THE KINEMATICS OF 3:1 MERGER REMNANTS AND THE FORMATION OF LOW-LUMINOSITY ELLIPTICAL GALAXIES

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Received 2000 September 7; accepted 2001 February 16

ABSTRACT

We test the formation of low-luminosity elliptical galaxies through collisionless mergers of unequal-mass disk galaxies. The kinematic properties of a small survey of simulated merger end products with initial disk mass ratios of 3:1 are compared to a sample of seven low-luminosity galaxies observed by H.-W. Rix and coworkers that were chosen photometrically to be “ellipticals.” In this paper, we go beyond a comparison in terms of global properties (using one number to characterize a model or a galaxy, e.g., $<a_4>$, ellipticity at some fixed radius, or central velocity dispersion) and examine the detailed kinematics as a function of galactocentric distance. The merger remnants are “observed” through a slit along the major and minor axes, using a pixel binning and slit width similar to the ones used during the spectroscopic observations. Inside each bin, we determine the line-of-sight velocity distributions and parameterize them with Gauss-Hermite functions. We compare the rotational support of the merger remnants, i.e., the ratio of the mean line-of-sight velocity $v$ to the velocity dispersion $\sigma$ along the major axis, the normalized rotation on the minor axis, and the major-axis Gauss-Hermite moments $h_3$, to those of the observed galaxies. The $N$-body remnants are very flattened when viewed edge-on ($\langle \epsilon \rangle \sim 0.6$) and should be inclined before making a fair comparison with the data set of H.-W. Rix and coworkers (which has $\langle \epsilon \rangle \sim 0.3$). When the merger remnants are appropriately inclined, their $v/\sigma$ profiles rise slower than the observed ones: $v/\sigma_{\text{merger}}$ is in the range $[0.1, 0.8]$ at $R_{\text{eff}}$ and $[0.2, 1.6]$ at $2R_{\text{eff}}$, whereas $v/\sigma_{\text{observed}}$ spans the intervals $[0.8, 2.0]$ at $R_{\text{eff}}$ and $[1.4, 3.5]$ at $2R_{\text{eff}}$. Note that even when the remnants are viewed edge-on, the $v/\sigma$ profiles do not match the observations. The detailed comparison of the observations with our set of purely collisionless 3:1 merger remnants shows that these objects and low-luminosity ellipticals do not have similar kinematic profiles. This suggests that this kind of dissipationless merger (or mergers with more even masses, e.g., mass ratios of 2:1 or 1:1) is not likely to be the dominant formation channel for low-luminosity elliptical galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution —
galaxies: kinematics and dynamics — galaxies: structure —
methods: $n$-body simulations

On-line material: color figures

1. INTRODUCTION

Elliptical galaxies can be divided into two classes according to their morphology and kinematic properties. The giant ellipticals are generally boxy (probably triaxial), with shapes supported by anisotropy. They have slow rotation on the major axis with often comparable minor-axis rotation and occasionally kinematically decoupled cores. The intermediate and low-luminosity ellipticals are usually disky, isotropic rotators. They are mostly supported by rotation and have little minor-axis velocity (Bender 1988; Bender, Döbereiner, & Möllenhoff 1988; Kormendy & Bender 1996; Rix, Carollo, & Freeman 1999). These two families also show correlations with the inner slope of the surface brightness profile: galaxies with steep inner cusps are on average small disky objects, and galaxies with shallow or constant cores are the giant boxy ellipticals (Jaffe et al. 1994; Faber et al. 1997; Carollo et al. 1997).

Barnes (1998) proposed that fast-rotating elliptical galaxies could originate from the collisionless merger of unequal-mass disks. On the other hand, equal-mass mergers lead to slowly rotating, pressure-supported objects resembling giant elliptical galaxies (Barnes 1992). Recently Naab, Burkert, & Hernquist (1999, hereafter NBH) took the idea of Barnes one step further and showed that equal and unequal-mass mergers could reproduce most of the observed correlations mentioned above if one would analyze projections of the merger remnants using many random viewing angles (see their Fig. 3). They showed that the boxy family of galaxies could be explained by equal-mass mergers of disk galaxies (with bulges and dark halos), whereas the disky family was originating from 3:1 mergers, i.e., mergers in which the big disk galaxy is 3 times more massive than the small one.

