THE FORMATION OF DISKS IN ELLIPTICAL GALAXIES

THORSTEN NAAB AND ANDREAS BURKERT
Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
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ABSTRACT

We investigate detailed kinematical properties of simulated collisionless merger remnants of disk galaxies with mass ratios of 1 : 1 and 3 : 1. The simulations are performed by direct summation using the new special hardware device GRAPE-5. In agreement with observations, the shape of the line-of-sight velocity distribution (LOSVD) is Gaussian with small deviations. For most cases, we find that the retrograde wings of the LOSVD are steeper than the prograde ones. This is in contradiction with observations that show broad retrograde and steep prograde wings. This serious problem in the collisionless formation scenario of massive elliptical galaxies can be solved if all rotating elliptical galaxies, even boxy ones, contain an additional stellar disk component of approximately 15% of the total stellar mass and a scale length of order the effective radius of the spheroid. We propose that the progenitor galaxies of massive elliptical galaxies must have contained a significant amount of gas that did not condense into stars during the merger process itself but formed an extended gaseous disk before the star formation epoch. The heating source that prevented the gas from forming stars early and the origin of the large specific angular momentum required for the gas component to form an extended disk are still unsolved problems.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: interactions — galaxies: structure — methods: numerical

1. INTRODUCTION

The merger hypothesis (Toomre & Toomre 1972) assumes that elliptical galaxies form by major mergers of spiral galaxies. This is supported by observations of nearby merging systems that seem to evolve into systems with properties comparable to elliptical galaxies (Hibbard & Yun 1999). The gravitational interaction during the merger process also triggers massive star formation and, probably, the formation of massive central black holes and active galactic nuclei (Sanders & Mirabel 1996; Rigopoulou et al. 1999). On the theoretical side, numerous numerical simulations have shown that mergers lead to spheroidal systems with global properties comparable to elliptical galaxies (Barnes & Hernquist 1992; Barnes 1998; Bekki & Shioya 1997; Naab, Burkert, & Hernquist 1999). During the merging epoch, the galaxies are far from dynamical equilibrium. Gas, if added to the simulations, condenses into stars by massive bursts of star formation during the merging process or effectively loses angular momentum and falls into the central parts of the merger remnant, probably feeding a central black hole (Mihos & Hernquist 1996; Springel 2000; Bekki 2000). When the merger remnants have settled into dynamical equilibrium, phase mixing and violent relaxation have erased most information about the initial conditions. However, as violent relaxation is incomplete, the stellar phase-space distribution of elliptical galaxies should still show fine structure, which affects the isophotal shapes and velocity distributions. This fine structure provides fundamental insight into the formation epoch of elliptical galaxies.

Numerical simulations of collisionless mergers of disk galaxies have confirmed this conclusion. The line-of-sight velocity distributions (LOSVDs) of merger remnants and the orbit structure of their stars contain information about the initial disk orientations (Heyl, Hernquist, & Spergel 1996). The isophotal shapes and the dynamics of the merger remnants are primarily determined by their initial mass ratios (Naab et al. 1999; Bendo & Barnes 2000).

In this Letter, we show that the LOSVDs of most elliptical galaxies contain evidence for a second disk component with roughly 10%–20% the luminosity of the spheroid and a large scale radius that is on the order of the effective radius of the spheroid. This disk might have been formed by late gas infall from gas-rich progenitors, followed by star formation. Observationally, photometric and kinematic investigations of elliptical galaxies have already indicated the existence of large stellar disks of the same order of magnitude as predicted here, especially in disky, rotating elliptical galaxies (Rix & White 1990; Scorza et al. 1998). We demonstrate that this component is required in almost all elliptical galaxies, independent of whether they are disky or boxy, in order to bring the observations in agreement with the merger scenario of the formation of early-type galaxies.

2. THE MERGER MODELS

We used the method described by Hernquist (1993) to construct disk galaxies in dynamical equilibrium. The system of units was the following: gravitational constant $G = 1$, exponential scale length of the larger disk in the merger $h = 1$, and mass of the larger disk $M_p = 1$. The disks were exponential with an additional spherical, nonrotating bulge with mass $M_b = \frac{1}{4}$, a Hernquist density profile (Hernquist 1990), and a scale length $r_e = 0.2h$. The system lived in a spherical pseudo-isothermal halo with a mass $M_h = 5.8$, cutoff radius $r_c = 10h$, and core radius $\gamma = 1h$.

The $N$-body simulations were performed using a direct summation code with the new special purpose hardware GRAPE-5 (Kawai et al. 2000). The 1 : 1 merger was calculated adopting in total 400,000 particles with each galaxy consisting of 60,000 disk particles, 20,000 disk particles, and 120,000 halo particles. For the 3 : 1 merger, the parameters of the more massive galaxy were as described above. The low-mass galaxy contained one-third the mass and number of particles of the larger galaxy, with a disk scale length of $h = (\frac{1}{2})^{1/2}$, as expected from the Tully-Fisher relation.

