THE SPIN OF M87 AS MEASURED FROM THE ROTATION OF ITS GLOBULAR CLUSTERS

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ABSTRACT

We revisit the kinematical data for 204 globular clusters in the halo of M87. Beyond 3reff along the major axis of the galaxy light, these globular clusters exhibit substantial rotation (\(\sim 300 \pm 70\) km s\(^{-1}\)) that translates into an equally substantial spin (\(\lambda \sim 0.18\)). The present appearance of M87 is most likely the product of a single major merger, since this event is best able to account for so sizable a spin. A rotation this large makes improbable any significant accretion of material after this merger, since that would have diluted the rotation signature.

We see weak evidence for a difference between the kinematics of the metal-poor and metal-rich population, in the sense that the metal-poor globular clusters appear to dominate the rotation. If, as we suspect, the last major merger event of M87 was mainly dissipationless and did not trigger the formation of a large number of globular clusters, the kinematic difference between the two could reflect their orbital properties in the progenitor galaxies; these differences would be compatible with these progenitors having formed in dissipational mergers. However, to put strong kinematic constraints on the origin of the globular clusters themselves is difficult, given the complex history of the galaxy and its last dominant merger event.

Key words: galaxies: elliptical and lenticular, cD — galaxies: individual (M87) — galaxies: star clusters

1. INTRODUCTION

Little is known about the kinematics of the halos of elliptical galaxies. Unlike spiral galaxies, ellipticals contain little gas that could serve as a kinematical tracer, and studies of the stellar light seldom extend further than 2 effective radii (r_\text{eff}), due to the decreasing surface brightness and the difficulty obtaining spectra of the diffuse stellar light. Furthermore, companion galaxies, which could serve as kinematical probes in the outer halo, are usually not numerous and too distant to probe the range between 2 and 10 (or more) r_\text{eff}. Recently, however, globular clusters and planetary nebulae have become popular test particles to probe the kinematics in the halo of giant ellipticals. With the commissioning of 8 m class telescopes, large samples of radial velocities can be obtained, extending out to several r_\text{eff} from the center of the galaxies. Globular clusters are especially numerous around central giant ellipticals and therefore are probably the best tracers of the outer kinematics in these galaxies.

The kinematics derived from the globular clusters can be used to constrain galaxy formation history. For example, cosmological N-body simulations make specific predictions of the amount of spin that will result from the torques caused by the multiple accretion of objects (see § 4.2); moreover, a formation via dissipational mergers predicts both varying kinematics of the globular clusters with radius and different kinematics between the newly formed globular clusters and the ones brought in by the progenitors (see § 4.3).

Thus, the kinematics of a large sample of globular clusters provides not only constraints on the formation and evolution of the galaxy, but also a better understanding of the formation of the globular cluster systems. In the central cD galaxy in Fornax (NGC 1399), the kinematics of the globular clusters constrain the origin of the large over-abundance of globular clusters (Kissler-Patig et al. 1998a). In the other dominant giant elliptical in Virgo (NGC 4472), the kinematics of the globular clusters suggest a formation via two massive gas-rich galaxies (Sharples et al. 1998).

Here we revisit the central giant elliptical in the Virgo galaxy cluster, M87 (NGC 4486), and derive the kinematics in a region between 1 and 5r_\text{eff} using published radial velocities for over 200 globular clusters (Cohen & Ryzhov 1997). Previous work on the kinematics of globular clusters around M87 also include studies from Huchra & Brodie (1987), Mould et al. (1990), and Brodie & Huchra (1991). These studies were based on 20–45 objects. Interestingly, Mould et al. reported dynamically significant rotation in both M87 and M49. In M87 their study extends to \(\sim 400^\circ\) radius; they report a rotation along the major axis of 0.60 \(\pm 0.27\) km s\(^{-1}\) arcsec\(^{-1}\), i.e., 240 \(\pm 108\) km s\(^{-1}\) at their extreme radius. The extension of this result is the main motivation for this work.

In the next section (§ 2) we briefly describe the sample and our new analysis before presenting in § 3 the velocity dispersion and rotation velocity both as a function of radius and an estimate for the dimensionless spin parameter \(\lambda\) for the galaxy. We discuss our findings and present our conclusions on the formation history of M87 in § 4.

