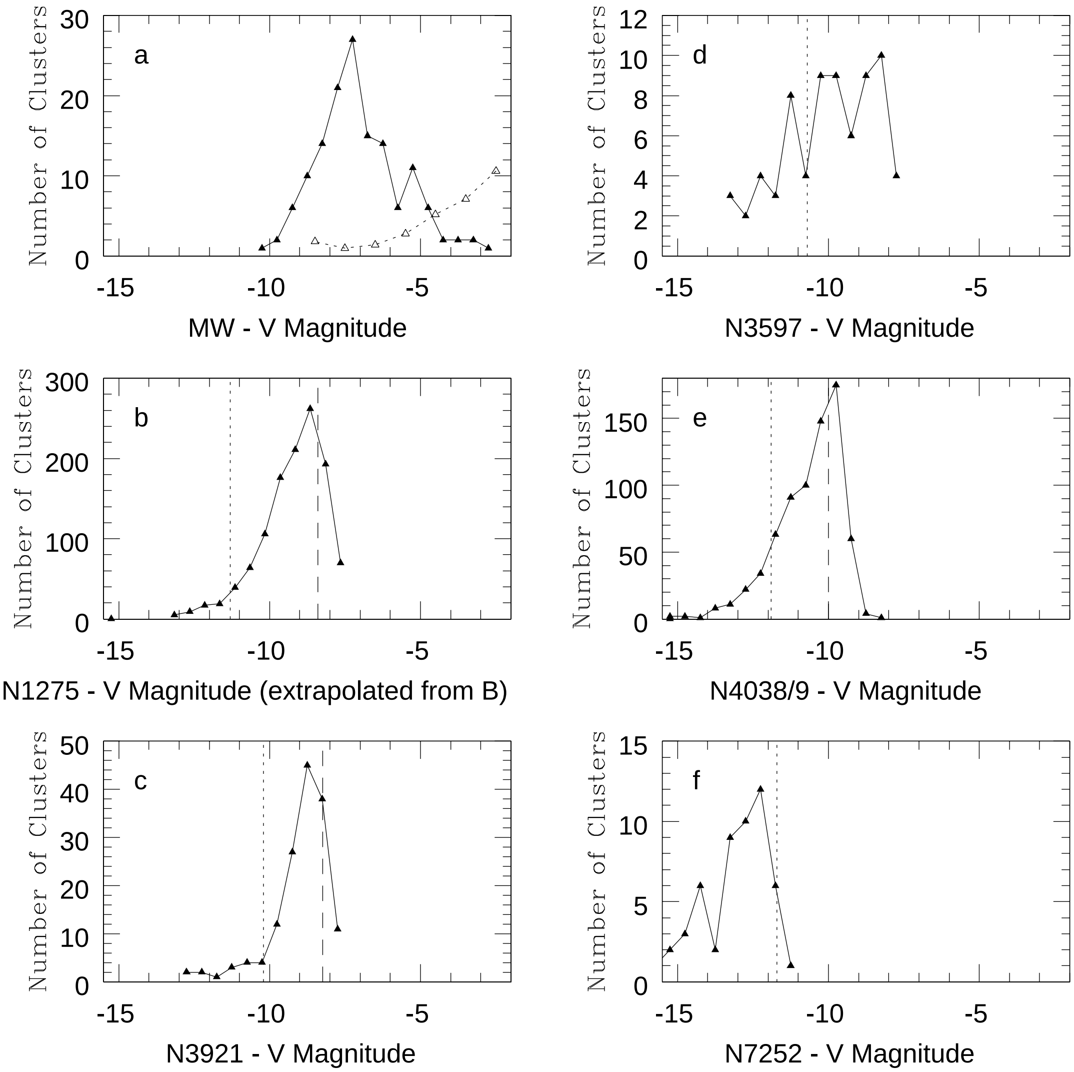

FIG. 8.—Luminosity functions for the Milky Way and five blue cluster galaxies. (*a*) Milky Way globular (Harris 1996) and open clusters (van den Bergh & Lafontaine 1984); (*b*) NGC 1275; (*c*) NGC 3921 (Schweizer et al. 1996); (*d*) NGC 3597 (Holtzman et al. 1996); (*e*) NGC 4038/4039 (Whitmore & Schweizer 1995); (*f*) NGC 7252 (Whitmore et al. 1993). Completeness limits are shown as dashed lines (where available). The predicted turnover in the luminosity function if the population is identical to Galactic globular clusters, but younger, is shown as a dotted line.

through two-body relaxation can preferentially destroy lower mass clusters as their stars escape the cluster potential well and are captured by the gravitational potential well of the galaxy. Gnedin & Ostriker (1997) predict that from half to three-quarters of the initial globular cluster population in a galaxy may be destroyed by a combination of these processes in a Hubble time.

