

THE AGES OF GLOBULAR CLUSTERS IN NGC 4365 REVISITED WITH DEEP *HST* OBSERVATIONS¹

ARUNAV KUNDU,² STEPHEN E. ZEPF,² MAREN HEMPEL,² DAVID MORTON,^{2,3} KEITH M. ASHMAN,³ THOMAS J. MACCARONE,⁴
MARKUS KISSLER-PATIG,⁵ THOMAS H. PUZIA,⁶ AND ENRICO VESPERINI⁷

Received 2005 August 4; accepted 2005 October 12; published 2005 November 8

ABSTRACT

We present new *Hubble Space Telescope* (*HST*) NIC3, near-infrared *H*-band photometry of globular clusters (GCs) around NGC 4365 and NGC 1399 in combination with archival *HST* WFPC2 and ACS optical data. We find that NGC 4365 has a number of globular clusters with bluer optical colors than expected for their red optical-to-near-infrared colors and an old age. The only known way to explain these colors is with a significant population of intermediate-age (2–8 Gyr) clusters in this elliptical galaxy. On the other hand, our result for NGC 1399 is in agreement with previous spectroscopic work that suggests that its clusters have a large metallicity spread and are nearly all old. In the literature, there are various results from spectroscopic studies of modest samples of NGC 4365 globular clusters. The spectroscopic data allow for either the presence or absence of a significant population of intermediate-age clusters, given the index uncertainties indicated by comparing objects in common between these studies and the few spectroscopic candidates with optical-to-near-IR colors indicative of intermediate ages. Our new near-IR data of the NGC 4365 GC system with a much higher signal-to-noise ratio agree well with earlier published photometry, and both give strong evidence of a significant intermediate-age component. The agreement between the photometric and spectroscopic results for NGC 1399 and other systems lends further confidence to this conclusion and to the effectiveness of the near-IR technique.

Subject headings: galaxies: general — galaxies: star clusters — globular clusters: general

Online material: color figures

1. INTRODUCTION

Globular clusters (GCs) are invaluable probes of the major star formation episodes in the life of a galaxy because each individual GC has a specific age and metallicity that reflects the physical conditions at the epoch of its formation. Thus, the observed color and spectrum are much easier to interpret than the complex superposed populations seen in integrated light (e.g., Ashman & Zepf 1998). Despite the simple nature of the stellar population of a GC, determining both the age and metallicity of any unresolved population requires overcoming the well-known age-metallicity degeneracy that causes both increasing age and increasing metal content to have similar effects on optical colors and spectral features.

One way to break this age-metallicity degeneracy is to combine optical and near-infrared colors, as the near-IR is mostly sensitive to the metallicity of the giant branch while optical colors are affected by both metallicity and age. Puzia et al. (2002, hereafter P02) employed this technique on ground-based, VLT *K*-band observations in combination with Wide Field Planetary Camera 2 (WFPC2) data to study two early-

type galaxies, NGC 3115 and NGC 4365. P02 found that the globular cluster system of NGC 4365 has a significant intermediate-age (2–8 Gyr old) component, which has no counterpart in the predominantly old NGC 3115 clusters. The discovery of intermediate-age GCs in a fairly typical elliptical galaxy such as NGC 4365 is a powerful illustration of the ability of GCs to probe major formation episodes of galaxies. Subsequent spectroscopy of a handful of bright GCs in these galaxies (Larsen et al. 2003, hereafter L03; Kuntschner et al. 2002) and studies of the cluster systems of several other galaxies with both optical-to-near-IR photometry (Hempel et al. 2003) and spectroscopy (Puzia et al. 2005) agree on the age and metallicity distribution determined by the two techniques. However, a recent spectroscopic analysis of a small sample of NGC 4365 clusters by Brodie et al. (2005, hereafter B05) suggests that the previously photometrically and spectroscopically identified intermediate-age GCs are instead an old population. Given the interest in determining whether there are intermediate-age GCs in early-type galaxies and its implications on how galaxies form, it seems important to analyze independent data for NGC 4365.

We have obtained deep *H*-band images of NGC 4365 using the NIC3 camera on board the *HST* in order to study the mass function of its GCs. We present a new, entirely *HST*-based study of the cluster system of NGC 4365. We compare our analysis to the aforementioned published studies, and a control sample in NGC 1399 using the exact same *HST* instruments, to comment on the constraints on the age distribution of the intermediate-metallicity GC population.