2. GLOBULAR CLUSTER SAMPLE AND DATA ANALYSIS

2.1. The Sample

We used the sample of 230 globular cluster candidates around M87 for which Cohen & Ryzhov (1997) published radial velocities, including an additional cluster (ID 682) and the update on five velocities given in Cohen, Blakeslee, & Ryzhov (1998). The coordinates were obtained from Strom et al. (1981). Following Cohen & Ryzhov, we excluded galactic stars by selecting a subsample of 204 globular clusters with velocities v_r > 250 km s\(^{-1}\). We also excluded an additional candidate at v_r = 350 km s\(^{-1}\). The velocity offsets from the systemic velocity for the remaining

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objects are well below the escape velocity of the galaxy. Also, we do not expect any torques or tidal influence on the velocities from the Virgo cluster, since M87 is located at its exact center (see, e.g., Schreier, Gorenstein, & Feigelson 1982). The resulting sample is shown in Figure 1, where we plot the position of all of the globular clusters. The symbol sizes reflect the difference between the cluster velocities and our adopted systemic heliocentric velocity for M87 of $1282 \pm 9 \text{ km s}^{-1}$, taken from the RC3 (de Vaucouleurs et al. 1991). Open circles show approaching globular clusters, and filled circles show receding globular clusters; the dashed line marks $r_{\text{eff}}$ ($\sim 100''$; see, e.g., Goudfrooij et al. 1994) of the galaxy light, and the solid line marks $3r_{\text{eff}}$.

2.2. Analysis

Cohen & Ryzhov (1997) comprehensively present and discuss the velocity dispersion of the globular clusters as a function of distance from M87. The authors also discuss rotation but only divide their data into two radial bins (within and outside 180$^\circ$), and they find no significant deviation in these two subsamples compared with the rotation of the whole sample: about 100 km s$^{-1}$ along a position

Fig. 1.—Position of the globular clusters around M87. The sizes of the symbols reflect the difference between the globular cluster velocity and the systemic velocity of the galaxy. Open circles represent approaching globular clusters, filled circles represent receding globular clusters; the dashed and solid lines mark $r_{\text{eff}}$ and $3r_{\text{eff}}$ of the galaxy, respectively.

Fig. 2.—Projected velocity dispersion, projected rotational velocity, position angle, and $v \sin i/\sigma_v$ as functions of radius. Dotted lines mark the 68% confidence bands.
angle (measured from north through east throughout this paper) of $\sim 150^\circ$, defined as the angle of maximum positive rotation.

We extend their study by investigating the radial profiles of the rotation, position angle, and velocity dispersion. For each globular cluster, we use the nearest 75 data points in radius to measure the above three parameters, allowing this subsample to drop to 30 data points at the extreme radii, 80" and 400". For each subsample, a maximum-likelihood fit determines the position angle, rotation amplitude, and dispersion at that radius (see Pryor & Meylan 1993, e.g., for the basic approach). The fit measures the best sinusoid for the velocity data as a function of position angle. We fix the mean velocity of the subsamples to be equal to the global mean velocity. The amplitude of the fit provides the rotation, the angle of maximum positive rotation provides the PA, and the standard deviation about the sinusoid provides the velocity dispersion. The uncertainty in the fit is derived in two ways: using the classical covariance matrix and using a bootstrap. For the bootstrap uncertainties, at each location where a cluster exists, we draw a point from a Gaussian distribution with the mean given by the rotation amplitude and PA at that radius, and the standard deviation given by the dispersion at that radius. A velocity uncertainty of 50 km s$^{-1}$ is also included. This sampling provides one realization, and we similarly fitted the three parameters. Generating 100 realizations then allows for a distribution of values at every radius; using the 16th and 84th percentile values provide the 68% confidence band. The 68% confidence band and the classical 1 $\sigma$ uncertainties are similar at each radius; in all of the figures we plot the confidence band based on the bootstrap technique.

As mentioned above, each realization results from the assumption of a Gaussian distribution in the velocity differences from the rotational velocity. We have also used the actual differences for the bootstrap simulations; i.e., we randomly draw with replacement from the distribution of differences to generate a simulated data set. There is no difference in the results using either a Gauss or the actual distribution.

Cohen & Ryzhov (1997) quote a error of 100 km s$^{-1}$ for their velocities, but suggest that this is an overestimation; we therefore use an uncertainty of 50 km s$^{-1}$. However, we verified that there is no difference in the results for either

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**Fig. 3.**—Projected velocity dispersion, projected rotational velocity, and $v \sin i/\sigma_v$ as functions of radius for a fixed position angle of 120°. Dotted lines mark the 68% confidence bands.
uncertainty, as is expected since the high-velocity dispersion (about 370 km s$^{-1}$) dominates the uncertainty in the estimation of the rotational velocity.

Our results are shown in Figures 2 and 3, where the projected rotation $v \sin i$, projected velocity dispersion $\sigma_v$, position angle, and $v \sin i/\sigma_v$ (with their associated 68% confidence bands) are plotted against radius. Figure 2 shows the results when the PA is allowed to vary, and Figure 3 shows the results for a fixed PA at 120° (the mean value for the PA past $3r_{eff}$). Figure 4 plots the individual velocity measurements versus position angle in four radial bins of equal width (100°) with mean radii of 1, 2, 3, and $4r_{eff}$, together with the derived rotation at these radii; rotation is clearly present in the outermost radial plot. Using Monte Carlo simulations and given a velocity dispersion of about 370 km s$^{-1}$, the probability of measuring a rotation this large, when no rotation is present, is less than 0.1%.

