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THE VELOCITY DISPERSION OF GLOBULAR CLUSTERS IN NGC 1399

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ABSTRACT

Low-dispersion spectra of 47 globular clusters within 9′ of the core of NGC 1399 have been used to determine individual cluster velocities to a precision of ~ 150 km s^{-1}. The sample as a whole has a mean velocity of 1518 ± 91 km s^{-1} and a velocity dispersion of 388 ± 54 km s^{-1}. If the clusters are on purely circular orbits, we can place a lower limit on a globally constant mass-to-light (M/L) ratio of 79 ± 20 $M_\odot/L_{\odot B}$. This is several times larger than values of M/L determined from the stellar component closer to the core and implies that M/L must increase substantially with radius. The velocity dispersion of the globular cluster system is almost a factor of 2 larger than the velocity dispersion measured for the stellar component at 90″ but is very similar to the unusually low velocity dispersion of member galaxies of the Fornax Cluster. This implies that the globular cluster system (and by extension the cD envelope) is better associated with the Fornax Cluster as a whole than with NGC 1399 itself.

Subject headings: cooling flows — galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 1399) — galaxies: kinematics and dynamics — galaxies: star clusters

1. INTRODUCTION

NGC 1399 is in many respects an interesting and unusual galaxy. While it is the brightest member of the relatively poor Fornax Cluster of galaxies, it is also a cD galaxy with an unusually extensive stellar envelope (Schombert 1986). While having both a central radio jet (Killeen, Bicknell, & Ekers 1988) and a central velocity dispersion spike (Bicknell et al. 1989, hereafter BCKB), its core surface brightness profile as determined from *Hubble Space Telescope* Planetary Camera images appears unremarkable and is very nearly flat at $r \approx 0\farcs1$ (T. R. Lauer, private communication). NGC 1399 is enveloped by X-ray–emitting gas (Mason & Rosen 1985; Thomas et al. 1986) which has a virial temperature in the range (1–3) $\times 10^7$ K (Killeen & Bicknell 1988, hereafter KB; Ikebe et al. 1992; Kim, Fabbiano, & Trinchieri 1992; Serlemitsos et al. 1993). Finally, NGC 1399 is surrounded by one of the most populous globular cluster systems known (Hanes & Harris 1986; Harris & Hanes 1987; Bridges, Hanes, & Harris 1991).

With a view toward reconciling the temperatures inferred by KB from the X-ray data and stellar velocity dispersion measurements, we have undertaken a spectroscopic study of the globular clusters lying at $r < 9'$. The wealth of clusters around NGC 1399 together with their bright intrinsic luminosities provides us with the opportunity to trace the potential field of the galaxy in the region where the integrated stellar light becomes too weak to yield useful results. The advent of spectrographs with multiobject capabilities has made it possible to reliably determine velocity dispersions for globular cluster systems out to a distance of ~ 15 Mpc (Mould, Oke, & Nemec 1987; Mould et al. 1989; Huchra & Brodie 1987). We report here the salient results of our study; the data set and a more extensive analysis will be published elsewhere.

2. OBJECT SELECTION

The selection of globular cluster candidates in the vicinity of NGC 1399 was based on photographic photometry derived from deep B_J (IIIa-J + GG 385) and R_F (IIIa-F-RG 630) prime-focus plates taken with the 3.9 m Anglo-Australian Telescope (AAT). A rectangular region centered on NGC 1399 with length 20′ in the east-west direction and 12′ in the north-south direction was scanned on each plate using the PDS microdensitometer at the Anglo-Australian Observatory. For this purpose a 20 μm (0″31) square measuring aperture was used, as was also a 20 μm step size. Object detection was conducted via visual inspection of the blue digitized image, and magnitudes for these objects were measured using a 3″ diameter aperture on both the blue and red scans. A comparison with deep B and R CCD photometry for objects within a $3' \times 4'$ region centered on NGC 1399 provided a zero-point calibration for the photographic magnitudes, accurate to $\sim \pm 0.1$ mag. Examination of the number of objects as a function of magnitude indicated that our photographic photometry was complete to $B \sim 23$ mag.