2. OBSERVATIONS

We obtained deep, dithered, *H*-band (F160W), Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) NIC3 observations of 5568 s each at three positions in NGC 4365 on 2003 November 17, 2004 June 15, and 2004 June 17 for our

¹ Based 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, Inc., under NASA contract NAS 5-26555.

² Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-2320; akundu@pa.msu.edu, zepf@pa.msu.edu, hempel@pa.msu.edu.

³ Department of Physics, University of Missouri, 5100 Rockhill Road, Kansas City, MO 64110; dlmnn7@umkc.edu, ashman@umkc.edu.

⁴ Department of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK; tjm@astro.soton.ac.uk.

⁵ European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany; mkissler@eso.org.

⁶ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; tpuzia@stsci.edu.

⁷ Department of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104; vesperin@physics.drexel.edu.

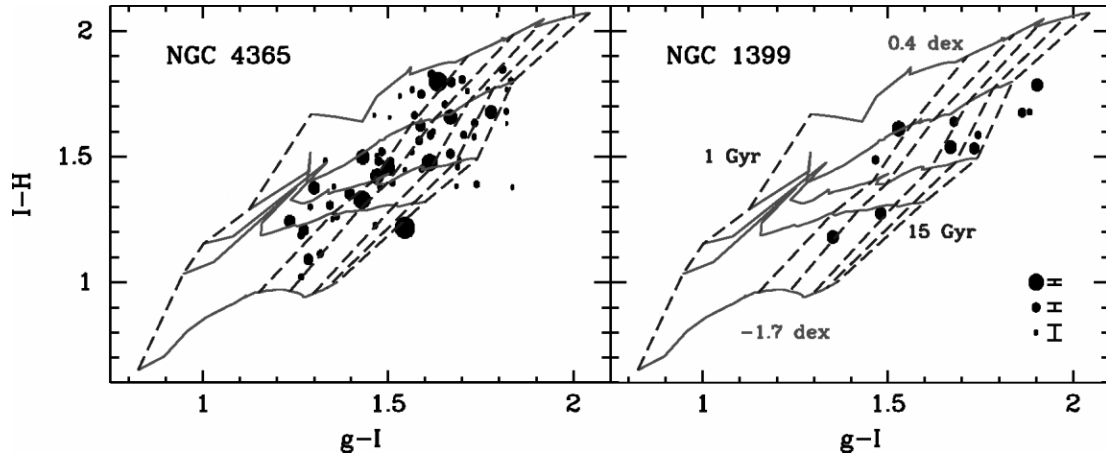


FIG. 1.—The $g - I$ vs. $I - H$ plots of globular clusters in NGC 4365 and NGC 1399. Only GCs with uncertainties less than 0.1 mag in each axis are shown. The lines trace age (1, 3, 5, 8, 11, and 15 Gyr from the left) and metallicity ($[\text{Fe}/\text{H}] = -1.7, -0.7, -0.4, 0$, and 0.4 dex from the bottom) contours from BC03 models. The size of the points are inversely proportional to the $I - H$ uncertainty as shown at the bottom right. The $g - I$ uncertainties are comparable to the $I - H$ values in NGC 4365 and are much smaller than the $I - H$ estimates in NGC 1399. [See the electronic edition of the *Journal* for a color version of this figure.]

HST program GO-9878. These observations coincided with the WF chips of archival WFPC2 V (F555W, 2200 s) and I (F814W, 2300 s) images obtained on 1996 May 31. The galaxy was observed in the g (F475W, 750 s) and z (F850LP, 1120 s) with the Advanced Camera for Surveys (ACS) on 2003 June 6. NGC 1399 was imaged in the H (F160W, 384 s) with the NIC3 on 1997 December 18, the B (F450W, 5200 s) and I (F814W, 1800 s) with the WFPC2 on 1996 June 2, and the g (F475W, 760 s) and z (F850LP, 1130 s) on 2004 September 11 with the ACS.