3. KINEMATICS OF M87 BETWEEN 1 AND 5$ r_{eff}$

Within $1r_{eff}$, there is only marginal evidence for rotation in the sample, a result compatible with the lack of any significant rotation of the stars (Javis & Peletier 1991; Sembach & Toney 1996 and references therein). At $\sim 1.5r_{eff}$, a group of globular clusters rotating along an axis offset by $\sim 60^\circ$ from the major axis possibly exists; however, the result is only marginally significant. We will come back to this point in § 3.2. The main feature is the monotonic increase of rotation past $2r_{eff}$.

3.1. Kinematics beyond $2r_{eff}$

Beyond $2r_{eff}$, the globular clusters rotate roughly along the major axis of the galaxy ($\sim 150^\circ$; see, e.g., Goudfrooij et al. 1994), with higher velocities in the SE. The position angle remains stable and the rotation amplitude increases from $\sim 50$ km s$^{-1}$ at $2r_{eff}$ to $\sim 300$ km s$^{-1}$ at $4r_{eff}$. The velocity dispersion remains constant at $\sim 370$ km s$^{-1}$ from $2$ to $4r_{eff}$. The increase in the velocity dispersion at the largest radii reported by Cohen & Ryzhov (1997) is likely due to increasing rotational velocity. Accordingly, $v \sin i/\sigma_v$ increases with radius from values around 0.2 to a value close to 0.8 at $4r_{eff}$. Further evidence in support of the rotation is the correspondence of the major-axis position angle of the galaxy isophotes to the position angle of the maximum rotation. In addition, the amount of isophotal flattening is consistent with an isotropic oblate rotator given the amplitude of $v/\sigma$. For an oblate rotator, we would expect an ellipticity of $\epsilon \approx 0.25$ for the $v/\sigma_v \approx 0.5$ seen at $\sim 350^\circ$, and $\epsilon \approx 0.45$ for the $v/\sigma_v \approx 0.9$ seen at $\sim 400^\circ$ (Binney & Tremaine 1987).

McLaughlin, Harris, & Hanes (1994) studied in detail the spatial structure of the globular clusters in M87 and found the system to be elliptical, aligned along the major axis, with the ellipticity $\epsilon$ increasing steadily to values of $\sim 0.3$ at about 300°. The diffuse stellar light was studied to even larger radii (Liller 1960; King 1978; Carter & Dixon 1978). These studies posit similar findings; the stellar light of M87 is flattened with an ellipticity smoothly increasing to values of $\epsilon$ between 0.35 and 0.4 at 350°–400°. These observations strongly support the rotation and its amplitude detected in the globular clusters at these large radii.

In order to compare our rotation to various theoretical predictions in § 4, we calculate the dimensionless spin parameter (Peebles 1971) $\lambda = J/E^{1/2}G^{-1}M^{-5/2}$, where $J$, $E$, and $M$ are the angular momentum, total energy, and total mass of the galaxy, respectively, and $G$ is the gravitational constant. $\lambda$ measures the total spin of a galaxy; however, since globular cluster radial velocities only exist over a limited radial range, we only measure a fraction of the total spin. We must therefore either extrapolate to include the whole galaxy or use the $\lambda'$ parameter introduced by Barnes (1992). $\lambda'$ is given by $J/J_{\max}$, where $J$ is the angular momentum of the subsample and $J_{\max}$ is the maximum angular momentum that the subsample can have. These two spin parameters are not directly comparable; i.e., a cold disk has $\lambda = 0.43$ and $\lambda' = 1.0$ (Barnes 1992). Below we calculate both parameters for comparison with theoretical predictions.

To estimate the spin parameters, we deproject the velocity profile with various assumptions, use the logarithmic potential given by Weil et al. (1998), and thus compute the mass, binding energy, and angular momentum as functions of radius. For the logarithmic potential we use $v_0 = 550$ km s$^{-1}$, $R_e = 100'$, and $q = 0.85$, corresponding to a total mass of M87 of $M(R = 120$ kpc) $\sim 1.2 \times 10^{13} M_\odot$. For the deprojection of the rotational velocity we use the Abel equation and the surface brightness and density profile of Weil et al. Assuming that the galaxy is edge-on, we numerically integrate

$$v(r)v_\phi(r) = -\frac{r}{\pi} \int_{-\infty}^{+\infty} d\sigma \left[ \frac{1}{x} \Sigma(x) v(x) \right] \frac{dx}{\sqrt{x^2 - r^2}},$$

(1)
to obtain the rotational velocity along the major axis. Here $v$ is the density used in Weil et al., $\rho_0$ is the internal rotational velocity, $\Sigma$ is the surface brightness profile (given in Weil et al.), and $v_\phi$ is the projected rotation in Figure 3. The integral extends to $r = \infty$, but our data only go out to 400", thus requiring an extrapolation. We use four different extrapolations beyond our last data point: zero rotation outside of 400", rotation decreasing linearly with increasing radius (by 0.375 km s$^{-1}$ arcsec$^{-1}$), constant rotation, and rotation increasing linearly with increasing radius (by 0.625 km s$^{-1}$ arcsec$^{-1}$).

