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THE KINEMATICS OF THE OUTER HALO OF M87[1]

JUDITH G. COHEN[2]

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ABSTRACT

Radial velocities are presented for a new sample of globular clusters in the outer halo of M87 at a distance of 300″–540″ (24–43 kpc) from the center of this galaxy. These are used to augment our previously published data, and an analysis of the rotation and velocity dispersion of the M87 globular cluster system is carried out. The rotation is $\sim$300 km s^{-1} at $R = 32$ kpc, at which point the velocity dispersion is also still quite high, $\sim$450 km s^{-1}. The high rotation is interesting. The outer halo of M87 is, as was found in our previous kinematic analysis, very massive.

Key words: galaxies: individual (M87) — galaxies: fundamental parameters — galaxies: star clusters

1. INTRODUCTION

Cohen & Ryzhov (1997, hereafter CR97) present an analysis of the kinematics of M87 based on radial velocities for 205 globular clusters (GCs) in the halo of M87. In that paper we adopted a rotation curve that rises linearly with radius from the center of M87 (R) until reaching 180 km s^{-1} at a radius of 225″. Beyond that point, and particularly beyond $R \sim 350''$, our sample became too sparse to establish a meaningful rotation curve, and, following the example of the Galaxy, we adopted the fixed value of 180 km s^{-1} as the rotation of the outer part of M87.

The rotation of M87 is important for two reasons. The total angular momentum of M87 is a clue to the mode of formation of this massive elliptical galaxy at the center of the Virgo cluster cooling flow. This parameter can help distinguish between formation via a gravitational collapse as advocated by Peebles (1969) and formation via a merger model. In addition, a major goal of CR97 was the determination of the enclosed mass of M87 as a function of R. A proper dynamical mass estimate requires knowledge of both rotation and dispersion.

Kissler-Patig & Gebhardt (1998) suggested, based on a reanalysis of our previously published data, that the rotation in the outer part of M87 is large and decreases the observed σ_v more than we allowed for in our previous work. Since our sample of GCs there is very sparse, the purpose of this paper is to present radial velocities for an additional group of M87 globular clusters selected to be in spatial positions that maximize their ability to constrain the rotation of the outer halo of M87. We then combine this new data with our previously published data to reexamine the issue of the rotation and velocity dispersion in the outer part of M87.

Whitmore et al. (1995) derive a distance to M87 of 17 Mpc from the turnover of the M87 GC luminosity function. This is in excellent agreement with the mean of the Cepheid distances for Virgo cluster spirals from Pierce et al. (1994) and from Ferrarese et al. (2000) of 16 Mpc, ignoring NGC 4639 (Saha et al. 1996) as a background object. Hence we adopt 16.3 Mpc (80 pc arcsec^{-1}) as the distance to M87.

2. NEW OBSERVATIONS OF M87 GC CANDIDATES

We observed a single-slit mask of M87 GC candidates with the Low Resolution Imaging Spectrograph (LRIS) (Oke et al. 1995) at the Keck Telescope during the spring of 1999. This mask was designed to include objects located along the major axis of M87, $\approx$400″ southeast of the nucleus, with the slit length running perpendicular to the major axis. It contains objects with $R \sim 300''$–540″ from the center of M87. Candidates from the catalog of Strom et al. (1981) in this area were checked on existing direct images to determine if they appeared to be M87 GCs. Those that are brighter than $B = 22$ mag and that were not observed by CR97 were included here. In addition, our new sample is at the maximum radius from M87 of the Strom et al. survey. Since we wish to include M87 GCs at even larger radii, we selected several stellar objects from the area on these LRIS images beyond that of the Strom et al. survey that appeared to be M87 GCs. Finally, we included the object in this region with the most discordant v_r from CR97.

The slit mask was observed with the same instrumental configuration of LRIS as was used in CR97, but the grating was tilted to center the spectra at Hα. Only Hα was used to determine the radial velocities. Because of the plethora of night-sky lines and the use of a 1″ wide slit, these v_r are more accurate than those of CR97, with typical 1 σ errors of only $\pm$50 km s^{-1}. Table 1 lists the new radial velocities. There are 20 entries, four of which are included in CR97. Two of the M87 GCs were found through the procedure described above and have not been previously cataloged. They are assigned identifying numbers beginning with 6000; their location and brightness in the R filter bandpass using the standard stars of Landolt (1992) are given in footnotes to the table. Both are more than 500″ from the center of M87.

