THE ASTROPHYSICAL JOURNAL, 409:L17–L19, 1993 May 20

THE FIRST DETECTION OF A COLLAPSED CORE GLOBULAR CLUSTER IN M31

O. BENDINELLI,[1] C. CACCIARI,[2] S. DJORGOVSKI,[3] L. FEDERICI,[2] F. R. FERRARO,[2] F. FUSI PECCI,[2]
G. PARMEGGIANI,[2] N. WEIR,[3] AND F. ZAVATTI[1]
Received 1993 January 21; accepted 1993 March 2

ABSTRACT

We report on the observations of a globular cluster (designated G105 = Bo 343) in the nearby spiral galaxy M31, using the *Hubble Space Telescope* (*HST*). Image deconvolutions using three different methods indicate that this cluster has a density profile with the morphology characteristic of stellar systems which have undergone core collapse, i.e., a power-law density cusp near the center. This is the first such detection in a galaxy as distant as M31. This discovery may lead to extensive future statistical studies of the globular cluster system of M31, and thus a better understanding of its evolution.

Subject headings: galaxies: individual (M31) — galaxies: star clusters — techniques: image processing

1. INTRODUCTION

One of the central topics in stellar dynamics and astrophysics of globular star clusters is the problem of core collapse; numerous good reviews of this subject can be found in Elson, Hut, & Inagaki (1987), Goodman & Hut (1985), Grindlay & Philip (1988), and Meylan & Djorgovski (1993). The collapse and a subsequent recovery lead to the appearance of a characteristic surface brightness profile morphology near the cluster center: a power-law cusp with a slope ~ -0.5 to -1, extending up to a few parsecs out in radius. Approximately one-fifth of all known globulars in our Galaxy show this morphology (Djorgovski & King 1984, 1986), which distinguishes them from the standard, King model clusters with flat, extended cores and steeper envelopes (King 1966). Dynamical evolution of clusters can be speeded up by the tidal shocks along their orbits, and a census of post–core collapse clusters as a function of their position in the parent galaxy can thus serve as a powerful probe of the evolution of the system; so far, this was done only for our own Galaxy (Djorgovski 1988; Chernoff & Djorgovski 1989). Core collapse can also affect the stellar populations in significant ways which are not yet fully understood (Djorgovski et al. 1991; Fusi Pecci et al. 1993a).

The only other galaxies for which a systematic search for post–core collapse clusters has been done are the Magellanic Clouds (Meylan & Djorgovski 1987). So far, measurements of the morphology of globulars in other galaxies, the nearest major one being M31, have been precluded by their distance and a seeing-limited resolution of ground-based data. Systematic cataloging of the M31 globular cluster system has been done by many groups (Sargent et al. 1977; Battistini et al. 1982; Battistini et al. 1987; Crampton et al. 1985). Attempts to recover their morphology using seeing deconvolution of ground-based data have met only with a limited success so far (Cohen & Freeman 1991; Bendinelli et al. 1990). The *Hubble Space Telescope* (*HST*) is a powerful new tool with which to address this problem.

We are conducting a long-term effort to study the M31 globulars with the *HST*. Our selection criteria of the clusters to observe and the preliminary results have been reported elsewhere (Bendinelli et al. 1992; Cacciari et al. 1992), with a full paper to follow (Fusi Pecci et al. 1993b). Here we report on the discovery of a cluster with apparently post–core collapse morphology. This object G105 = Bo 343 = V199 (names from Sargent et al. 1977, Battistini et al. 1987, and Vetesnik 1962, respectively), is located about 12 kpc from the nucleus of M31, it has an apparent magnitude $V = 16.34$, colors $(U-B) = 0.14$, $(B-V) = 0.73$, and $(V-K) = 2.69$, an estimated metallicity $[Fe/H] \simeq -1.3$, and the observed radial velocity $v_r = -295.8$ km s^{-1} (Bònoli et al. 1987; Federici, Fusi Pecci, & Marano 1990). Assuming the distance modulus to M31 of $(m - M) = 24.37$, and the foreground reddening $E_{B-V} = 0.10$, its inferred absolute magnitude is $M_V \simeq -8.0$, i.e., it is a relatively bright, but otherwise unremarkable, cluster. Since the Galactic collapsed core clusters appear to be concentrated toward the Galactic center, it might be worthy of notice that this cluster is located at quite a large distance from the nucleus.