However, the conclusion of NBH is based only on global properties (average $a_4$, ellipticity measured at one radius, or central velocity dispersion) and does not compare kinematic quantities as a function of radius. In this paper, we perform such a comparison, using a setup similar to the one used during the observations of Rix et al. (1999, hereafter R99), in which kinematics along the principal axes were obtained, extending well beyond $R_{\text{eff}}$. R99 selected these elliptical galaxies only on the basis of their low luminosities ($M_B \approx -19.5$); i.e., no prior kinematic information or degree of diskiness was used.

In § 2, we summarize our merger models and their initial conditions. In § 3, we describe how we extract the kinematic quantities of the merger remnants. We discuss the results of a small survey of 16 different merger remnants in § 4. We perform a comparison between models and observations using the rotational support (i.e., $v/\sigma$ along the major axis), the amount of minor- to major-axis rotation, and the Gauss-Hermite (GH) moment $h_3$ along the major axis. All
FIG. 1.—First four moments of the GH decomposition along the major axis of one merger remnant (case 1; see Table 1): mean line-of-sight velocity $v$ (in kilometers per second), line-of-sight velocity dispersion $\sigma$ (in kilometers per second), and GH moments $h_3$ and $h_4$. The top panel shows the rotational support, i.e., the ratio $v/\sigma$. The remnant is viewed edge-on here. The left-hand side of the remnant (dashed line) has been folded onto the right-hand side to estimate the asymmetry. [See the electronic edition of the Journal for a color version of this figure.]

Table 1. Angles Specifying the Initial Conditions for the Two Disk Galaxies

| $i$ (deg) | $\alpha_1$ (deg) | $i_2$ (deg) | $\omega_1$ (deg) | $\omega_2$ (deg) |
|-----------|------------------|-------------|------------------|------------------|
| 1         | -30              | -30         | 30               | 30               |
| 2         | 90               | 0           | 0                | 0                |
| 3         | 0                | 0           | 0                | 0                |
| 4         | 180              | 0           | 0                | 0                |
| 5         | -71              | 90          | 109              | 90               |
| 6         | 30               | 0           | 0                | 0                |
| 7         | 60               | 0           | 0                | 0                |
| 8         | -90              | 90          | 90               | 90               |
| 9         | -30              | 0           | 0                | 0                |
| 10        | -60              | 0           | 0                | 0                |
| 11        | 60               | 60          | -60              | -60              |
| 12        | 120              | 0           | 0                | 0                |
| 13        | 150              | 0           | 0                | 0                |
| 14        | -120             | 30          | 60               | -30              |
| 15        | 60               | -30         | -120             | -30              |
| 16        | 60               | 30          | -60              | -30              |

Note.—Col. (1) gives the number of the simulation, col. (2) the angle between the spin plane and the orbital plane for the massive disk galaxy, and col. (3) the angle between the line of nodes and the pericenter. Cols. (4) and (5) are the same as cols. (2) and (3) but for the small spiral galaxy.

these quantities are compared as functions of distance from the center. The edge-on and inclined merger models fail to match the observed quantities of the R99 sample.

In a similar study, Bendo & Barnes (2000, hereafter BB) examined eight equal-mass merger remnants and eight unequal-mass (3:1) merger remnants. Their unequal-mass merger models display similar major-axis kinematic profiles to ours. However, the authors reach different conclusions from the comparison with the R99 data set, namely, that "unequal-mass mergers can produce the same relations between $v/\sigma$ and radius." In this paper, we do a more direct comparison of $N$-body merger remnants with this data set. We compare not only edge-on but also inclined remnants that match the apparent ellipticities of the observed galaxies. We conclude that, on average, the kinematics of the simulated 3:1 mergers do not reproduce those of low-luminosity galaxies. Therefore, we suggest that the 3:1 collisionless mergers are probably not a major mechanism responsible for the bulk formation of these objects.