The NGC 4365 NIC3 observations are subpixel-dithered at four positions. Using the drizzle algorithm (Fruchter & Hook 2002), we reconstructed high-resolution images, alleviating the effect of the undersampled $0''.2$ NIC3 pixels. Importantly, the dithering placed the center of each GC at different locations with respect to the center of a pixel, thus reducing the effects of intrapixel-sensitivity variations in the NIC3 array (Xu & Mobasher 2003). The NICMOS observations of NGC 1399 were obtained with NIC1 and NIC2 in focus. Since NIC3 does not share a common focus with these instruments, the NIC3 images are out of focus. However, the instruments on the *HST* are well studied and characterized; hence, we were able to extract valuable information from these data. We both drizzled the NGC 1399 NIC3 images and shifted and added them on the original scale. The photometry determined from each image was in excellent agreement. We chose to use the shifted images to minimize possible uncertainties due to centering issues in out-of-focus images. Interestingly, the out-of-focus nature of the NGC 1399 NIC3 image mitigates intrapixel-sensitivity effects. The WFPC2 data for both galaxies were dithered by integer pixels. The images were shifted and added to remove cosmic rays and charge traps. After inspection, we also analyzed the drizzled, geometric distortion-corrected ACS images of both galaxies.

Candidate GCs were identified in the WFPC2 and ACS images using the constant signal-to-noise ratio (S/N) detection technique described in Kundu et al. (1999). The lists and the results described below for each set are in good agreement. We use the ACS-selected candidates due to the higher S/N and the slightly improved ability to distinguish between GCs and contaminating objects.

Aperture photometry was performed in each image using zero points from the *HST* data handbook. Aperture corrections

from small radii were measured from our data to account for the partially resolved GC profiles in *HST* images (Kundu et al. 1999). Foreground reddening corrections from Schlegel et al. (1998) were also applied. All photometry in this Letter is reported in the Vegamag system. Where applicable, we have transformed ABMAG magnitudes to VEGAMAG using zero-point offsets from Sirianni et al. (2005).

While a $0''.5$ aperture was used for photometry in the NGC 4365 NIC3 images, the NIC3 observations of NGC 1399 did not have a small core, and so a large 5 pixel radius ($1''$) aperture was used for aperture photometry. Aperture corrections were determined from TinyTim models (Krist 1995). Although the NICMOS focus history indicated that the Pupil Alignment Mechanism (PAM) position for best focus for the NGC 1399 NIC3 images should be near -13 mm, comparison of point sources with TinyTim models revealed that a PAM position of -10 mm provided the best fit to the data. Varying the center of an object within a pixel and allowing PAM positions between -5 and -16 mm changed the correction by 0.04 mag rms. This factor was added in quadrature to the photometric uncertainty.

3. RESULTS AND DISCUSSION

In the rest of this analysis, we study the GCs in the ($g - I$, $I - H$)-plane because both galaxies have been observed in these filters with the same instruments and because this choice of filters provides the largest baseline for both optical and infrared colors. The conclusions of this study are unaffected by the choice of optical and infrared color baselines selected from the filter set available to us.

Figure 1 plots the $g - I$ versus $I - H$ colors for 70 GCs in NGC 4365 and 11 GCs in NGC 1399 with photometric uncertainties of less than 0.1 mag in each color. The least luminous source in the g , I , and H filters plotted in Figure 1 are 25.83 ± 0.07 , 23.40 ± 0.05 , and 21.43 ± 0.07 in NGC 4365 and 23.62 ± 0.02 , 21.74 ± 0.02 , 20.08 ± 0.10 in NGC 1399, respectively. Fiducial lines of constant metallicity and constant age from the simple stellar population models of Bruzual & Charlot (2003, hereafter BC03) are also plotted. It is apparent that there is a significant excess of GCs with blue $g - I$ colors for a given $I - H$ color in NGC 4365 as compared to NGC