2. OBSERVATIONS AND REDUCTIONS

We obtained three exposures of the cluster, of 1495, 1495, and 1288 s duration, using the Faint Object Camera (FOC) on the *HST*, in its f/96 mode, and through the F430W filter (*B* band). Separate exposures of an isolated standard star were used to obtain the point-spread function (PSF). The data have been reprocessed, the three exposures co-added, and the surface brightness profiles extracted using standard techniques (Djorgovski 1988; Bendinelli et al. 1990, 1992; Cacciari et al. 1992).

3. DECONVOLUTIONS AND RESULTS

We employed three different image deconvolution techniques in order to compensate for the notorious spherical aberration of the *HST*: the Richardson-Lucy technique (RL) (Richardson 1972; Lucy 1974), the maximum entropy method (MEM) (Weir & Djorgovski 1990; Weir 1991), and the regularized multi-Gaussian technique (RMG) (Bendinelli 1991). Figure 1 (Plate L3) shows the original cluster image, and the results of RL and MEM deconvolutions (the RMG method is applied on the surface brightness profiles only).

We performed numerous and extensive tests of the three deconvolution methods, both in the context of these data, and in other, related, applications (Bendinelli et al. 1990, 1992; Cacciari et al. 1992; Weir et al. 1990; Weir 1991; King et al.

[1] Dipartimento di Astronomia, Università di Bologna, Via Zamboni 33, I-40126 Bologna, Italy.
[2] Osservatorio Astronomico di Bologna, Via Zamboni 33, I-40126 Bologna, Italy.
[3] Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125.