4.3. *Surface Density Profile*

Figure 9 shows the surface density distribution of red and blue clusters (*open and filled triangles*, respectively). Corrections have been made for incomplete annuli at large radii, for masked areas, and for differing completeness levels with distance from the bright galaxy center. Error bars are simple Poisson errors in counts of clusters. The central area, within 18 pixels (0″.8) from the core of the galaxy, has been omitted from the surface density profile on account of the bright nucleus. It is clear that the blue clusters are more centrally concentrated than the red ones.

We fit the surface density distribution of the blue and red cluster systems from 4″ to 120″ with power laws. For the blue clusters, we find that a power-law slope of -1.3 provides a reasonable fit over the entire range. For the red clusters, we note a flattening in the inner portion of the distribution and fit the surface density with two power laws. Inside 0′.5, we measure a slope of -0.6, while outside 0′.5 we find a slope of -1.0. Flattening in the central part of the surface density distribution of a globular cluster system is also seen in other similar galaxies, such as M87 (McLaughlin 1995) and NGC 5128 (Harris et al. 1984). Our measurements for the distribution of old clusters are in good agreement with those of Kaisler et al. (1996). However, they adopt a power-law slope of -1.3, based on the observational relation between galaxy magnitude and power-law slope of the surface density distribution of the globular cluster system (Harris 1986, 1993). We note that our measured outer slope is sensitive to the choice of break point between the inner and outer regions; the data show a sign of steepening even more in the outermost parts. The spatial distribution of the clusters agrees with the galaxy merger model of Ashman & Zepf (1992), which predicts that the younger clusters will be peaked toward the center of the galaxy, while the older clusters will be more flattened in their distribution.