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Globular cluster candidates were chosen by imposing the following color, magnitude, and radial constraints: (1) $0.7 \leq B-R \leq 1.4$, (2) $B \leq 22.5$, (3) $r \leq 9'$. The purpose of the color restriction was to minimize the contamination of our final set of target objects by foreground Galactic stars and, at the same time, concentrate on the color range within which globular clusters belonging to NGC 1399 were most likely to lie (Bridges et al. 1991). The imposed magnitude limit represented a realistic limit, in terms of the available telescope time and resolution of the spectrograph (see below), to which we could acquire spectra with sufficient signal-to-noise ratio to yield velocity measurements of the required precision. Finally, we chose not to pursue objects more than 9′ from the center of NGC 1399 because of the low surface density of globular clusters beyond this limit.

3. OBSERVATIONS AND RESULTS

Spectroscopy of these objects was carried out during two observing seasons using the multislit Low Dispersion Survey spectrograph (LDSS) (Wynne & Worswick 1988; Colless et al. 1990) on the AAT. This instrument was used in its "high-dispersion" mode, giving a reciprocal dispersion of 165 Å mm^{-1}. It has an imaging field 12′.3 in diameter, with a useful field size for spectroscopy of about 11′ × 7′. The UCL Image Photon Counting System (IPCS) was employed as the detector yielding a spectral resolution of 13 Å FWHM. The scale on the detector in the spatial direction is 26″.4 mm^{-1}. Combined with a detector resolution of 30 μm, this yelds a spatial resolution of 0″.8, somewhat better than the typical seeing (1″.5).

Three aperture masks were manufactured to sample candidate objects in overlapping fields centered on NGC 1399. A BG 39 filter was used to limit the wavelength coverage and thereby allow more objects to be observed without their spectra overlapping. Between 34 and 38, 1″.5 wide slits were etched into each of the three masks, and a 2′ overlap between adjoining fields allowed several repeated measurements as an aid in estimating our errors. Total integration times were ~27,000 s per mask in seeing ranging from 1″ to 3″.

Our reduction procedures are essentially identical to those of Colless et al. (1990). Owing to both the radial gradient in the background stellar light and slight nonuniformities in slit widths, marginal profiles for each slit were generated by integrating counts over the wavelengh coordinate. The sky levels appropriate to the spatial position of the objects were then determined by fitting low-order polynomials to the slit profiles.

The final, co-added spectra were cross-correlated with a variety of template spectra using standard cross-correlation techniques (Tonry & Davis 1979). Template spectra included high signal-to-noise ratio, integrated cluster spectra of Galactic globular clusters NGC 7078, NGC 7089, NGC 2808, and 47 Tuc taken with the RGO spectrograph on the AAT and the Cassegrain spectrograph on the 74 inch (1.7 m) telescope at Mount Stromlo Observatory. In addition, we used a composite spectrum of six globular clusters in the Fornax dwarf spheroidal, an integrated spectrum of the metal-weak, Fornax dwarf elliptical G79, and a composite K-giant spectrum. The best-matching templates were determined both by visual examination of target spectra and by the peak height of the cross-correlation function (CCFPH). The final velocity for each object was taken as a mean of velocities determined using the three best-matching templates.

Thirteen objects were observed twice using different masks and slit geometries. Three of these objects have radial velocities exceeding 3000 km s^{-1} and are classified as background galaxies. Because of their high redshifts and mismatch with the available template spectra, the velocities we determine for these objects are unreliable and we exclude them from this analysis. The pairwise differences in velocity for the remaining 10 objects yield an rms velocity uncertainty per observation of 171 ± 38 km s^{-1}. Extensive simulations have shown that velocities determined from CCFPHs < 0.2 are unreliable. Excluding two objects whose CCFPHs fall below this limit, we obtain an rms velocity uncertainty of 150 ± 38 km s^{-1}.

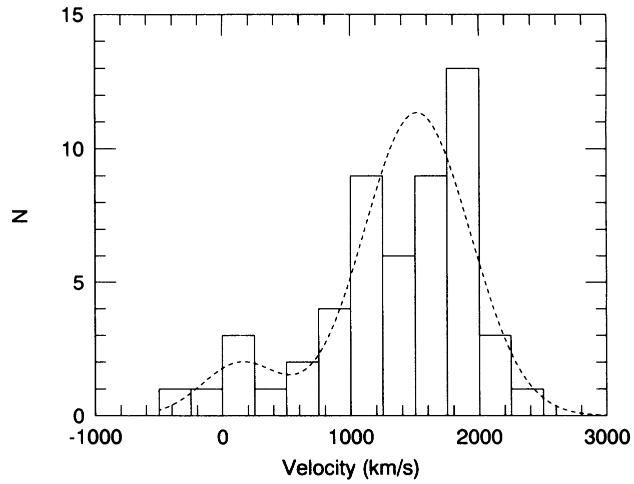

FIG. 1.—Velocity distribution of all objects with $v < 3000$ km s^{-1}. The dashed curve corresponds to a maximum-likelihood fit of two Gaussians to the distributions of halo stars and NGC 1399 globular clusters.