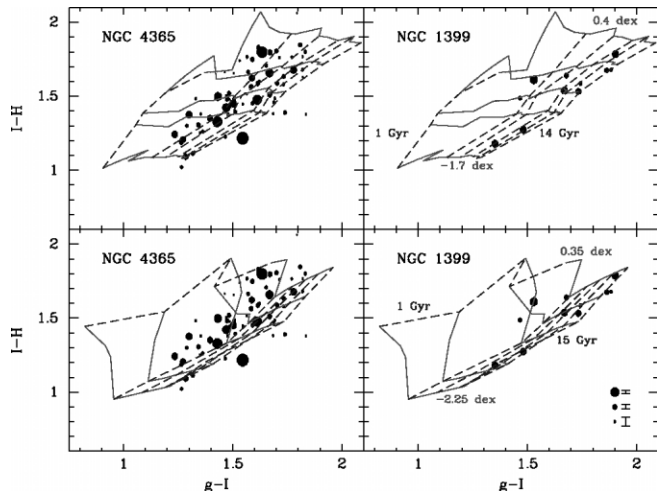


FIG. 2.—Same as in Fig. 1, but with Anders & Fritze-v. Alvensleben (2003) models in the upper panels and Maraston (2005) models in the lower ones. Lines in the upper plots represent $[\text{Fe}/\text{H}] = -1.7, -0.7, -0.4, 0$, and 0.4 dex from the bottom and 1, 3, 5, 8, 11, and 14 Gyr from the left. Lines in the lower panels trace $[\text{Fe}/\text{H}] = -2.25, -1.35, -0.33, 0$, and 0.35 dex from the bottom and 1, 3, 5, 8, 11, and 15 Gyr from the left. [See the electronic edition of the Journal for a color version of this figure.]

1399. Such colors can only be explained by the presence of an intermediate-age population of GCs younger than ≈ 8 Gyr. In contrast, the GCs in NGC 1399 appear to be primarily old.

The reason for the relative paucity of GCs in NGC 1399 is because it represents a single out-of-focus NIC3 field. Although the lower S/N of the NGC 1399 NIC3 image causes a preferential selection of red, young, and/or metal-rich GCs, most of the metal-rich GCs in NGC 1399 appear to be older than 10 Gyr despite this bias. This suggests that the overwhelming majority of GCs in this galaxy are old, with a handful of possible young ones. This is completely consistent with the spectroscopic analyses of GCs in NGC 1399 by Kissler-Patig et al. (1998) and Forbes et al. (2001), who found that the majority of their samples of 18 and 10 GCs, respectively, are old, with a range of metallicities extending to roughly solar. In consonance with our results, each of these studies identified two possible/likely young GCs in their respective samples.

The color-color plot of NGC 4365 GCs provides a striking contrast to NGC 1399 with a clear excess of GCs younger than ~ 8 Gyr, consistent with the conclusions of P02 and the spectroscopic follow-up by L03. Figure 2 compares our data with Anders & Fritze-v. Alvensleben (2003) and Maraston (2005) models. While the models differ in detail due to the choice of stellar track and calibration technique, the conclusion that NGC 4365 has a large population of intermediate-age GCs and that NGC 1399 does not is independent of the choice of model.

3.1. Statistical Significance of the Age Distributions

The direct determination of the epochs and efficiency of the major episodes of star formation from color-color plots are complicated by issues like selection effects and photometric errors. We choose instead to apply the modeling technique of Hempel & Kissler-Patig (2004). In brief, we create input models with two populations of clusters using Monte Carlo simulations and stellar models. The cumulative age distribution of a range of input models is then compared to the data to find the distribution that best fits the data.

Figure 3 plots the cumulative fraction of GCs that are older

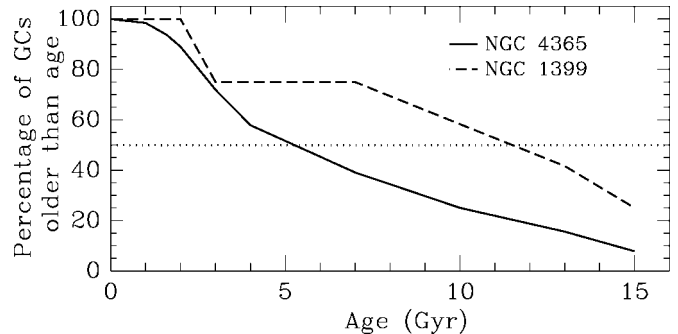


FIG. 3.—Cumulative fractional age distributions of the GCs in NGC 1399 and NGC 4365 from BC03 models.