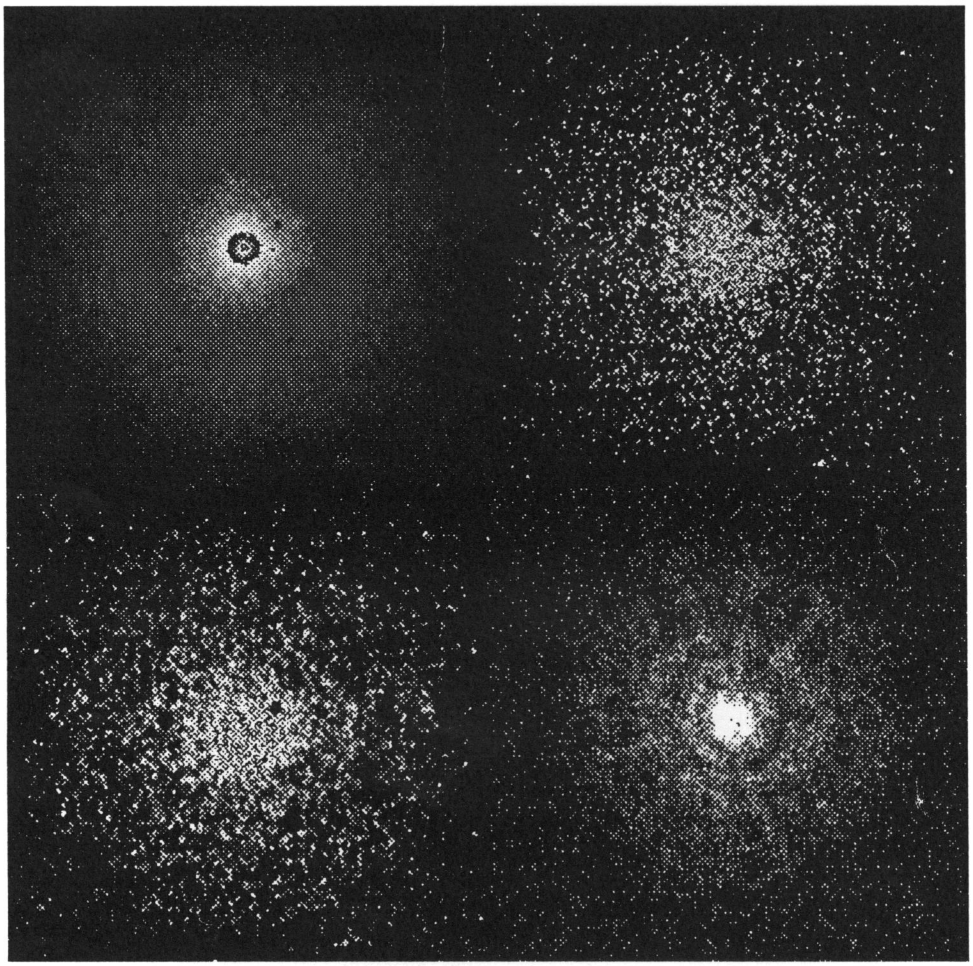

FIG. 1.—Images of the M31 globular cluster G105 = Bo 343, obtained with the *HST*. *Top left:* the original stacked image. *Top right:* a deconvolved image, using the maximum entropy method. *Bottom left:* a deconvolved image, using the Richardson-Lucy technique. Most of the luminosity spikes in the deconvolved images are probably *not* individual stars, but rather just enhanced noise peaks (the brightest ones may be actually individual red giants). The overresolution at these small spatial scales does not perceptibly affect the surface brightness profiles. *Bottom right:* the observed point-spread function.

BENDINELLI et al. (see 409, L17)