Two more assumptions are necessary to obtain the total angular momentum: the relation of the globular cluster's
rotation profile to the galaxy rotation profile and the two-dimensional structure of the velocity field. We assume that the galaxy has the same rotation profile as the globular cluster system. For the velocity field, we assume constant rotation on cylinders and obtain the rotation at every position in the galaxy from the major axis rotation profile. The total angular momentum for the galaxy is then given by

\[ J(r) = 2\pi \int_0^r r'^2 dr' \int_0^{2\pi} v_\phi(R, r') R P(R, z) \sin \theta \, d\theta, \]

where \( R = r' \sin \theta \) and \( z = r' \cos \theta \). Similarly, we substitute \( v_{\max}(R) \) for \( v_\phi(R) \) in equation (2) to obtain the maximum angular momentum, \( J_{\max}(r) \). For \( v_{\max}(R) \), we use \([v_\phi^2(R) + \sigma^2]^{1/2}\), where \( \sigma = 370 \) km s\(^{-1}\), the measured projected velocity dispersion. The calculated \( v_{\max} \) is very similar to the circular velocity at all radii, and using either one provides similar values for \( J_{\max} \).

Figure 5 plots \( \lambda' \) as a function of radius for the various assumptions. The confidence bands are calculated in the same manner as in Figure 4. In the extreme case, where the rotation velocity drops to 0 beyond our last observed point, \( \lambda' \) rises steeply to values around 0.8 past 300°. In the more realistic cases, where we assume that the points at the largest radii are near the maximum net rotation and that the rotation curve remains approximately flat beyond our last point, \( \lambda' \) reaches values of more than 0.10 ± 0.05. To decrease \( \lambda' \) even further at \( r < 400° \), we would have to assume that the rotation velocity continues to rise steeply beyond 400° to values well above 700 km s\(^{-1}\), an unrealistic probability. For any assumption, however, \( \lambda' \) obtains a high value; putting all of the rotation at \( r < 400° \) results in \( \lambda' \) around 0.8, whereas allowing the largest rotation to be at \( r > 400° \) suggests a lower \( \lambda' \) for the inner radii, but \( \lambda' \approx 0.7 \) at larger radii. The significant rotation seen around \( r = 400° \) (\( v/\sigma = 0.8 \)) forces M87 to obtain high values of \( \lambda' \) independent of the rotational-velocity extrapolation used.

Equation (2) is used to calculate \( \lambda' \) integrated from zero to \( R \). However, \( \lambda' \) can also be computed in radial bins (see, e.g., Hernquist & Bolte 1992). Figure 6 plots the local \( \lambda' \) integrated over a 40° region around \( R \).

Note that we make several important assumptions. First, we speculate that M87 is seen edge-on, which could lead to an underestimation of the derived angular momentum (by \( \approx 15% \) for \( i = 60° \)). However, the amount of flattening in the isophotes for M87 at large radii (\( e \approx 0.4 \)) implies that it is nearly edge-on, since any inclined orientation would require an unlikely more flattened system. Our second assumption is that the rotational velocity of the globular clusters represents the rotation velocity of the total mass. If the globular clusters rotate twice as fast as the rest of the mass—an extreme case when compared to results for rotation velocities of galaxies in cosmological N-body simulations, see § 4—we would overestimate \( J \), i.e., \( \lambda' \), by a factor of 2. Simulations, however, tend to show that the globular cluster system rotates more slowly than the stellar body (Hernquist & Bolte 1992). Finally, we use a mass normalization for the logarithmic potential of Weil, Bland-Hawthorn, & Malin (1998) of \( v_0 = 550 \) km s\(^{-1}\); using extreme values as low as \( v_0 = 400 \) km s\(^{-1}\) or as high as \( v_0 = 650 \) km s\(^{-1}\) results in values of \( \lambda' \approx 0.2 \) and \( \approx 0.05 \), respectively, at 400°.

In addition to \( \lambda' \), we estimate \( \lambda \). For \( \lambda \), we need the mass, angular momentum, and the binding energy. We cannot use \( \lambda \) as measured from a subset of a bound system since \( \lambda \) measures the total spin for a bound system; we must therefore extrapolate to large radii to compare our measured \( \lambda \) to the theoretical predictions discussed below. The theoretical calculations generally use objects out to 1–2 half-mass radii to estimate the spin parameter. For M87, the half mass radii is anywhere from 150–300 kpc (assuming a distance of 16.5 Mpc), depending on where one truncates its halo. The
globular cluster velocity data only extend to around 35 kpc, so we must make an enormous extrapolation to determine the angular momentum. For the mass and binding energy, there is no extrapolation since the mass model incorporates the data at these radii. The integral over the density times the potential yields the binding energy, and the integral of the density provides the mass profile. We extrapolate the net rotation by assuming that it is constant between our last point and the half-mass radius, and equation (2) then provides the measurement of the angular momentum. With this extrapolation, \( \lambda \) asymptotes to a value of 0.18 at a radius around 600\( ' \) (60 kpc) and stays constant beyond there.