The v_r from CR97 for the four cases in common are listed in the last column of Table 1. The agreement is very gratifying and suggests yet again that the quoted error estimates for these GC radial velocities are realistic.

Several interlopers were also found among these new spectroscopic observations. Strom 81 is a galaxy showing strong Hα emission with $z = 0.335$, and Strom 87, 221, and 286 are Galactic stars.

3. ROTATION AND VELOCITY DISPERSION ANALYSIS

The sample of 16 new GCs in M87 presented in Table 1 more than doubles the sample with spectroscopic v_r with $R > 420''$. This should produce credible measures of the

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[2] Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, CA 91125; jlc@astro.caltech.edu.

TABLE 1
NEW RADIAL VELOCITY MEASUREMENTS FOR M87 GLOBULAR CLUSTERS

ID[a]	R[b] (arcsec)	v_r (± 50 km s^{-1})	v_r from CR97 (km s^{-1})
16	530	1115	...
28	494	1157	...
41	486	1814	...
66	517	2212	2260
77	367	1774	...
94	393	963	...
103	375	1092	...
137	367	1764	...
176	502	2167	2210
177	479	1540	1629
300	455	1977	...
314	309	1167	1236
379	413	2244	...
415	395	1817	...
477	363	1584	...
514	412	1617	...
603	397	1741	...
731	383	960	...
6003[c]	516	1741	...
6004[d]	540	1741	...

[a] ID from Strom et al. 1981 except as noted.
[b] Distance from the center of M87.
[c] New M87 GC located 2″.7 W and 27″.3 S of Strom 176, $R = 21.05$ mag.
[d] New M87 GC located 1″.2 W and 54″.4 S of Strom 176, $R = 21.22$ mag.

rotation and velocity dispersion in the outer part of M87. The sample of M87 GC radial velocities we utilize below is that of CR97, as augmented and updated in Cohen, Blakeslee, & Ryzhov (1998), plus the new material presented in Table 1. This gives a total of 222 objects believed to be M87 GCs.

3.1. *Qualitative Results*

To demonstrate in a simple yet convincing manner that significant rotation exists in the outer halo of M87, we assume that the rotation is about a fixed position angle, that characteristic of the isophotes of M87. A modern study of the isophotes of M87 by Zeilinger, Moller, & Stiavelli (1993) finds the major axis of the galaxy to be at P.A. = 160° and the effective radius to be $\sim 90''$ (7.2 kpc). The ellipticity they deduce increases with radius outside the core, reaching 0.2 at $1.3r_{\rm eff}$. (In early work on this galaxy, Cohen 1986 found $\epsilon \sim 0.2$ at $R = 230''$ with a position angle of 155°.) McLaughlin, Harris, & Hanes (1994) establish that the P.A. of the M87 GC system is identical to that of the underlying galaxy halo light. Kundu et al. (1999) find the P.A. of the globular cluster system very close to the center of M87 to be somewhat larger, ~190°. The analysis of the isophotes of this galaxy by J. P. Blakeslee (1999, private communication) covers this entire range of R and shows the twisting of their major axis within the central 20″ and the increase of ϵ outward.

We further assume that the mean velocity at all radii is the systemic velocity of M87, 1277 ± 5 km s^{-1} (van der Marel 1994). Figure 1 shows the rotation curve deduced under these assumptions for all M87 GCs beyond $R = 380''$ with separate symbols for the new observations presented here and for the published data of CR97. The horizontal

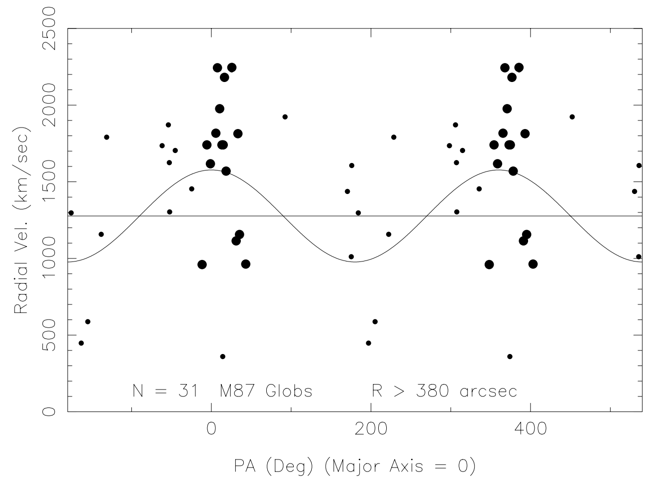

FIG. 1.—Radial velocity of M87 GCs with $R > 380''$ as a function of position angle about the major axis of M87: data of Table 1 (*large circles*) and M87 GCs from CR97 (*small circles*). The curve shows the projected rotation as a function of θ with amplitude of 300 km s^{-1} about the systemic velocity (*horizontal line*).