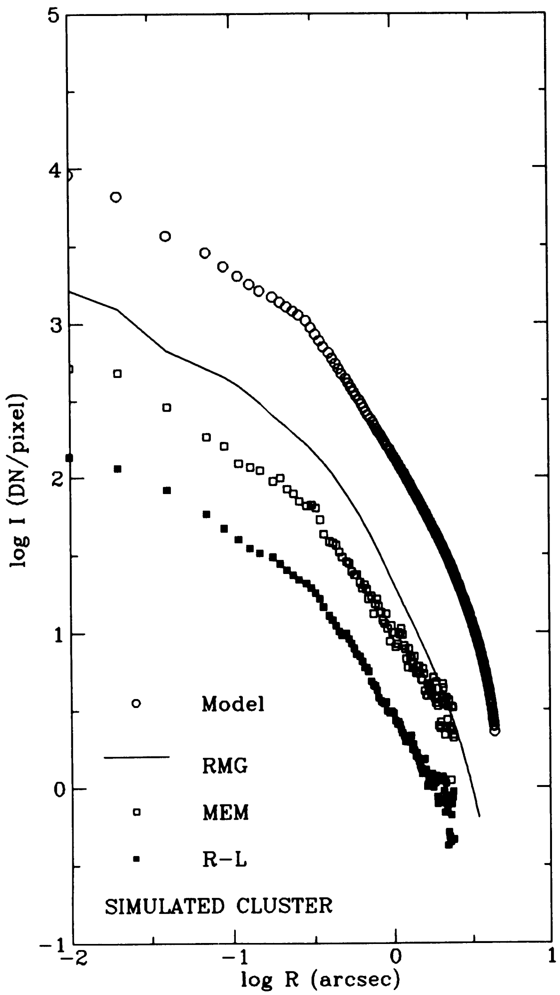

FIG. 2

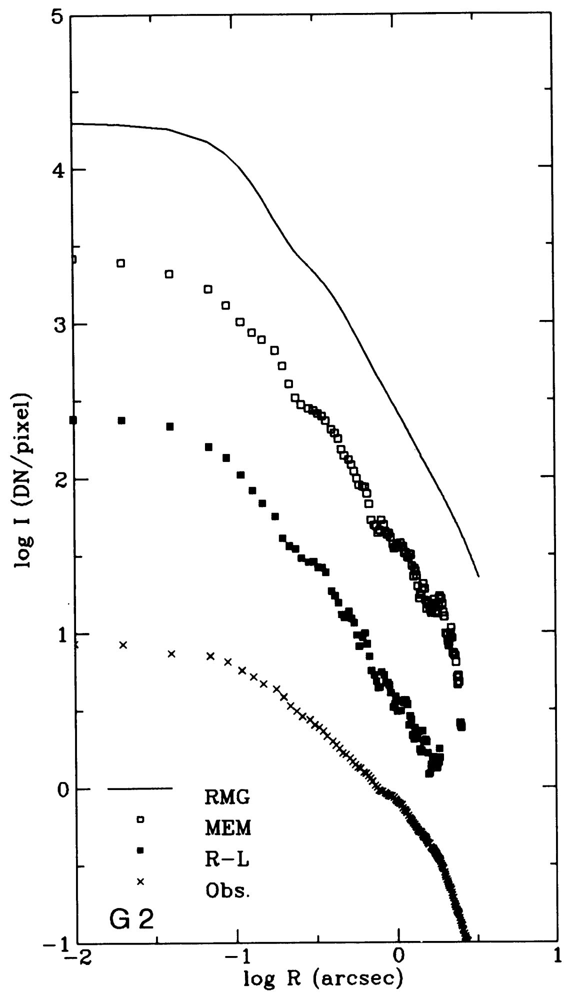

FIG. 3

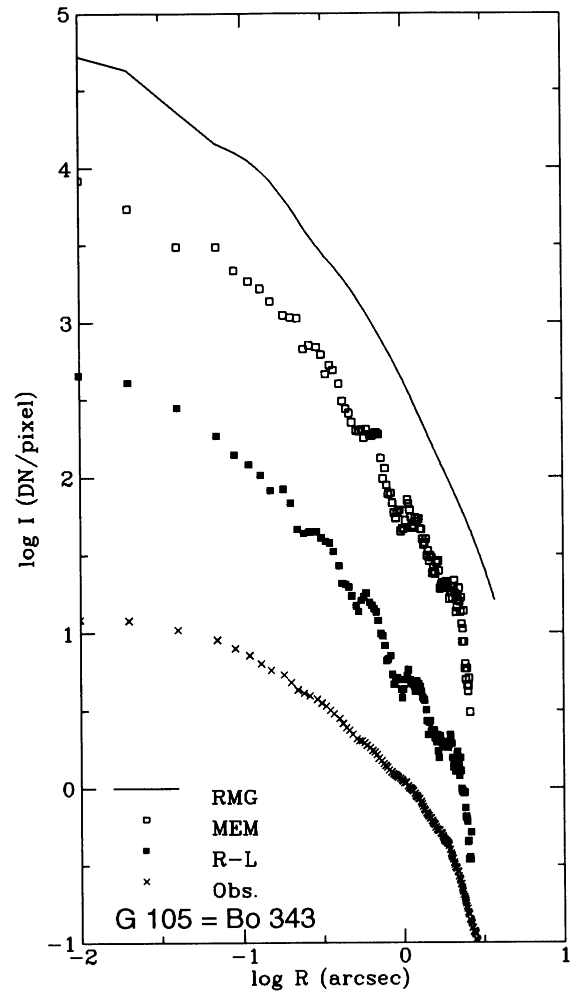

FIG. 4

FIG. 2.—Tests of the reliability of the deconvolution technique, using a simulated cluster. An artificial cluster (modeled after the well-studied post–core collapse clusters in our Galaxy) was constructed and placed at the distance to M31, convolved with the observed PSF, and then deconvolved with each of the three techniques. The true surface brightness profile (*top*) and the recovered deconvolved profiles are shown, shifted vertically for clarity.