In summary, our best values for the dimensionless spin parameters of M87 are \( \lambda' \approx 0.7 \) at \( r > 600' \) and \( \lambda \approx 0.18 \) for the whole system. We will discuss the implications for the formation of M87 in §4.

3.2. The Kinematics around \( 1.5 r_{\text{eff}} \)

Two groups of clusters with 4–5 members each—immediately outside 1.5\( r_{\text{eff}} \) to the north and south of the galaxy center (see Fig. 1)—appear to produce the rotation seen at \( 1.5 r_{\text{eff}} \) around an axis offset from the rotation axis at large radii. This pattern does not extend further out. The statistical significance is a little greater than 1\( \sigma \) and still compatible within the errors with a constant low rotation out to 2\( r_{\text{eff}} \) along the major axis. The offset axis may, however, be due to incomplete azimuthal coverage of the data and, in particular, the lack of data in the NW around 2\( r_{\text{eff}} \). Alternatively, this rotation could be due to a separate group of clusters on orbit around M87 (e.g., from an accreted system). Abundances are available for eight of these clusters (Cohen et al. 1998). The values scatter over 75% of the range spanned by the full sample (Mg\( _B \) < 3 \( \AA \)), neither supporting nor excluding the accretion of a dwarf companion. The exact nature of these clusters remain to be investigated but do not influence our results beyond 2\( r_{\text{eff}} \).

4. CONSTRAINTS ON THE FORMATION OF M87

We compare the kinematical properties of the globular clusters with galaxy formation scenarios and briefly discuss why our results can not be explained by a single infalling satellite. From hierarchical formation scenarios the high value derived for the spin parameter suggests that the evolution of M87 was likely dominated by one major merger event.

4.1. Only an Infalling Satellite?

We must verify that the measured rotation is characteristic of the system and not a group of globular clusters associated with a satellite or originating from a tidal tail of an interacting, stripped galaxy. Evidence against these latter hypotheses is the alignment of the globular clusters with the major axis, the match with the stellar rotation, and the relatively smoothly increasing rotation and ellipticity of the whole system. Weil et al. (1998) recently reported diffuse (28 mag arcsec\(^{-2}\)) stellar light around M87 and suggest that it results from the accretion of a small spheroidal galaxy. The fan of light nearly aligns with the major axis with a large opening angle, suggesting that the orbit must have passed close to the center. However, their simulations show that the accreted galaxy must have been of low mass (10\(^9\)–10\(^{10}\) \( M_\odot \)), and the associated number of globular clusters would be small. By comparison with numbers of globular clusters per unit mass for similar galaxies in the compilation of Zepf & Ashman (1993), the total number of globular clusters associated with such a galaxy would be of the order 3–30; the number present in our magnitude limited sample would be a factor of 3–4 lower. Thus, it is not possible for these accreted clusters to dominate the globular cluster system of M87 at 4\( r_{\text{eff}} \).

Three other dwarf galaxies are potential candidates for satellites: NGC 4486A, NGC 4486B, and IC 3443. They are projected within 10\( ' \) of the center of M87 and within 30\( ' \) of the PA of the major axis and could be at a similar distance as the central giant elliptical. Both NGC 4486A and NGC 4486B are counter-rotating with respect to the stars and globular clusters with velocities differences of \( \approx 800 \) and \( \approx 200 \text{ km s}^{-1} \), respectively, compared to the systemic velocity of M87. IC 3443 is a dwarf galaxy with \( M_\odot \approx -15.5 \), and it seems unlikely that it could have contributed many globular clusters to M87. Finally, we checked the abundances published by Cohen et al. (1998) for the clusters that dominate the rotation at large radii. No systematic pattern is visible; the values scatter over the range spanned by 75% of the range of the full sample, on the metal-poor side.

In summary, no companion can significantly contribute to the globular cluster system of M87 at 4\( r_{\text{eff}} \), so the rotation must be intrinsic to the globular cluster system associated with M87.

4.2. An Explanation for the High Spin Parameter

Peebles (1969, 1971) first estimated the resulting angular momentum of a galaxy formed by gravitational instability. More recently (see, e.g., Ueda et al. 1994 and references therein), specific predictions were made for hierarchical clustering models with large cosmological \( N \)-body simulations. The results of the different simulations agree well; all simulations appear to predict a lower dimensionless spin parameter \( \lambda \) than we observe in M87. Values for \( \lambda \) vary between 0.01 and 0.1 with a mean around \( \lambda = 0.05 \) and are mostly insensitive to cosmological parameters and fluctuation spectrum shape. In addition, \( \lambda \) tends to be lower in high-density environments and appears to be anticorrelated with galaxy mass (Ueda et al. 1994; Efstathiou & Jones 1979; Barnes & Efstathiou 1987).