2. THE MERGER MODELS

We briefly summarize some properties of the initial disk model (see Hernquist 1993 and NBH for more details). Each disk galaxy consists of an exponential disk, a Hernquist (1993) spherical bulge, and a pseudoisothermal spherical dark halo with 5.8 times the mass of the disk. In our "low-resolution" simulations, the more massive galaxy has 6666 bulge particles, 20,000 disk particles, and 40,000 dark halo particles, while the less massive galaxy has one-third the number of particles in each component. In two "high-resolution" cases, we rerun models with 3 times as many particles. The $N$-body computations were performed using a direct summation code on the special purpose hardware GRAPE-3 (Sugimoto et al. 1990).

Before the encounter, the two disk galaxies follow a quasi-parabolic orbit with an initial separation of 30 scale lengths of the massive exponential disk. The pericentric approach is taken as 2 disk scale lengths. Once the orbits and the masses of the two initial spiral galaxies are fixed, we still have two free parameters for each galaxy: the inclination between the galaxy orbital plane and its spin plane (angle $i$) and the argument of pericenter (angle $\omega$), i.e., the angle between the line of nodes and the pericentric distance (see Fig. 6a of Toomre & Toomre 1972). Table 1 summarizes our choices for these angles: $i_1$, $\omega_1$ for the more massive spiral galaxy and $i_2$, $\omega_2$ for the less massive one.

3. OBSERVING THE MERGER REMNANT

We analyze the kinematic structure of the merger remnants 10 dynamical times after the merger has been com-
completed, so that they had enough time to settle into an equilibrium state. We plot the kinematic quantities of the remnant in units of the half-light radius $R_{\text{eff}}$, i.e., the projected radius on the plane of the sky of the circle containing half of the luminous particles. The average $R_{\text{eff}}$ of the R99 data set is $\sim 13''$, corresponding to 3.34 kpc. In the merger remnants, $1R_{\text{eff}}$ is 3.5 kpc: this distance is chosen to be 10'' for comparison with observations. We use a slit width of 2.5'', i.e., 0.875 kpc. After binning, we have 21 pixels on the major axis and 16 on the minor axis. The bin size increases with distance from the center, according to the observations of R99.

In each binned pixel, we construct the histograms of the line-of-sight velocities ($v_{\text{los}}$) of all the luminous particles whose projected coordinates on the sky ($x'$ and $y'$) fall within the pixel boundaries. This quantity is called the velocity profile (VP). Subsequently, we parameterize the VPs using the GH series (van der Marel & Franx 1993; Gerhard 1993). We checked to see that the kinematic parameters of each VP ($v$, $\sigma$, $h_3$, and $h_4$) do not depend on the choice of the velocity bin size. Furthermore, to increase the signal-to-noise ratio, and since most remnants are close to an axisymmetric shape (in the equatorial plane, the average axis ratio at $1R_{\text{eff}}$ is roughly 0.8–0.9), we average the results over 10 different position angles of the slit between 0° and 90° in the equatorial plane.

We estimate the errors on each kinematical quantity by bootstrapping. For each spatial bin, we generate 100 boot-
trapped VPs and recompute the GH decomposition. The error bar is then estimated as the variance among the 100 bootstrapped results.

In Figure 1, we show the basic kinematic output of our simulations, the first four moments of the VPs, i.e., \( v, \sigma, h_3, \) and \( h_4, \) and the degree of ordered motion \( v/\sigma \) on the major axis for the high-resolution simulation (266,666 luminous and dark particles) of case 1 (see Table 1). The initial inclination angles of the two disk galaxies are \([i_1, \omega_1, i_2, \omega_2] = [-30^\circ, -30^\circ, 30^\circ, 30^\circ]\). The curves have been folded onto the positive side of the major axis (with a sign change for the odd moments \( v \) and \( h_3 \)). In this way, we can estimate the left/right asymmetries. In most geometries analyzed in this paper, the left-hand and right-hand sides of the major axis are similar within the errors. For this model, the mean velocity increases linearly until \( 1R_{\text{eff}} \) and then rises more slowly to reach 150 km s\(^{-1}\) at \( 3R_{\text{eff}} \). In other geometries, the rise is more monotonic but reaches the same value at \( 3R_{\text{eff}} \). The velocity dispersion decreases from central values of 140–160 to 80–100 km s\(^{-1}\) at \( 3R_{\text{eff}} \). The innermost point shows a lower value (by \( \sim 20 \) km s\(^{-1}\)) compared with its immediate neighbors. BB observed the same behavior in their simulations and interpreted it as follows: all the merger remnants have a large fraction of particles from the Hernquist bulges of their progenitors in their inner regions. These particles still follow an \( r^{-1} \) density profile at small radii and therefore have velocity dispersions that scale as \( r^{-1/2} \), producing the central dip.