FIG. 3.—Deconvolved surface brightness profiles of cluster G2, using the three techniques as indicated, and shifted vertically for clarity. This cluster is well resolved with our data and deconvolution techniques, suggesting that our methodology does not generate spurious central cusps.

FIG. 4.—Deconvolved surface brightness profiles of G105 = Bo 343, using the three techniques as indicated, and shifted vertically for clarity. There is an obvious central power-law cusp, extending from the resolution limit of our data (~0".03) out to ~0".3 radius (about 1 pc at the distance to M31), with a steeper fall-off thereafter. This is a morphology typical of the post–core collapse globular clusters in our Galaxy.

1991; Zavatti et al. 1991), and more tests will be presented in a forthcoming paper. As a rule, we find that surface brightness profiles produced by the three deconvolution methods agree very well, especially in the central regions where the signal-to-noise ratio is high. We also did separate deconvolutions of individual FOC exposures using MEM and again found an excellent internal agreement. We varied different MEM parameters and again found the results to be quite robust.

As an illustration, Figure 2 shows surface brightness profiles (the original, and the three deconvolutions) of a simulated post–core collapse cluster, which was "moved" to the distance of M31, convolved with the observed PSF, and then restored. All three deconvolutions mutually agree and clearly show the presence of a central power-law cusp.

Figure 3 shows the deconvolution of another cluster (G2), from very similar data. Again, the three deconvolutions agree very well. This cluster appears to be safely resolved with the *HST*, with the core radius $r_c = 0''.12 \pm 0''.02$, and an apparently normal King model morphology. The results for most of our other clusters are qualitatively very similar.

In contrast to that, Figure 4 shows the surface brightness profiles for G105 = Bo 343. There is an apparent central density cusp, with a power-law slope $\simeq -0.75$, uncertain by about 10%, and an unresolved core. This is a typical slope for the central cusp profiles of post–core collapse clusters in our Galaxy (Djorgovski & King 1984, 1986; Djorgovski 1988). Curiously, it is also the power-law slope characteristic of star clusters around massive black holes (Bahcall & Wolf 1976); perhaps deep *ROSAT* X-ray observations of this cluster might be of some interest. The cluster is not resolved down to the limit of our data, i.e., $r_c < 0''.05$, or roughly 0.2 pc at the distance to M31; this is perfectly consistent with the observed core radii or upper limits on them for the Galactic post–core collapse clusters. We thus conclude that this is the first detection of a collapsed cluster core outside our Galaxy or its nearest satellites.

We are unable to think of any reasonable alternative explanation for the observed profiles. Our tests have convinced us that *given the data in hand*, the deconvolution results are reliable. There are two basic limiting factors for any image deconvolution: the signal-to-noise ratio, and the possible PSF mismatch between the object and the PSF star exposures. The former does not seem to be a problem here. We have no control over the latter, but we note that the PSF mismatching would in general tend to *smear* the deconvolved images and profiles and thus hide the central cusp or the unresolved core. If the PSF was at fault, we would have probably seen similar effects in our exposures of other clusters, and we do not. Whereas the only way to be certain is to obtain independent follow-up observation, we feel that the case for a collapsed core in G105 = Bo 343 is quite good.

The significance of this result is that it opens the possibility of morphological classification of globular clusters in M31, much in the same way as it was done for our Galaxy with using ground-based observations. This, in turn, would lead to a better understanding of the globular cluster system of M31, its dynamical evolution, and comparisons with that of our own Galaxy.

It is a pleasure to thank our collaborators P. Battistini, F. Bònoli, R. Buonanno, I. R. King, and R. Walterbos for their efforts in this project. This research was supported by the Consiglio delle Ricerche Astronomiche (CRA) of the Ministero delle Università e della Ricerca Scientifica e Tecnologica (MURST), Italy, and by the National Aeronautics and Space Administration, and the National Science Foundation, USA.