than a given age in each of the galaxies, based on BC03 models. This analysis is restricted to GCs with $[\text{Fe}/\text{H}] \geq -0.4$ dex to minimize the effects of incompleteness. Figure 3 shows that the NGC 1399 GCs are older, on average, with a median age of ≈ 12 Gyr as compared to ≈ 5 Gyr for NGC 4365. Next we fixed the age of the older population to 13 Gyr and conducted the simulations described in Hempel & Kissler-Patig (2004) for a two-burst model. Figure 4, which plots the reduced χ^2 comparing the model with the data, shows that approximately 60% of the NGC 4365 metal-rich GCs in our field of view were formed about 4 Gyr ago. The corresponding fraction for NGC 1399 is only about 20%, although, given the selection biases in NGC 1399, this is likely an upper limit on the constraints. We note that only a handful of old, metal-poor GCs are observed in NGC 4365. This is not surprising since the optical color magnitude diagram (Kundu & Whitmore 2001) suggests that GCs with colors of $V - I \approx 0.95$ corresponding to the typical metal-poor peak are fainter than the other GCs in NGC 4365, as is expected for older clusters. We shall investigate the luminosity and mass functions of NGC 4365 GCs in a future paper.

3.2. Comparison with Previous Observations

As discussed above, the inferred age and metallicity distributions of our program galaxies are in good agreement with previous photometric and spectroscopic studies (P02; L03; Kissler-Patig et al. 1998; Forbes et al. 2001). The recent spectroscopic analysis of NGC 4365 by B05, however, reaches a different conclusion, suggesting that the intermediate-age GCs

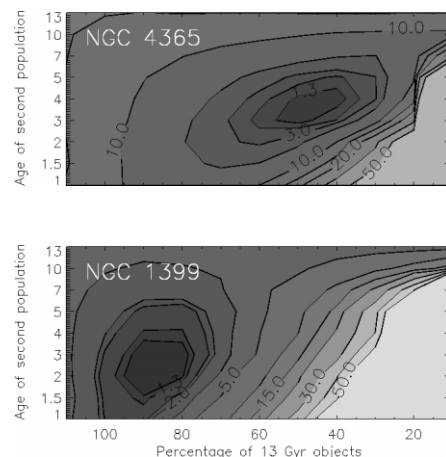


FIG. 4.—Reduced χ^2 plots comparing the age distributions of GCs in NGC 4365 and NGC 1399 with simulated cluster systems.

are actually old, intermediate-metallicity clusters. Unfortunately, the B05 study has very few GCs with known near-IR and optical colors.

Specifically, of the large sample of NGC 4365 GCs with optical and near-IR colors, there are 12 shown in Figure 8 of B05 as having spectroscopic data. Of these, nine have been observed by L03, providing reasonable overlap with the photometric data. B05 observed three GCs with known near-IR and optical colors, including two in L03. The remaining two of the 12 are an object with a given position more than $2''$ from any candidate in P02, and thus an uncertain photometric counterpart, and an object with unreliable colors due to likely cosmic-ray events in the WFPC2 image. B05 observed a total of six objects with intermediate optical colors: the three above with near-IR colors, and three without such colors to allow an age estimate (see Fig. 1). A recent shallow near-IR imaging study by Larsen et al. (2005) observed additional B05 clusters and suggested a broad spread of GC colors consistent with P02 and this study. However, the authors express reservations about their own calibration. Important aspects of the data presented here are the much smaller error bars that both clearly show that GC colors indicate an age spread and are consistent with the shallower data sets.

In Figure 5, we plot the $(g - I, I - H)$ -colors of the six matches with the L03 data and the subset of two sources observed by B05 that fall within our fields of view. We note that most of these GCs appear to be of intermediate age with moderate metallicity, in agreement with the results of L03. Given the small overlap with the B05 observations, model uncertainties, and one candidate that lies on the 8 Gyr isochrone and is consistent with an old age, no strong conclusions can be drawn from the B05 data. We also note that B05 found significantly different Lick index values than L03 for the three GCs in common between the two studies. The up to 3σ difference between the indices of these objects in the age-sensitive Balmer lines indicates that the uncertainties in these index measurements, and therefore the error in the age and metallicity constraints in one or both spectroscopic studies, are underestimated. On the other hand, the photometric analyses of the NGC 4365 GCs agree unambiguously. Given the agreement of these and L03 for NGC 4365, and the agreement between the NGC 1399 spectroscopic and photometric results, we believe the