In Figure 1 we plot a velocity histogram for the 53 objects with $v \leq 3000$ km s^{-1} and CCFPH > 0.2. In view of possible blending of the velocity distributions of Galactic halo stars and globular clusters belonging to NGC 1399, we use the maximum-likelihood method described by Morrison, Flynn, & Freeman (1990) to determine simultaneously the relative contributions and the most probable dispersions of the two samples. Assuming Gaussian velocity distributions, we find that 6 ± 1 objects are probably foreground halo stars based on their velocities alone. These stars have a mean velocity of 144 ± 254 km s^{-1} and dispersion of 269 ± 167 km s^{-1}. These values are consistent with the Galactic model of Sommer-Larsen (1987), which predicts a mean velocity of 110 km s^{-1} and a dispersion of 115 km s^{-1} for stars in the direction of NGC 1399. The number of halo stars agrees well with the 7 ± 1 stars predicted by the Bahcall-Soneira model (Bahcall & Soneira 1980; Mamon & Soneira 1982) to lie within the color and magnitude limits imposed by our selection criteria.

We take the remaining 47 objects to be globular clusters belonging to NGC 1399. The best-fitting Gaussian has a mean velocity of 1517 ± 91 km s^{-1} and a dispersion (corrected for instrumental dispersion) of $\sigma_g = 388 \pm 54$ km s^{-1}, where the uncertainties correspond to 1 standard deviation. The mean velocity of the cluster system is consistent with the 1425 km s^{-1} radial velocity of the stellar component (BCKB). The mean rotation velocity of the system is, to within the uncertainties, consistent with zero. There is no evidence for a nonzero radial gradient in the velocity dispersion profile of the globular clusters, although the uncertainties do not allow us to establish meaningful bounds in this respect.

4. ANALYSIS

In Figure 2 we compare the velocity dispersion we measure for the globular clusters with the velocity dispersion measurements for other components of NGC 1399 and the Fornax Cluster. The dispersion we find for the globular cluster system is considerably higher than that found for the integrated stellar light within 1'.5 of the core (BCKB; Franx, Illingworth, & Heckman 1989; Winsall & Freeman 1993). Are we to conclude that M/L and/or orbital anisotropy must undergo dramatic changes in the region $1'.5 < r < 5'.5$?

For a spherical potential, hydrostatic equilibrium requires that

$$\frac{GM(r)}{r} = -\sigma_r^2\left(\frac{d\ln\rho}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right) \quad (1)$$

(Binney & Tremaine 1987), where $M(r)$ is the total mass interior to radius r, σ_r is the radial component of the velocity dispersion, $\rho(r)$ is the volume density of test particles, and the anisotropy parameter β is defined as $1 - \sigma_\theta^2/\sigma_r^2$. We consider first the simplest case where the cluster velocity distribution is assumed to be isothermal and isotropic [$\sigma_r(r) = \sigma_g$, $d\ln\sigma_r^2/d\ln r = 0$, $\beta = 0$). The volume density of globular clusters goes approximately as $\rho_g(r) \propto r^{-2.45}$ (Bridges et al. 1991). Assuming a distance modulus for NGC 1399 of 30.6 (BCKB), we have $M(r) \simeq 3.3 \times 10^{11} r(\text{arcmin})\ M_\odot$. We obtain the luminosity density from an Abel inversion of the surface brightness profile (BCKB; Schombert 1986). We find a total integrated luminosity within 5'.5 of $2.7 \times 10^{10}\ L_{\odot B}$ and obtain an integrated M/L_B of $67 \pm 19\ M_\odot/L_\odot$, where the quoted error reflects only the uncertainty in σ_g.