REFERENCES

Bahcall, J. N., & Wolf, R. A. 1976, ApJ, 209, 214
Battistini, P., Bònoli, F., Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1982, A&A, 113, 39
Battistini, P., Bònoli, F., Braccesi, A., Federici, L., Fusi Pecci, F., Marano, B., & Börngen, F. 1987, A&AS, 67, 447
Bendinelli, O. 1991, ApJ, 366, 599
Bendinelli, O., Parmeggiani, G., Zavatti, F., & Djorgovski, S. 1990, AJ, 99, 774
Bendinelli, O., et al. 1992, in Science with the *Hubble Space Telescope* (ST-ECF/STScI Workshop), ed. P. Benevenuti & E. Schreier (Garching: ESO), 271
Bònoli, F., Delpino, F. E., Federici, L., & Fusi Pecci, F. 1987, A&A, 185, 25
Cacciari, C., et al. 1992, in Science with the *Hubble Space Telescope* (ST-ECF/STScI Workshop), ed. P. Benevenuti & E. Schreier (Garching: ESO), 157
Chernoff, D., & Djorgovski, S. 1989, ApJ, 339, 904
Cohen, J. G., & Freeman, K. C. 1991, AJ, 483
Crampton, D., Schade, D. J., Chayer, P., & Cowley, A. P. 1985, ApJ, 288, 494
Djorgovski, S. 1988, in IAU Symp. 126, Globular Cluster Systems in Galaxies, ed. J. Grindlay & A. G. D. Philip (Dordrecht: Reidel), 333
Djorgovski, S., & King, I. R. 1984, ApJ, 277, L49
———. 1986, ApJ, 305, L61
Djorgovski, S., Piotto, G., Chernoff, D., & Phinney, E. S. 1991, ApJ, 372, L41
Elson, R., Hut, P., & Inagaki, S. 1987, ARA&R, 25, 565
Federici, L., Fusi Pecci, F., & Marano, B. 1990, A&A, 236, 99
Fusi Pecci, F., Ferraro, F., Bellazzini, M., Djorgovski, S., Piotto, G., & Buonanno, R. 1993a, AJ, in press
Fusi Pecci, F., et al. 1993b, in preparation
Goodman, J., & Hut, P., eds. 1985, IAU Symp. 113, Dynamics of Star Clusters (Dordrecht: Reidel)
Grindlay, J., & Philip, A. G. D., eds. 1988, IAU Symp. 126, Globular Cluster Systems in Galaxies (Dordrecht: Reidel)
King, I. R. 1966, AJ, 71, 64
King, I. R., et al. 1991, AJ, 102, 1553
Lucy, L. B. 1974, AJ, 79, 745
Meylan, G., & Djorgovski, S. 1987, ApJ, 322, L91
———. eds. 1993, Structure and Dynamics of Globular Clusters (ASP Conf. Series), in press
Richardson, W. H. 1972, J. Opt. Soc. Am., 62, 55
Sargent, W. L. W., Kowal, C. T., Hartwick, F. D. A., & van den Bergh, S. 1977, AJ, 82, 947
Vetesnik, M. 1962, Bull. Astron. Inst. Czechoslovakia, 13, 180
Weir, N. 1991, in 3d ESO/ST-ECF Data Analysis Workshop, ed. P. Grosbol & R. Warmels (Garching: ESO), 115
Weir, N., & Djorkovski, S. 1990, in The Restoration of *HST* Images and Spectra, ed. R. L. White & R. J. Allen (Baltimore: STScI), 31
Zavatti, F., Bendinelli, O., Gatti, M., & Parmeggiani, G. 1991, in 3d ESO/ST-ECF Data Analysis Workshop, ed. P. Grosbol & R. Warmels (Garching: ESO), 179