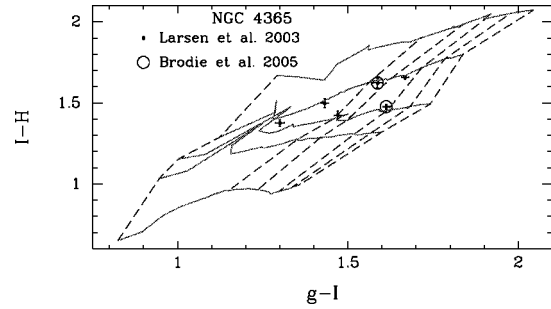


FIG. 5.—The $g - I$ vs. $I - H$ plots of GCs studied spectroscopically. Fiducial lines trace BC03 models as in Fig. 1. [See the electronic edition of the Journal for a color version of this figure.]

preponderance of evidence points toward the presence of intermediate-age GCs in NGC 4365. To determine the full spatial extent of this intermediate-age population will require deep near-IR imaging over a wider field.

4. CONCLUSIONS

Globular clusters provide fossil records of the major star formation episodes in a galaxy. Thus, constraining the ages and metallicities of cluster subpopulations provides important insight into the process of galaxy formation and evolution. The near-IR and optical color photometric technique and spectroscopy measure the ages and metallicities of clusters by probing different physical phenomena and provide independent sanity checks. We have analyzed the cluster system in the inner regions of NGC 1399 and NGC 4365 and conclude that the metal-rich clusters in NGC 1399 are predominantly old while many of the corresponding clusters in NGC 4365 are of intermediate age. These results are in good agreement with previous spectroscopic and photometric studies of these galaxies and hence give us further confidence in the photometric technique.

This research was supported by STScI grant HST-GO-09878.01-A and NASA-LTSA grants NAG5-11319 and NAG5-12975.

REFERENCES

- Anders, P., & Fritze -v. Alvensleben 2003, A&A, 401, 1063
 Ashman, K. M., & Zepf, S. E. 1998, Globular Cluster Systems (Cambridge: Cambridge Univ. Press)
 Brodie, J. P., Strader, J., Denicolo, G., Beasley, M. A., Cenarro, A. J., Larsen, S. S., Kuntschner, H., & Forbes, D. A. 2005, AJ, 129, 2643 (B05)
 Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000 (BC03)
 Forbes, D. A., Beasley, M. A., Brodie, J. P., & Kissler-Patig, M. 2001, ApJ, 563, L143
 Fruchter, A. S., & Hook, R. N. 2002, PASP, 114, 144
 Hempel, M., Hilker M., Kissler-Patig, M., Puzia, T. H., Minniti, D., & Goudfrooij, P. 2003, A&A, 405, 487
 Hempel, M., & Kissler-Patig, M. 2004, A&A, 419, 863
 Kissler-Patig, M., Brodie, J. P., Schroder, L. L., Forbes, D. A., Grillmair, C. J., & Huchra, J. P. 1998, AJ, 115, 105
 Krist, J. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco: ASP), 349
 Kundu, A., & Whitmore, B. C. 2001, AJ, 121, 2950
 Kundu, A., Whitmore, B. C., Sparks, W. B., Macchetto, D., Zepf, S. E., & Ashman, K. M. 1999, ApJ, 513, 733
 Kuntschner, H., Ziegler, B. L., Sharples, R. M., Worthey, G., & Fricke, K. J. 2002, A&A, 395, 761
 Larsen, S. S., Brodie, J. P., Beasley, M. A., Forbes, D. A., Kissler-Patig, Kuntschner, H., & Puzia, T. H. 2003, ApJ, 585, 767 (L03)
 Larsen, S. S., Brodie, J. P., & Strader, J. 2005, A&A, in press
 Maraston, C. 2005, MNRAS, 362, 799
 Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, R., Goudfrooij, P., & Hempel, M. 2005, A&A, 439, 997
 Puzia, T. H., Zepf, S. E., Kissler-Patig, M., Hilker, M., Minniti, D., & Goudfrooij, P. 2002, A&A, 391, 453 (P02)
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
 Sirianni, M., et al. 2005, PASP, 117, 1049
 Xu, C., & Mobasher, B. 2003, NICMOS Instrum. Sci. Rep. 2003-009