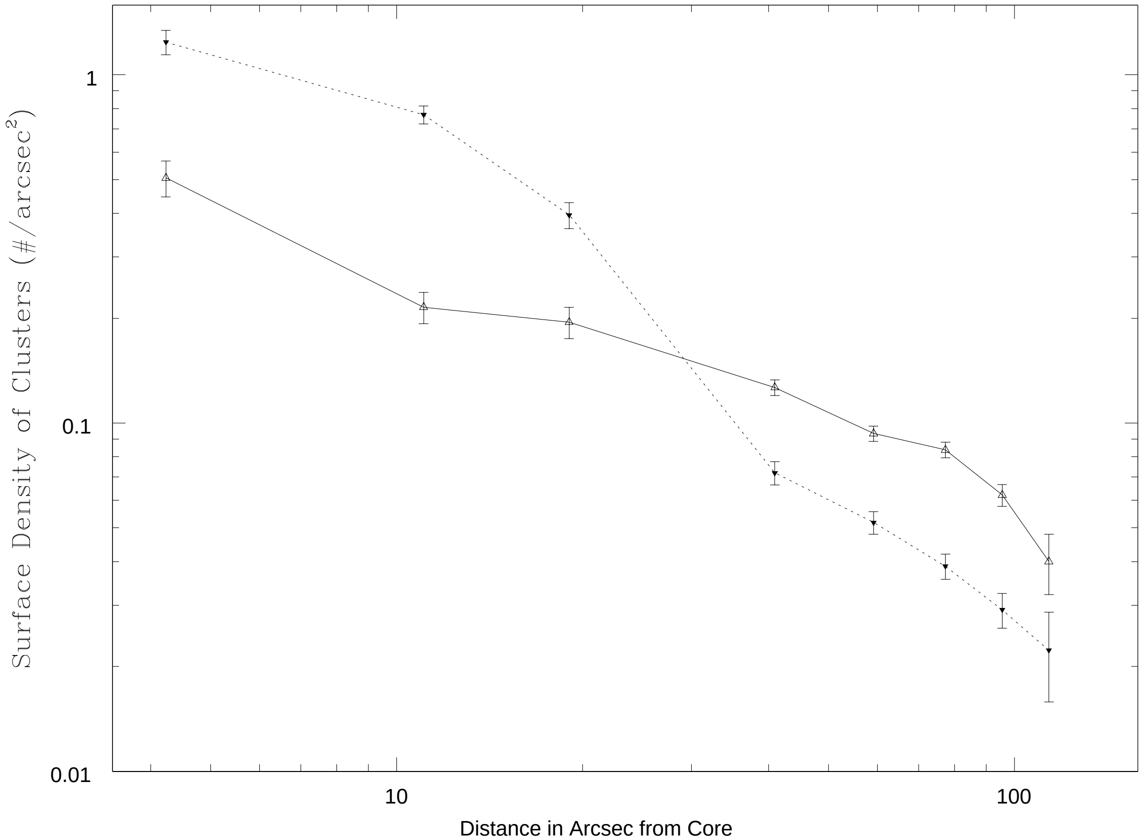

FIG. 9.—Surface density profile of the red clusters ($B-R > 1.1$, *solid line*) and the blue clusters ($B-R < 1.1$, *dotted line*)

4.4. *Specific Frequency*

The specific frequency of globular clusters in a galaxy is given by

$$S_N = N_T \, 10^{0.4(15+M_V)}$$

(Harris & van den Bergh 1981), where N_T is the total number of clusters and M_V is the absolute V magnitude of the galaxy. This is of interest in light of the hypothesis that elliptical galaxies form via mergers of spirals and the observation that ellipticals have a higher specific frequency of globular clusters than spirals. Consequently, the merger hypothesis requires that globular clusters form during mergers with a higher specific frequency than that of the progenitor population. Also, it requires that clusters form in numbers comparable to those of the old cluster population (Zepf & Ashman 1993). To address these questions, we calculate the specific frequency of the old population, the current specific frequency of the merger-related population, and the predicted specific frequency of the merger-related population in 13 Gyr.

To calculate specific frequencies, we need to estimate the total number of clusters associated with each population. These estimates come from integrating the surface density profiles of the red and blue clusters from the galaxy core to 100 kpc. This integration suggests that the total number of blue clusters is 5 times the number of clusters that we observe. For the red clusters, we correct this number for the clusters fainter than our completeness cutoff based on a Gaussian fit to the part of the magnitude distribution that we have observed. For the blue clusters, we make no correction for missing faint clusters and consider the resultant specific frequency to be a lower limit. To make a rough prediction of the number of clusters from the merger-related population that survive to be 13 Gyr old, we assume that the cluster luminosity function will come to resemble the globular cluster luminosity function of the Galaxy after 4 mag of fading and substantial cluster destruction. We assume that no clusters brighter than the predicted turnover of $M_B = -10.6$ are destroyed, and that the remaining clusters fainter than the turnover are equal in number to those brighter than the turnover, forming a Gaussian luminosity function. We note that this would require the destruction of $\sim$90% of the young clusters in NGC 1275 seen within our field. If the young cluster population is older than 10^8 yr, less cluster destruction would be required, and we would derive a higher specific frequency. Of course, if some fraction of the massive clusters are destroyed as well, we would derive a lower specific frequency. Our corrections yield estimates of 12,700 clusters for the old population, 5700 clusters for the young population, and 550 clusters remaining from the young cluster population after 13 Gyr.

We also need to estimate what fraction of the underlying stellar component is associated with each of the populations. NGC 1275 clearly has an excess blue population over what is normally observed in central cluster galaxies (Romanishin 1987). It is unknown whether this blue population is related to star formation in a recent merger or whether it is related to the presence of the cooling flow centered on NGC 1275. Assuming that all of the excess blue light comes from a merger-related population, we derive a