The spin parameter that we derive for M87 is \( \lambda \approx 0.18 \). The result is somewhat sensitive to our different assumptions, but should not be off by more than a factor of 2 (see §3.1). That is, the result for M87 is only marginally consistent with the simulations and lies at the upper end of, or above, the simulation results.

Interestingly, Warren et al. (1992) noticed in their simulations the apparent decrease of \( \lambda \) at masses comparable to M87, which they attributed to their finite computational volume rather than to a physical process: the most massive halos in simulations have no similar large halos to tidally torque them. That is, M87 would have to have encountered an equally massive galaxy in order to gain enough angular momentum to explain values of \( \lambda \) around 0.1 or higher. High values of \( \lambda \) have also been borne out in other types of simulations. Hernquist (1992, 1993) showed in merger simulations of two equal-sized galaxies how the spin parameter could increase in the outer halo. Hernquist & Bolte (1992) made specific predictions for globular clusters at different radii in the end product of such a merger and noticed that \( \lambda' \) rises from values around 0.05 in the center to values as high as 0.2–0.3 at several effective radii.
These simulations seem to indicate that the most likely scenario is that M87 gained its large amount of angular momentum through a merger of two large galaxies of about equal mass. This scenario does not exclude a hierarchical formation for the progenitor galaxies or further accretion of smaller companions (see §4.1, but *the present appearance of M87 must have been created by one single major merger event*. It seems very unlikely that several merging galaxies would fall into M87 on the same orbital path so as to not dilute each other’s rotation signatures. Given the total stellar mass of M87 (several $10^{12} M_\odot$), the two progenitors must have had stellar masses around $10^{12} M_\odot$ or above, which effectively rules out that M87 is the product of the merger of two (several $10^{11} M_\odot$) spiral galaxies. The most likely progenitors are two giant ellipticals, perhaps central dominant galaxies in their own groups, given the large masses involved. In agreement with this, M87 shows no significant recent burst of star formation; the last major merger appears to have been gas-poor or mainly dissipationless, unless it happened well before $z = 1$.

4.3. *A Comparison with NGC 4472 and NGC 1399*

We carried out a similar analysis for two other giant elliptical galaxies: NGC 4472 (M49), the brightest galaxy in the Virgo galaxy cluster, for which we used 57 globular cluster radial velocities compiled by Sharples et al. (1998); and NGC 1399, the central cD galaxy in the Fornax galaxy cluster, for which we used 74 globular cluster radial velocities compiled by Kissler-Patig et al. (1998b). We only summarize the results here since we feel that the samples are too small to draw strong conclusions. However, we note that in both cases the rotation at large radii is significantly smaller than in M87, resulting in smaller spins.

In NGC 4472 the clusters out to $\simeq 1.5 r_{\text{vir}}$ have significant rotation, driving the value of $\lambda^\prime$ up to $\simeq 0.5$, but it decreases to $\simeq 0.1$ at the last data point (around $2.5 r_{\text{vir}}$) and, extrapolating with constant rotation amplitude, $\lambda^\prime$ remains approximately constant out to larger radii. The total spin parameter $\lambda$ around the virial radius is low, around 0.01. The result for $\lambda^\prime$ is very sensitive to a particular group of $\simeq 10$ objects at small radii.

In NGC 1399 no significant rotation could be detected in the inner regions, and only small rotation ($\simeq 150 \pm 100$ km s$^{-1}$) was measured past 300" ($\simeq 6 r_{\text{eff}}$). Accordingly, we derive values of $\lambda^\prime$ around 0.3, but compatible with 0. The total spin parameter $\lambda$ near the virial radius lies around 0.05. These derived values for the spin parameters are in good agreement with the values obtained by cosmological N-body simulations for the formation of central cD galaxies.

5. *DIFFERENCES BETWEEN THE RED AND BLUE GLOBULAR CLUSTERS*

5.1. *Kinematics of the Globular Cluster Subpopulations*

The globular cluster system of M87 is known from photometry to host two distinct population of globular clusters (Whitmore et al. 1995; Elson & Santiago 1996). In order to investigate whether these two subpopulations differ in their kinematics, we divide the kinematic sample according to the metallicity obtained spectroscopically for 150 candidates by Cohen et al. (1998). The “blue” and “red” populations are defined as globular clusters with $[\text{Fe/H}] < -0.9$ (80 candidates) and $[\text{Fe/H}] > -0.9$ (70 candidates), respectively. This cut is motivated by the gap at similar metallicities in the globular cluster population of the Galaxy (see, e.g., Zinn 1985) and the metallicity corresponding to the gap in the $V-I$ color distribution of the globular clusters in M87 (see, e.g., Whitmore et al. 1995; Elson & Santiago 1996). The analysis was performed in the same manner as for the full sample (see §2). Figure 7 shows the results using a fixed position angle (120°): velocity dispersion $\sigma_v$ and rotation velocity $v \sin i$ of the blue (thick solid line) and red (thin solid line) samples are plotted as a function of radius (see also Table 1). The 68% confidence bands (dotted lines) are similar for both samples and are shown only for the blue sample.