In Figures 2 and 3, we show the \( v/\sigma \) and \( h_3 \) profiles of two cases, in which each simulation was rerun with 3 times more particles. The low-resolution simulations (with 88,887 particles) do not show significantly different results compared with the high-resolution cases. In case 1, the low-resolution models have more left/right asymmetry, but if one takes the average between the two sides, then the \( v/\sigma \) and \( h_3 \) profiles are very similar. Therefore, in the remainder of this paper, we will explore various initial conditions using only low-resolution simulations. Similarly, Figure 3 displays the \( h_3 \) profiles for the high/low-resolution simulations: \( h_3 \) is typically zero or positive inside \( 1R_{\text{eff}} \) (see also BB).

Figures 4 and 5 demonstrate that the results of this paper still hold if we consider individual projected profiles rather than averaging 10 position angles together.

4. DISCUSSION

4.1. Edge-on Remnants

Figure 6 overplots the observed \( v/\sigma \) profiles of the R99 sample and the \( v/\sigma \) profiles of all our merger models (see Table 1) when viewed edge-on. In the models, the left-hand and the right-hand sides have been averaged. The \( v/\sigma \) profiles of the remnants can reach values between 1 and 2.2 in the very outer parts, i.e., at \( 3R_{\text{eff}} \). At smaller radii, e.g., at \( 1R_{\text{eff}} \), they attain only \([0.1, 1.0]\), depending on the geometry. BB find similar results for their 3:1 merger remnants, as indicated by the shaded region in Figure 6. The R99 data set shows higher values of \( v/\sigma \) at all radii: \( v/\sigma_{\text{observed}} \) covers the range \([0.8, 2.0]\) at \( 1R_{\text{eff}} \) and \([1.4, 3.5]\) at \( 2R_{\text{eff}} \). Note also the sharp increase in \( v/\sigma_{\text{observed}} \) at small radii (\( R \leq 0.5R_{\text{eff}} \)). Furthermore, the merger simulations do not reproduce the central peak in \( \sigma \) observed by R99 (see their Fig. 1). From this comparison alone we could conclude that dissipationless simulations cannot reproduce the observed kinematics of the R99 sample. In the next section, we will also use the GH moment \( h_3 \) and the minor-axis rotation to compare the observations.

4.2. Inclined Remnants

When viewed edge-on, our merger remnants have an apparent ellipticity \( \epsilon_{\text{remnant}} \approx 0.5–0.6 \) at \( 1R_{\text{eff}} \), much more flattened than the objects of R99 with \( \langle \epsilon_{\text{observed}} \rangle = 0.3 \) (see
their Fig. 3). In order to make a fair comparison with this data set, we need to incline our merger remnants such that they have the same ellipticity $v_{\text{remnant}} \approx 0.3$ at $1R_{\text{eff}}$. As can be expected, the mean line-of-sight velocity is lowered (compared to the edge-on case). The velocity dispersion is also diminished, but not as much as the velocity. Therefore, the $v/\sigma$ profiles of the inclined cases do not rise as fast as those of the edge-on cases (Fig. 7).