line indicates the systemic velocity, while the curve shown is for $v_{\rm rot} \sin i = 300$ km s^{-1}. The sample at such large distance from the center of M87 is now reasonably large (31 M87 GCs), with good coverage near P.A. = 160° and 340°, i.e., along the major axis both toward the southeast and the northwest from the center of M87, and clearly demonstrates that the outer part of M87 is rotating rapidly. In addition, Figure 1 shows that the velocity dispersion of the M87 GC system is still very large, ~400 km s^{-1}, even at the outermost point reached.

3.2. *Quantitative Determination of the Rotation Curve of M87*

Both the analysis given in CR97 and that of Kissler-Patig & Gebhardt (1998) suggest that the assumptions made above with respect to the position angle of the axis of rotation and the systemic velocity are correct, and we therefore adopt them for our detailed analysis of the rotation of M87.

GCs that are located on the minor axis constrain the mean velocity and velocity dispersion but contribute no information toward determining the amplitude of rotation. Having made the above assumptions, given the large velocity dispersion of the M87 GC system compared with the expected rotation, the GCs near the minor axis of M87 contribute mostly noise to the determination of the amplitude of rotation. We thus do not include clusters with $|\cos(\theta - \theta_0)| < 0.30$ in the rotation solution, the choice of angle being somewhat arbitrary but based on the ratio of $\sigma_v/v_{\rm rot}$. This excludes GCs in two arcs, each 35° long, centered on each end of the minor axis, or 19% of the total sample, if the GCs are distributed uniformly in angle at all radii. All GCs, including the ones rejected here, are subsequently utilized to determine the velocity dispersion.

The rotation analysis is thus reduced to finding a suitable statistically accurate representation of the set of values $[v_{\rm rot}(R)]_i = [v_r(i) - v_{\rm sys}]/\cos(\theta - \theta_0)$ for GCs within a specified range of R. Within each radial bin considered, a two-step χ^2 minimization solution was implemented to solve for an appropriate value of the amplitude of the rotation, $v_{\rm rot}(R)$. The errors in the individual terms on the right-hand side of the above expression for a constant observational

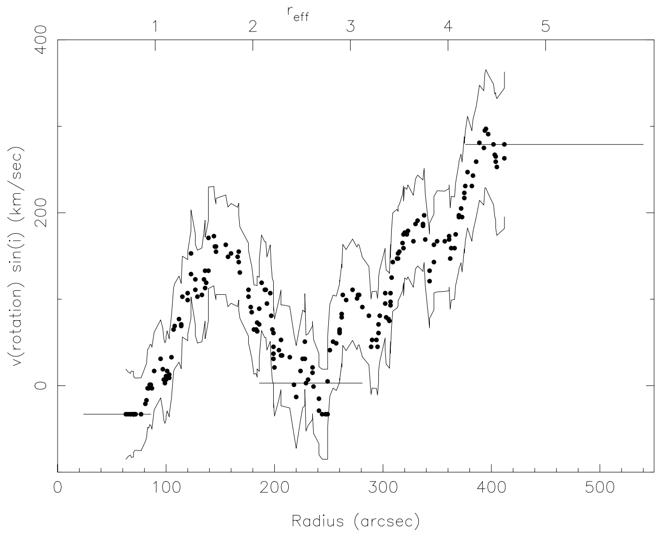

FIG. 2.—Projected rotational velocity inferred for M87 from its system of GCs as a function of *R*. Each point represents a group of GCs at similar radii. Horizontal lines show the range of radii included within three typical bins and 1 σ error bars for each point. Details of the binning scheme are described in the text.

uncertainty in v_r are highly variable and depend on θ. The procedure adopted allows for these varying uncertainties. In the first pass, an initial guess at $\sigma_v(R)$ is used, and a solution for $v_{\rm rot}(R)$ is found. This solution for $v_{\rm rot}(R)$ is used to derive $\sigma_v(R)$. Since $\sigma_v(R)$ is used as the error estimate for each point for $v_{\rm rot}(R)$, a second-pass solution, which only makes very small adjustments, is then carried out to derive $v_{\rm rot}(R)$.