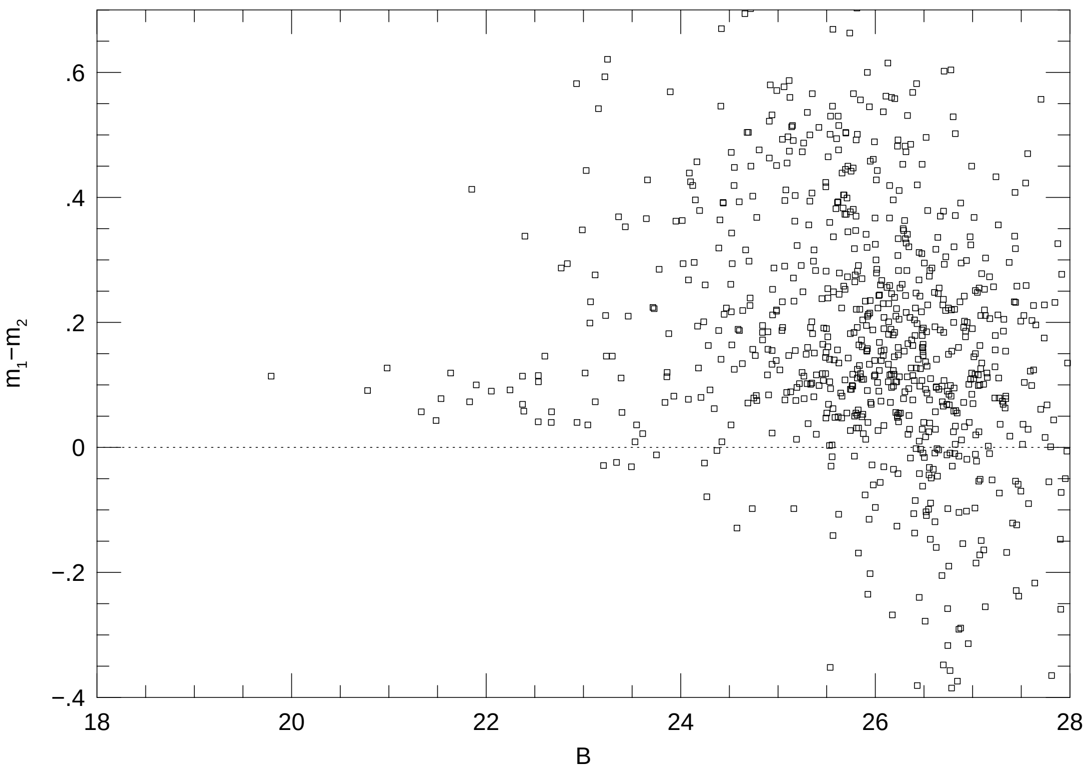

FIG. 10.—Measurements of $m_1 - m_2$ in F702W for all objects in the PC, where $m_1 - m_2$ is the difference between a 1 and a 2 pixel aperture magnitude relative to the same quantity measured on a model point source. Positive values suggest that the objects are marginally resolved.

lower limit for the specific frequency of globular clusters in such a population. Romanishin (1987) estimates that 15% of the total B light comes from an excess blue population, and we adopt this contribution as an upper limit for the V band as well. With a total brightness of $V = 11.88$ (de Vaucouleurs et al. 1991, vol. 2, p. 262), our adopted $A_V = 0.53$, and $H_0 = 75$ km s^{-1} Mpc^{-1}, we derive $M_V^{\rm tot} = -22.89$. Using a 15% contribution for the merger-related population yields $M_V^{\rm young} = -20.83$ and $M_V^{\rm old} = -22.71$. In order to estimate the specific frequency of the merger-related population *as it would appear in* $\sim$13 Gyr, we need to allow for a fading of the background population, and we adopt 4 mag of fading based on the population synthesis models.

We combine the information on the total number of clusters with the total V magnitudes for the populations to calculate specific frequencies. These estimates yield an $S_N \sim 10$ for the old population, an $S_N \sim 27$ for the current young population (without corrections for background fading or for cluster destruction), and an $S_N \sim 102$ as an estimate of the specific frequency of the young population after 13 Gyr of cluster destruction and 4 mag of background fading. Even without correction for clusters outside the WFPC2 field of view, we would predict 150 clusters surviving for 13 Gyr and a specific frequency of 28. All of these numbers, however, have significant uncertainties, as the corrections for completeness, cluster destruction, and fading are very substantial while at the same time being highly uncertain. From shallower ground-based observations over a larger field, Kaisler et al. (1996) determined the S_N for the old cluster population to be 4.3. The main sources of disagreement are that they have adopted a steeper surface density profile and a different total V magnitude.