The $h_3$ profiles are less sensitive to inclination; i.e., they are similar to those of the edge-on case. In Figure 8, we only show the $h_3$ values of the merger remnants in the inclined case. These profiles are essentially zero (or slightly positive) inside $1R_{\text{eff}}$, whereas the observed $h_3$ values show an outward decline toward $\langle h_3 \rangle = -0.06$ within the same radial interval. The model values reach $-0.1$ only at very large radii ($3R_{\text{eff}}$). Bender, Saglia, & Gerhard (1994) observed a sample of 44 elliptical galaxies and found $\langle h_3 \rangle = -0.1$ for the disky ($a_d/a = 0.02$) objects (see their Fig. 14a). We choose the disky subsample since they correlate with the low-luminosity ellipticals. Their low values of $h_3$ are roughly consistent with the R99 profiles since Bender, Saglia, & Gerhard obtained spectra only inside $\frac{1}{2}R_{\text{eff}}$.

4.3. Minor-Axis Rotation

We have computed the normalized minor-axis rotation, defined as $v_{\text{min \_norm}} = v_{\text{min}} / \left( \sigma_{\text{major}}^2 + \sigma_{\text{major}}^2 \right)^{1/2}$ for all merger models and observations. Note that the normalization by the total kinetic energy avoids a division by zero in the center. We find that both the merger remnants and the galaxy sample observed by R99 have only a small amount of minor-axis rotation: $\langle v_{\text{min \_norm}} \rangle_{\text{merger}} = 0.04$ and $\langle v_{\text{min \_norm}} \rangle_{\text{R99}} = 0.08$. The spatial average has been done inside $2R_{\text{eff}}$.

4.4. Comparison with S0 Galaxies

Fisher (1997) observed a sample of 18 S0 galaxies and derived GH moments along their major and minor axis. In most cases, these major-axis $h_3$ profiles show a similar behavior to those observed in our merger remnants: going from the center to the outer parts, $h_3$ values increase from zero to some positive value then decrease and change sign, finally remaining negative. The maximum value of $h_3$ reached by the data is in the range 0.05–0.1. However, the change of sign occurs at (or within) $1R_{\text{eff}}$ for these S0 galaxies, whereas it is between $1R_{\text{eff}}$ and $2R_{\text{eff}}$ for the merger remnants. Furthermore, the shape of the S0 galaxies’ velocity curves is very different compared with the one of the merger remnants (see Fig. 10 of Fisher 1997), and their $v/\sigma$ values are even higher than the low-luminosity ellipticals.
5. Could small ellipticals still be merger products?

In this section, we speculate on some possible scenarios that could still save the 3:1 merger of disks as a viable route for the formation of fast-rotating ellipticals. In addition, one (nonmerger) mechanism is mentioned that could also lead to the formation of similar objects.

If we start with submaximal initial disks, a weaker bar instability occurs since massive dark haloes tend to stabilize disks against bars. Therefore, the disks are less heated during the merger and could produce a remnant with a higher \(v/\sigma\) profile, in agreement with the R99 sample. Using a fast-rotating bulge in the initial spiral galaxy could increase the \(v/\sigma\) profile of the remnant in the inner parts. Finally, the inclusion of a dissipative component in the merger is also likely to increase the amount of ordered motion: in gas-rich 3:1 merger simulations, large (\(\sim 1R_{\text{eff}}\)) gaseous disks form in the remnant (Naab 2001). If new stars are subsequently formed in such disks, the final rotational support is increased. It is, however, not clear what fraction of the gas is turned into stars (and under what conditions and timescale).

In a cluster environment, mergers occur rarely since the velocity dispersion is too high. However, galaxy harassment is likely to play a significant role. According to Moore, Lake, & Katz (1998), disk galaxies in rich clusters undergo a complete morphological transformation from “disks” to “spheroidals.” These objects probably retain a large amount of rotation and may therefore have a high \(v/\sigma\).

Finally, we have compared our merger remnants with the low-mass end of the elliptical sequence. Intermediate ellipticals \((-19 < M_\text{g} < -20)\) show more modest \(v/\sigma\) profiles. The kinematics of these objects may still be explained by 3:1 collisionless mergers.