We can place a lower limit on a *globally constant M/L* by assuming that the globular clusters are on purely circular orbits. If the surface density profile of the globular clusters follows that of the stellar light (Harris & Hanes 1987), then the expectation value for the line-of-sight velocity dispersion at projected radius R is

$$\sigma_p^2(R) = \frac{R^2}{2}\left[\int_R^\infty \frac{v_c^2(r) l(r) r\,dr}{r^2(r^2 - R^2)^{1/2}}\right]\left[\int_R^\infty \frac{l(r) r\,dr}{(r^2 - R^2)^{1/2}}\right]^{-1}, \quad (2)$$

where

$$v_c^2(r) = \frac{GM(r)}{r} = \frac{4\pi GA}{r}\int_0^r l(r')r'^2\,dr', \quad (3)$$

$l(r)$ is the luminosity density determined from the stellar photometry, and A is the global mass-luminosity ratio. Sampling the velocity dispersion profile predicted by equation (2) over the same distribution of projected radii as is present in our data, we find $A = 79 \pm 20\ M_\odot/L_\odot$. That this value is higher than the integrated M/L computed above is a consequence of differing mass distributions; the total mass contained within 100 kpc would be ~ 2 times larger in the isotropic case.

This limit on a constant M/L is several times larger than the values between 14 and 17 determined by BCKB from observations of the stellar component, and we are led to conclude that *M/L must* vary substantially with radius. Following Mould et al. (1989), we have conducted Monte Carlo tests to determine to what extent the value we obtain for the globular cluster velocity dispersion could have arisen by chance. Starting with a nonrotating model in which all clusters have circular orbits and in which $M/L = 17$ and is constant with radius, we have sampled velocities from normal distributions with model-predicted line-of-sight dispersions at the radii of each of our clusters. We find that the sample velocity dispersions are greater than our observed dispersion in less than 1% of the simulations. Hence we can reject the constant M/L models at the 99% confidence level.

The values of M/L we determine from the simple models above are consistent with $M/L \simeq 70$–260 (90% confidence interval) at $r = 10'$, determined by KB from *Einstein* observations of the X-ray emission. More recent observations made with *Ginga* (Ikebe et al. 1992) and the Broad Band X-Ray Telescope (Serlemitsos et al. 1993), and a reanalysis of the *Einstein* data by Kim et al. (1992), put the temperature of the X-ray gas between 1.2×10^7 and 1.7×10^7 K. Combining this temperature range with KB's empirical isothermal model implies $48 \lesssim M/L \lesssim 72$, which is in even closer agreement with our results.

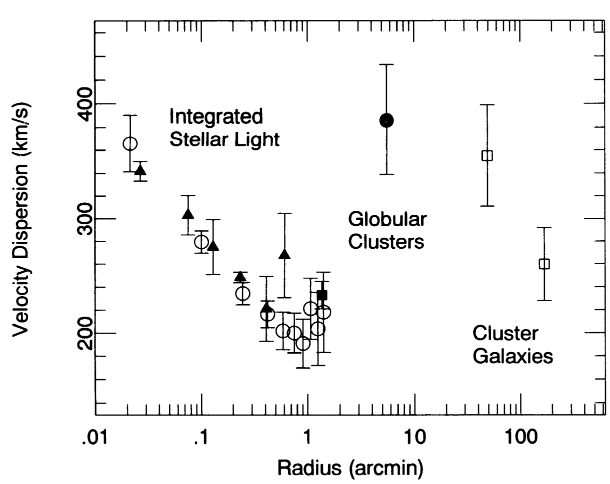

FIG. 2.—Velocity dispersion profile of NGC 1399. Open circles indicate the integrated stellar light measurements of BCKB; filled triangles correspond to the data of Franx, Illingworth, & Heckman (1989); and the filled square is from Winsall & Freeman (1993). The filled circle indicates the measured velocity dispersion of the globular clusters. The open squares correspond to the velocity dispersions of Fornax galaxies deemed by Ferguson (1989) to be likely members of the Fornax Cluster.

5. DISCUSSION

The velocity dispersion we find is very similar to the velocity dispersion of the Fornax Cluster itself. Could we in fact be measuring the potential field of the cluster as a whole? Does the apparent minimum in the velocity dispersion profile in Figure 2 at $r \sim 90''$ define a limiting radius, separating galaxy from cluster? Are the globular clusters we have observed part of a larger population of intracluster "tramps" (Muzzio 1987)?