The increase in the *overall* specific frequency of the galaxy from this event, however, is small, as the number of these clusters predicted to survive 13 Gyr is small; only about 550 new clusters would be added to a population of 12,700. Whether the specific frequency increases significantly in a merger depends on the mass and gas content of the merging bodies. However, the numbers are intriguing, because they suggest that, even allowing for substantial cluster destruction, the specific frequency of a merger-related population in 13 Gyr will be much higher than that typically observed in spiral galaxies. While this particular merger event will not have a large impact on the overall specific frequency in NGC 1275, it does show that a merger population can have a large specific frequency, which is the first requirement for increasing the overall specific frequency in a merger. Consequently, the observation that elliptical galaxies have a higher specific frequency of globular clusters is not inconsistent with the hypothesis that these galaxies have formed via the merging of spiral systems.

Our calculation indicates that an estimate of the future specific frequency is difficult to make, as several large corrections must be applied. The most uncertain of these is probably the estimate of the number of clusters that will be destroyed. Future work will need to carefully consider the probability of cluster destruction as a function of cluster mass and density if one wants to put serious constraints on the merger hypothesis for elliptical galaxies from observations of their globular cluster systems.

4.5. *Sizes*

Holtzman et al. (1996) estimated the sizes of marginally resolved clusters in WFPC2 images using the difference between a 1 and a 2 pixel aperture magnitude. These measurements are compared with measurements of simulated objects made by convolving a model PSF with a modified Hubble profile. The comparison yields an estimate of the cluster core radius *if* the cluster shape is well modeled by a modified Hubble profile. Figure 10 shows measurements of $m_1 - m_2$ in F702W for the NGC 1275 objects; note that values are near zero, because $m_1 - m_2$ is defined differentially with respect to a model point source placed at the same location on the frame as each cluster (see Holtzman et al. 1996 for details). Positive values of $m_1 - m_2$ indicate that the objects are resolved, and core radii are estimated using Figure 4 of Holtzman et al. (1996). For the brighter objects, we find that the objects are most likely resolved, with estimated core radii of $\sim$0.01–0.05 pixels, corresponding to $\sim$0.15–0.75 pc using our adopted distance to NGC 1275. Despite the uncertainties in these measurements, it seems clear that these objects are compact, and much more comparable to globular clusters than to open clusters.

5. CONCLUSIONS

From new deep observations of NGC 1275 with *HST*, we identify roughly 3000 objects that appear to be compact star clusters. The color distribution of the cluster system is bimodal, with a blue population that has $(B-R)_0 \sim 0.4$ and a red population that has $(B-R)_0 \sim 1.3$. We suggest that the red objects are members of the old globular cluster system and that the blue objects are members of a young globular cluster system. In an apparently dust-free region, the spread in the colors of the blue clusters is small enough that it is entirely attributable to scatter from errors in the photometry, mostly due to errors in sky subtraction. This suggests that the blue clusters are a single-color, single-age population. This argues against the hypothesis that clusters have been forming continuously from the cooling flow, and supports the hypothesis that their formation may have been triggered by a previous merger.

The luminosity function continues to rise to the limit of our observations, and is inconsistent with a Gaussian globular cluster luminosity function peaking near $M_V = -7.3$ after correction for evolutionary effects. A similar luminosity function observed in NGC 4038/4039 (the Antennae) has been used by van den Bergh (1995) to argue that the young clusters observed there are not true globular clusters. However, the masses and sizes of the individual young clusters appear to be comparable to those of globulars. We suggest that either the luminosity function evolves, with fainter clusters being preferentially destroyed as time passes, or that the initial luminosity-mass function of the young cluster system is different from that of typical old globular cluster systems.

If cluster destruction is responsible for the difference in luminosity function, a destruction mechanism that preferentially destroys fainter, lower mass clusters must be invoked. In order to create a turnover in the luminosity function at the same mass as in old cluster systems, the destruction of over 90% of the clusters currently seen in NGC 1275 would be required, given our assumption of 4 mag of fading. Given these likely differences in the luminosity functions of different globular cluster systems, whether caused by evolutionary effects or by initial differences, it is clear that some caution must be exercised in using the cluster luminosity function as a distance indicator.