6. Conclusions

We have compared various kinematic characteristics of a limited sample of 3:1 \(N\)-body merger remnants with observations of low-luminosity elliptical galaxies in order to test if the collisionless merger of disk galaxies (with mass ratios of 3:1) are a likely formation mechanism for such objects. The simulated merger remnants and the observed galaxies both show rapid rotation along the major axis and little rotation along the minor axis. A detailed comparison between simulations and data shows, however, that on average the rotational support \(v/\sigma\) of the simulated remnants is too small compared with the observed galaxies. A comparison of the line-of-sight VP, quantified by \(h_3\), reveals that the merger remnants have VPs with zero or positive \(h_3\) inside \(1R_{\text{eff}}\), whereas the observed VPs have \(\langle h_3 \rangle \sim -0.06\) in the same interval. These more direct comparisons with the data support the conclusion of R99 based on simpler models; i.e., the low-luminosity galaxies have different dynamics than the 3:1 merger remnants. In particular they have, on average, more ordered motion. These conclusions differ from the ones reached by BB, even though the results of our simulations agree with theirs. The difference can be traced to the more detailed and rigorous data model comparison performed here.

At face value this suggests that either the last merger that this class of small “ellipticals” experienced had a mass ratio greater than 3:1 or that a substantial stellar disk formed by gas dissipation after the last major merger. Note that we...
have been conservative by looking at 3:1 mergers in the
sense that the 3:1 remnants are the most likely objects to
look like an elliptical and have high-rotation support: 1:1
mergers lead to boxy objects with far less rotation support,
and 5:1 mergers (or higher) do not form an elliptical
because the large disk mostly survives the interaction. It is
not clear quantitatively what the effect of the inclusion of
gas and star formation in the kinematics of the remnant is.
Furthermore, adding gas might not be the only way to save
the merging scenario. For example, starting the merger with
a submaximal disk could produce a remnant with a higher
$v/\sigma$ profile. On the other hand, galaxy harassment is a
plausible mechanism to heat the disk of spirals while
keeping some degree of ordered motion. However, harass-
ment is mainly operating in rich clusters, whereas mergers
are ubiquitous in a hierarchical formation scenario.

We thank Josh Barnes for his constructive comments on
the manuscript.

REFERENCES

Barnes, J. E. 1992, ApJ, 393, 484
———. 1998, in Galaxies: Interactions and Induced Star Formation, ed.
D. Friedli, L. Martinet, & D. Pfenniger (Saas-Fee Advanced Course 26;
Berlin: Springer), 275
Bender, R. 1988, A&A, 193, L7
Bender, R., Döbereiner, S., & Möllenhoff, C. 1988, A&AS, 74, 385
Bender, R., Saglia, R. P., & Gerhard, O. E. 1994, MNRAS, 269, 785
Bendo, G., & Barnes, J. 2000, MNRAS, 316, 315 (BB)
Binney, J., & Merrifield, M. R. 1998, Galactic Astronomy (Princeton:
Princeton Univ. Press)
Bottani, R. 1999, A&A, 348, 77
Carollo, C. M., Franx, M., Illingworth, G. D., & Forbes, D. 1997, ApJ, 481,
710
Corsini, E. M., et al. 1999, A&A, 342, 671
Faber, S. M., et al. 1997, AJ, 114, 1771
Fisher, D. 1997, AJ, 113, 950
Gerhard, O. E. 1993, MNRAS, 265, 213
Hernquist, L. 1993, ApJS, 86, 389
Jaffe, W., Ford, H. C., O’Connell, R. W., van den Bosch, F. C., & Ferrarese,
L. 1994, AJ, 108, 1567
Kormendy, J., & Bender, R. 1996, ApJ, 464, L119
Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139
Naab, T. 2001, in ASP Conf. Ser. 230, Galaxy Disks and Disk Galaxies, ed.
J. G. Funes & E. M. Corsini (San Francisco: ASP), 451
Naab, T., Burkert, A., & Hernquist, L. 1999, ApJ, 523, L133 (NBH)
Rix, H.-W., Carollo, C. M., & Freeman, K. C. 1999, ApJ, 513, L25 (R99)
Sugimoto, D., Chikada, Y., Makino, J., Ito, T., Ebisuzaki, T., & Umemura,
M. 1990, Nature, 345, 33
Toomre, A., & Toomre, J. 1972, ApJ, 178, 623
van der Marel, R. P., & Franx, M. 1993, ApJ, 407, 525