Blue and red samples have similar mean velocities ($1299 \pm 44$ km s$^{-1}$ and $1292 \pm 47$ km s$^{-1}$, respectively). The rotation in the red sample seems constant (and compatible with no rotation) at all radii, while the rotation of the blue cluster population seems to increase with radius past
200" and is significant beyond 300". However, given the sample sizes, the rotation amplitudes of the two samples only differ by \(\approx 1 \sigma\).

The blue and red samples have similar velocity dispersions at all radii; however, their rotation profiles differ, implying different total \(V^2 = (\sigma^2 + e_{rot}^2)\) profiles. Since both groups trace the same mass distribution, either their radial density profiles are different (e.g., one population has a flatter density profile than the other) or their families of orbits are very different (e.g., the globular clusters of one population having either primarily tangentially or radially biased orbits). Strom et al. (1981) first noticed that the mean color of the globular cluster system in M87 becomes bluer with increasing distance from the center. Neilsen, Tsvetanov, & Ford (1998) suggest that the color variation is due to a changing number ratio of blue to red clusters with radius (similar to what was seen in NGC 4472 by Geisler, Lee, & Kim 1996, and NGC 1380 by Kissler-Patig et al. 1997), suggesting different density profiles.

At 400", the ratio of the total \(V^2\) of the two samples is \(\approx 1.4\). Assuming isotropic orbital distributions, in order for the two populations to trace the same potential, this ratio translates into a ratio of \(\approx 1.4\) for the exponents of the density profiles. This ratio does seem typical for the exponents of the density profiles of the blue and red populations (e.g., the cases of NGC 4472 and NGC 1380) and for the ratio of the exponents for those globular cluster populations which follow the stellar light profiles and those whose density profile is more extended than the stellar light (see the compilation in Kissler-Patig 1997, for example).

Similar velocity dispersion profiles for the red and blue populations are therefore compatible with the larger rotation of the blue globular clusters if the red population has a steeper density profile; this also explains the color gradient in the system.

5.2. Constraints on the Formation of the Globular Clusters

M87 is known to host an extremely high number of globular clusters with respect to its mass (see, e.g., McLaughlin et al. 1994 and references therein), as well as hosting at least two different globular cluster sub-populations.