In Figure 3 we plot the optical surface brightness profile of NGC 1399 as determined by BCKB and Schombert (1986). Also shown are the arbitrarily normalized surface densities of globular clusters (Harris & Hanes 1987) and the smoothed contribution to the surface brightness by individual Fornax Cluster galaxies as determined from their total blue magnitudes (Ferguson 1989). *No normalization has been applied to the surface brightness contributions of the galaxies.* It is immediately apparent that there is remarkable uniformity among the different profiles. To within the uncertainties, all profiles beyond 10'' follow a power law of the form $\Sigma(R) \propto R^{-1.5}$. This would be consistent with a model in which the globular clusters and the cD envelope were formed out of the tidal debris generated during the collapse of the Fornax Cluster (Merritt 1984; White 1987). However, it would also be consistent with the continual, self-similar buildup of the envelope through

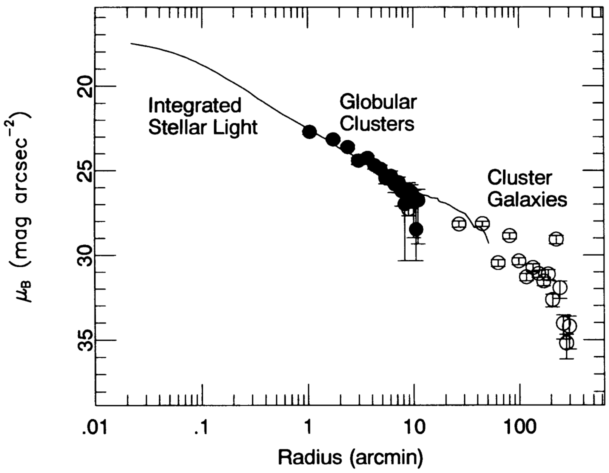

FIG. 3.—Surface brightness/density profile of NGC 1399 and its environs. The solid line is the optical surface brightness profile from CCD (BCKB) and photographic (Schombert 1986) measurements. The photographic surface brightness profile has been shifted vertically by 1.2 mag to match the *B*-band CCD observations. Filled circles show the (arbitrarily normalized) surface densities of globular clusters (Harris & Hanes 1987), and open circles show the smoothed, *unnormalized* surface brightness contributions of galaxies in the Fornax Cluster (Ferguson 1989).

postcollapse mergers (Quinn et al. 1990). The unusually low velocity dispersion of the Fornax Cluster suggests that dynamical evolution will have been more rapid than in most other clusters (Merritt 1984), and we might expect a significant number of mergers to have taken place over a Hubble time. Indeed, Ostrov, Geisler, & Forte (1993) find a multimodal metallicity distribution among NGC 1399's globulars, a finding consistent with the merger model of Ashman & Zepf (1992).

Models which have globular clusters forming out of cooled, infalling X-ray gas (Fabian, Nulsen, & Canizaries 1984) do not appear naturally consistent with our data. If the globular clusters formed near the cooling radius, their velocity dispersion should be low and their orbits fairly radial, and the line-of-sight velocity dispersion at the cooling radius should be near zero. The cooling radius for the gas surrounding NGC 1399 has been determined by Thomas et al. (1986) to occur at $\sim 8'$, within the region covered by our sample. As noted previously, we see no evidence for a decline in the velocity dispersion with radius.

The velocity dispersion we find for globular clusters in NGC 1399 is similar to values of 386 and 440 km s^{-1} found, respectively, by Mould et al. (1987, 1989) and Huchra & Brodie (1987) for globular clusters in M87. As in NGC 1399, these values are significantly higher than the velocity dispersion of the stellar component closer to the core (Sargent et al. 1978). On the other hand, the velocity dispersion of M87's globular cluster system is much less than that of the Virgo Cluster. Whereas NGC 1399's cluster system has a surface density profile similar to that of the stellar light, M87's cluster system is significantly more distended than the stellar envelope (Strom et al. 1981; Lauer & Kormendy 1986; Grillmair, Pritchet, & van den Bergh 1986). However, this may be largely due to the much broader extent of NGC 1399's surface brightness profile compared with that of M87. The globular cluster systems in these two galaxies appear to be more similar to one another in many respects than do their parent galaxies. The addition of kinematic data to the comparison should put better constraints on models of the formation of cD galaxies and the dynamics of galaxy clusters.

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