We have attempted to estimate the specific frequency of the young population seen in NGC 1275 to determine whether it is likely that the overall specific frequency as seen at a future time could be increased because of the proposed merger-related formation of globular clusters. We note that the overall specific frequency of NGC 1275 will only be slightly increased by the proposed merger event that formed the blue clusters, because of the small number of clusters expected to survive for a Hubble time. But we estimate a large specific frequency of the merger related population, which suggests that mergers are efficient in forming globular clusters. However, corrections for incompleteness at faint magnitudes, clusters residing outside the current field of view, uncertainties in the mass and luminosity of the stellar population formed during a merger event, and, especially, corrections for evolutionary effects in both the background and cluster populations are all significant effects for which we have only relatively crude estimates.

This work was supported in part by NASA under contract NAS 7-918 to the Jet Propulsion Laboratory and by a grant to M. N. C. from the New Mexico Space Grant Consortium.

REFERENCES

Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50
Bahcall, J. N., & Soneira, R. M. 1980, ApJS, 44, 73
Barth, A. J., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1995, AJ, 110, 1009
Bruzual A., G., & Charlot, S. 1993, ApJ, 405, 538
Burstein, D., & Heiles, C. 1984, ApJS, 54, 33
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Charlot, S., & Bruzual A., G. 1991, ApJ, 367, 126
Conti, P. S., & Vacca, W. D. 1994, ApJ, 423, L97
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer)
Elmegreen, B. G., & Efremov, Yu. N. 1997, ApJ, 480, 235
Elson, R. A., & Fall, S. M. 1988, AJ, 96, 1383
Gnedin, O. Y., & Ostriker, J. P. 1997, ApJ, 474, 223
Harris, G. L., Hesser, J. E., Harris, H. C., & Curry, P. J. 1984, ApJ, 287, 175
Harris, W. E. 1986, AJ, 91, 822
———. 1993, in ASP Conf. Ser. 48, The Globular Cluster–Galaxy Connection, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 472
———. 1996, AJ, 112, 1487
Harris, W. E., Pritchet, C. J., & McClure, R. D. 1995, ApJ, 441, 120
Harris, W. E., & van den Bergh, S. 1981, AJ, 251, 497
Hodge, P. W. 1981, in IAU Colloq. 68, Astrophysical Parameters for Globular Clusters, ed. A. G. D. Philip & D. S. Hayes (Schenectady: L. Davis), 205
———. 1983, ApJ, 264, 470
Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995a, PASP, 107, 1065
Holtzman, J. A., et al. 1992, AJ, 103, 691
———. 1995b, PASP, 107, 156
———. 1996, AJ, 112, 416
Hughes, D. H., & Robson, E. I. 1991, MNRAS, 249, 560
Kaisler, D., Harris, W. E., Crabtree, D. R., & Richer, H. B. 1996, AJ, 111, 2224
Leitherer, C., & Heckman, T. M. 1995, ApJS, 96, 9
Lutz, D. 1991, A&A, 245, 31
Mandushev, G., Spassova, N., & Staneva, A. 1991, A&A, 252, 94
Mateo, M. 1993, in ASP Conf. Ser. 48, The Globular Cluster–Galaxy Connection, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 387
McLaughlin, D. E. 1995, AJ, 109, 2034
Miller, B. W., Whitmore, B. C., Schweizer, F., & Fall, S. M. 1997, AJ, submitted
O'Connell, R. W., Gallagher, J. S., & Hunter, D. A. 1994, ApJ, 433, 65
Pryor, C., & Meylan, G. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 357
Richer, H. B., Crabtree, D. R., Fabian, A. C., & Lin, D. N. C. 1993, AJ, 105, 877
Romanishin, W. 1987, ApJ, 323, L113
Schweizer, F., Miller, B. W., Whitmore, B. C., & Fall, S. M. 1996, AJ, 112, 1839
Shields, J. C., & Filippenko, A. V. 1990, ApJ, 353, L7

Strauss, M. A., Huchra, J. P., Davis, M., Yahil, A., Fisher, K. B., & Tonry, J. 1992, ApJS, 83, 29
van den Bergh, S. 1981, A&AS, 46, 79
———. 1991, ApJ, 369, 1
van den Bergh, S. 1995, ApJ, 450, 27
Watson, A. M., et al. 1996, AJ, 112, 534
Whitmore, B. C., & Schweizer, F. 1995, AJ, 109, 960
Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, AJ, 106, 1354
Zepf, S. E., & Ashman, K. M. 1993, MNRAS, 264, 611
Zepf, S. E., Carter, D., Sharples, R. M., & Ashman, K. M. 1995, ApJ, 445, L19