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**TABLE 1**

| Radius (arcsec) | Rotation Velocity \(v \sin i\) (km s\(^{-1}\)) | Velocity Dispersion \(\sigma_v\) (km s\(^{-1}\)) | Spin \(\lambda\) |
|----------------|---------------------------------|---------------------------------|--------|
| 83 ........     | 56\(^{+4+3}\)                  | 333\(^{+27}\)                  | 0.06\(^{+0.06}\) |
| 93 ........     | 13\(^{+4+3}\)                  | 318\(^{+27}\)                  | 0.04\(^{+0.03}\) |
| 103 ........    | 18\(^{+3+4}\)                  | 319\(^{+28}\)                  | 0.04\(^{+0.03}\) |
| 114 ........    | 77\(^{+9+3}\)                  | 326\(^{+31}\)                  | 0.04\(^{+0.07}\) |
| 123 ........    | 42\(^{+4+1}\)                  | 336\(^{+29}\)                  | 0.06\(^{+0.07}\) |
| 134 ........    | 81\(^{+5+3}\)                  | 350\(^{+30}\)                  | 0.08\(^{+0.06}\) |
| 143 ........    | 71\(^{+3+2}\)                  | 349\(^{+32}\)                  | 0.09\(^{+0.07}\) |
| 154 ........    | 56\(^{+2+5}\)                  | 335\(^{+30}\)                  | 0.12\(^{+0.07}\) |
| 164 ........    | 62\(^{+2+9}\)                  | 345\(^{+32}\)                  | 0.14\(^{+0.08}\) |
| 174 ........    | 58\(^{+5+0}\)                  | 357\(^{+33}\)                  | 0.14\(^{+0.08}\) |
| 183 ........    | 35\(^{+5+3}\)                  | 362\(^{+31}\)                  | 0.13\(^{+0.08}\) |
| 193 ........    | 41\(^{+1+4}\)                  | 373\(^{+31}\)                  | 0.13\(^{+0.08}\) |
| 203 ........    | 41\(^{+4+5}\)                  | 369\(^{+32}\)                  | 0.12\(^{+0.09}\) |
| 213 ........    | 48\(^{+4+1}\)                  | 375\(^{+36}\)                  | 0.11\(^{+0.10}\) |
| 223 ........    | 41\(^{+2+4}\)                  | 380\(^{+33}\)                  | 0.11\(^{+0.10}\) |
| 233 ........    | 62\(^{+5+5}\)                  | 381\(^{+34}\)                  | 0.10\(^{+0.09}\) |
| 244 ........    | 23\(^{+5+3}\)                  | 375\(^{+34}\)                  | 0.09\(^{+0.09}\) |
| 253 ........    | 74\(^{+6+1}\)                  | 366\(^{+32}\)                  | 0.09\(^{+0.09}\) |
| 264 ........    | 45\(^{+5+5}\)                  | 354\(^{+30}\)                  | 0.07\(^{+0.10}\) |
| 273 ........    | 45\(^{+2+9}\)                  | 358\(^{+33}\)                  | 0.06\(^{+0.11}\) |
| 283 ........    | 74\(^{+2+4}\)                  | 359\(^{+32}\)                  | 0.05\(^{+0.11}\) |
| 294 ........    | 126\(^{+4+9}\)                 | 362\(^{+34}\)                  | 0.05\(^{+0.11}\) |
| 304 ........    | 134\(^{+5+0}\)                 | 356\(^{+35}\)                  | 0.10\(^{+0.10}\) |
| 314 ........    | 155\(^{+5+0}\)                 | 344\(^{+35}\)                  | 0.10\(^{+0.10}\) |
| 324 ........    | 187\(^{+5+3}\)                 | 354\(^{+33}\)                  | 0.12\(^{+0.11}\) |
| 333 ........    | 196\(^{+5+9}\)                 | 355\(^{+36}\)                  | 0.14\(^{+0.14}\) |
| 344 ........    | 199\(^{+5+9}\)                 | 362\(^{+39}\)                  | 0.18\(^{+0.15}\) |
| 353 ........    | 227\(^{+5+3}\)                 | 368\(^{+37}\)                  | 0.20\(^{+0.15}\) |
| 366 ........    | 219\(^{+6+3}\)                 | 364\(^{+36}\)                  | 0.20\(^{+0.16}\) |
| 373 ........    | 229\(^{+6+4}\)                 | 373\(^{+41}\)                  | 0.24\(^{+0.13}\) |
| 383 ........    | 267\(^{+5+1}\)                 | 381\(^{+43}\)                  | 0.31\(^{+0.12}\) |
| 388 ........    | 302\(^{+5+6}\)                 | 380\(^{+46}\)                  | 0.34\(^{+0.12}\) |

**Notes.**—All values were computed for a fixed position angle of 120° east of north. The radius is given in arcseconds; e.g., for a distance to M87 of 16.5 Mpc, 1° would correspond to \(\approx 80\) pc. The velocity dispersion is corrected for rotation and velocity errors. The listed spin was computed in a 40° bin around each point.
Several mechanisms can explain the presence of different globular clusters populations (see, e.g., Kissler-Patig et al. 1998b). In the case of M87, the last merger probably did not involve a large amount of star and globular cluster formation; a result supported by the findings of Cohen et al. (1998), who showed that the vast majority of globular clusters are old and must have formed in earlier events. In this case, the globular cluster kinematics cannot strongly discriminate between different formation scenarios since they were dominated by this last merger. Indeed, there is only weak evidence that the blue globular clusters cause most of the net rotation. We also stress that the last major merger cannot explain the globular cluster overabundance and point to Harris, Harris, & Mclaughlin (1998) and Côté, Marzke, & West (1998) for alternative scenarios in the case of M87.

It is possible that the apparent concentration of the net rotation in the blue globular clusters may be a relic from the situation in the progenitor galaxies. Hernquist (1993 and references therein) showed that, in an equal mass merger, the angular momentum of rotating components tends to be conserved. In the case of M87, the observations would be consistent with this expectation if we assume that the last major merger must have happened before the M87 merger. Indeed, there is only weak evidence that the blue globular clusters cause most of the net rotation. We also stress that the last major merger cannot explain the globular cluster overabundance and point to Harris, Harris, & Mclaughlin (1998) and Côté, Marzke, & West (1998) for alternative scenarios in the case of M87.

6. Summary

We have reanalyzed published radial velocities for 204 globular clusters around M87 and found significant rotation in the outer regions (\(> 250\)). We derive a dimensionless spin parameter for M87 of \(\lambda \approx 0.18\) (\(\lambda^* \approx 0.7\)) from the rotation of the globular clusters. A comparison with cosmological N-body simulations argues that such a high spin parameter is most likely the product of an equal mass merger. A single major merger must have been the dominant event shaping the kinematics and appearance of the galaxy. There is some evidence that the rotation is confined to the metal-poor globular clusters. If, as assumed, the last merger was mainly dissipationless, this kinematic difference could reflect the situation in the progenitor galaxies of M87.

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