The GCs in the spectroscopic sample are sorted in ascending order in *R*. The analysis is carried out with 30 point bins at the extreme inward and outward points, increasing to bins with 50 GCs wherever possible. The bin center is shifted outward by 1 GC, and the solution is repeated. Figure 2 displays the resulting solution for $v_{\rm rot}(R_m)$ as a function of the median distance (R_m from the center of M87) for the GCs in each bin. The errors are calculated assuming Gaussian statistics within each bin. The radial extents for a few typical bins are indicated by the horizontal lines in the figure. The rotation curve is heavily oversampled; there are only five independent points on this figure.

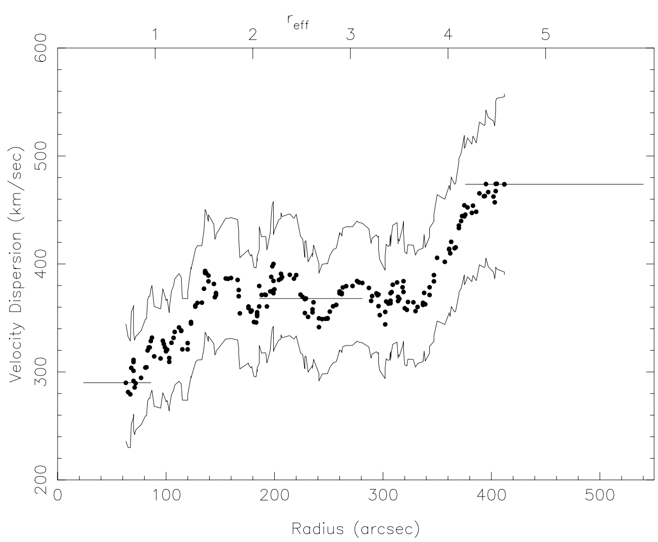

FIG. 3.—Same as Fig. 2, but for the velocity dispersion. The contribution of rotation to the observed σ_v has been removed.

3.3. *Determination of Velocity Dispersion*

The calculation of the velocity dispersion requires removal of the rotational velocity. This is done using a smoothed version of the rotation amplitude found as described above. The biweight estimator described in Beers, Flynn, & Gebhardt (1990), which is strongly resistant to outliers, is used. The instrumental contribution to $\sigma_v(R)$ is also removed in quadrature. The same variable binning with *R* used for the rotation solution is adopted here. The entire spectroscopic sample of M87 GCs is used.

The resulting radial profile of σ_v is shown in Figure 3. The radial extent of a few typical bins is indicated by the horizontal lines in the figure. As is the case for Figure 2, the velocity dispersion profile shown in this figure is heavily oversampled.

4. DISCUSSION

4.1. *Comments on Galaxy Formation*

Both the qualitative and the quantitative analyses show that the outer part of the halo of M87 with $R \sim 400''$, 32 kpc from the center of M87 and at $4.4 r_{\rm eff}$, is rotating with a projected rotational velocity of ~ 300 km s^{-1}. This is a very large rotational velocity to be found so far out in M87, implying that the total angular momentum of M87 is very large. It is interesting to note that the halo population of the Galactic globular cluster system shows a rotation of only 50 ± 23 km s^{-1}, while the disk population of Galactic GCs is highly flattened, with $v_{\rm rot} = 152 \pm 29$ km s^{-1} (Zinn 1985).

Among the various theories of galaxy formation, there are several that are often applied to elliptical galaxies. The theory of dissipationless collapse from a single gas cloud through a gravitational instability and acquisition of angular momentum through tidal torques was worked out by Peebles (1969). Binney (1978) calculated the expected rotation velocities of elliptical galaxies under various assumptions regarding orbit anisotropy. Detailed *N*-body simulations along these lines have been carried out by several groups, including Barnes & Efstathiou (1987), Stiavelli & Sparke (1991), and Ueda et al. (1994). The relevant parameter for comparison of observations with analytical and numerical models of galaxy formation is the spin parameter (Peebles 1971), a dimensionless combination of the total angular momentum, total mass, and total energy for a galaxy, $\lambda = JE^{1/2}G^{-1}M^{-5/2}$. This does not exceed 0.1 for such models, while Kissler-Patig & Gebhardt (1998) find $\lambda \sim 0.18$ for M87, with the caution that calculating λ from our existing observational material requires an extrapolation to the half-mass radius in the halo of M87, much farther out in *R*. The complication of possible triaxial shapes rather than oblate isotropic rotators, reviewed by de Zeeuw & Franx (1991), further obscures the validity of such calculations.

The other major theory currently in vogue for the formation of elliptical galaxies is the theory of formation through the merger of several large gas-rich fragments, as originally suggested by Toomre & Toomre (1972). Such models come in various flavors, with the mergers happening relatively late and the pieces being entire galaxies, as in Kormendy (1989) and Kormendy & Sanders (1992), or happening at early times and involving protogalaxy clumps, as in White & Rees (1978). Recent numerical simulations of this type of model, expanding on the earlier work of Barnes (1988), can be found in Hernquist & Bolte (1993) and in Bekki (1998). It is likely that such a model is more capable of reproducing the high rotation we find. Furthermore, the observation by Weil, Bland-Hawthorn, & Malin (1997) of nonsymmetric diffuse light in the halo of M87 extending 100 Kpc from its center may also be explained by the recent accretion of a low-mass galaxy. Ashman & Zepf (1998) explore the consequences of such a model for a galaxy's system of GCs.

4.2. *Effect of Present Results on Those of Cohen & Ryzhov (1997)*

Even with the large rotation we have found in the outer part of M87, we find the velocity dispersion after the observed values are corrected for the rotation to be still high there. In the outermost bin of CR97, σ_v agrees to within 5% with the value found here. In only one of the nine radial bins used by CR97 is σ_v from the current solution smaller than the values given in CR97. We therefore expect that the results of CR97 with respect to the distribution of mass within M87 are still approximately correct.

5. SUMMARY

We have presented spectroscopic observations of a new sample of M87 GCs chosen to put maximum leverage on a determination of the rotation in the outer halo of M87. Using this data combined with our previously published data, we find that the rotation of M87 increases outward and reaches a value of ~ 300 km s^{-1} at a distance of 400″ (32 kpc, 4.4$r_{\rm eff}$) from the center of this galaxy, confirming the suggestion of high rotation, based on our previously published set of M87 GC radial velocities, by Kissler-Patig & Gebhardt (1998). That is rather surprising. The velocity dispersion remains high even at that large R, and the enclosed total mass is very large, as our earlier work (see CR97) suggested.

The high rotation may provide a clue to the mode of formation of M87, but the calculation of total spin is uncertain, as it involves extrapolation to still larger radii. In addition, M87 is located in a very special place, the center of a very large mass concentration, a large cooling flow, etc. Its history may be quite different from that of most ellipticals, even of most massive ellipticals.

The results of the initial spectroscopic studies of the dynamics of elliptical galaxies in the early 1980s were very surprising. Davies et al. (1983) showed that low-luminosity ellipticals rotate as rapidly as spiral bulges and as rapidly as predicted by models with oblate figures and isotropic distributions of residual velocities. However, as was discovered by Illingworth (1977), high-luminosity ellipticals show surprisingly small values of $v_{\rm rot}/\sigma_v$. Our results for the outer part of M87, where $v_{\rm rot}/\sigma_v \sim 0.6$, include no correction to $v_{\rm rot}$ for projection effects, which would only make this ratio larger. Similar suggestions for high rotation in the outer parts of luminous ellipticals near the center of large clusters of galaxies have been obtained from the analysis of a sample of globular clusters in M49 by Sharples et al. (1998) and one in NGC 1399 by Kissler-Patig et al. (1999). This gives rise to some interesting questions. Is this large rotation in the outer parts of the M87 GC system also shared by the M87 stellar halo? How far out does this rotation continue? To be provocative, we might ask if most luminous elliptical galaxies have $v_{\rm rot}/\sigma_v > 0.5$ in their outer parts, and whether this was missed in earlier studies because of limitations on slit length and on surface brightness in those spectroscopic studies.

One of the few ways to explore these issues is to attempt to find large samples of GCs even farther out in the halo of M87. We have paved the way with a first identification of M87 GCs beyond the spatial limit of existing surveys.

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