For both mass ratios, the galaxies approached each other on nearly parabolic orbits with an initial separation of 30 length units and a pericenter distance of two length units. In this Letter, we focus on one corotating and one counterrotating geometry.
Then we placed a slit with a width of 0.2 unit lengths along the apparent long axis of each projected remnant. Thereafter, we binned all particles falling within each grid cell in velocity along the line of sight. The grid spacing was chosen to be 0.15 times the projected half-mass radius. The width of the velocity bins was set to a value of 0.2 for line-of-sight velocities \( v_{\text{los}} \) in the range \( -4 \leq v_{\text{los}} \leq 4 \). This resulted in 80 velocity bins over the whole velocity interval. Using the binned velocity data, we constructed line-of-sight velocity profiles for each bin along the grid. Subsequently, we parametrized deviations from the Gaussian shape of the velocity profile using Gauss-Hermite basis functions (van der Marel & Franx 1993; Gerhard 1993; Bendo & Barnes 2000). The kinematic parameters of each profile \( \langle \sigma_{\text{fit}}, v_{\text{fit}}, H_3, H_4 \rangle \) were then determined by least-squares fitting. The large number of simulated stellar particles (>100,000) guaranteed that at least 2000 particles fall within each slit inside one effective radius.

4. COMPARISON WITH OBSERVATIONS

The straight lines in Figure 1 indicate the observed local correlation between \( H_3 \) and \( v/\sigma \) for a sample of elliptical galaxies in low-density environments, published by Bender, Saglia, & Gerhard (1994). In all cases, \( H_3 \) and \( v/\sigma \) have opposite signs. The data indicate that all elliptical galaxies have LOSVDs with steep prograde wings and broad retrograde wings. Mehlert et al. (2000) have shown that this result also holds for cluster elliptical galaxies in Coma.

The local correlation between \( H_4 \) and \( v/\sigma \) for the simulated corotating (A, C) and counterrotating (B, D) 1 : 1 and 3 : 1 mergers, respectively, is shown by the dots in Figure 1. Every remnant is analyzed as seen from 50 random viewing angles. For the corotating mergers, the correlation between \( H_4 \) and \( v/\sigma \) is almost opposite to the observed one. This is also reflected in a positive effective value for \( H_3 \) (Fig. 2, left) for almost all projection angles, where \( \langle H_3 \rangle \) is defined as the mean value between 0.25 and 0.75 effective radii (Bender et al. 1994). Here a negative \( \langle H_3 \rangle \) corresponds to an anticorrelation between \( H_4 \) and \( v/\sigma \), such that \( H_4 > 0 \) for \( v/\sigma < 0 \) and vice versa. We find that \( \langle H_4 \rangle \) versus \( v/\sigma \) does not follow the observed correlation, indicated by the solid and dashed lines. The profiles have broad prograde wings and narrow retrograde wings. The counterrotating 3 : 1 merger (D) in Figure 1 shows a large spread around zero but also does not agree with observations. The only exception is the equal mass merger of counterrotating disks (B), which leads to a very anisotropic elliptical galaxy with no signature of rotation.

Note that the four simulations that we focus on in this Letter...
have been chosen because they are representative of a much larger set of simulations with different orbital geometries. These four models have been recalculated with high resolution for better statistics.

We conclude that collisionless mergers of disk galaxies in general fail to explain the detailed kinematics of all observed elliptical galaxies (also massive, boxy ones) that exhibit a significant amount of rotation ($v/\sigma \geq 0.2$) inside $1_{\text{eff}}$. Further evidence for a possible failure of the collisionless merger picture comes from Cretton et al. (2001), who showed that the kinematical properties of very faint and fast rotating, disky elliptical galaxies cannot be explained by collisionless mergers of disk galaxies.

5. THEORETICAL SUPPORT FOR DISKS IN ELLIPTICAL GALAXIES?

One plausible explanation for LOSVDs with negative $H_3$ is the superposition of a spheroidal body with a disklike component (Bender et al. 1994). With a simple experiment, one can test if the wrong correlations we find in our remnants result from a lack of such a component. We artificially added a thin (scale height $\approx 0.05r_{\text{eff}}$), cold (velocity dispersion perpendicular to the disk $\sigma = 0$), stellar disk with an exponential surface density profile. The disk was placed in the plane defined by the long and intermediate axes of the main stellar body, rotating in the same direction as the main stellar body. The particles of the disk were assumed to move around the center of the galaxy in centrifugal equilibrium with the gravitational potential arising from the total enclosed mass. No additional random motion was added. Under these simple assumptions, only two parameters remain free: the total mass of the disk $M_d$ in units of the total luminous mass of the remnant and its scale length $r_d$ in units of the projected half-light radius $r_{\text{eff}}$. The results for the corotating 3 : 1 remnant (C) are summarized in Figures 3 and 4. This case is representative for all our unequal mass merger remnants. In general, we find that disks with small masses or radii do not change the LOSVDs of the stellar component. Disks with masses and radii in the region indicated by the circles in Figure 4, on the other hand, lead to a significant change in the resulting line profile. The prograde wings become steeper than the retrograde ones, in very good agreement with observations. This effect is shown in Figure 3 for a disk with 15% of the spheroid mass and $r_d = 1.25r_{\text{eff}}$. The influence on the ($H_3$) versus $v/\sigma$ correlation and its dependence on projection effects is shown on the right-hand side of Figure 2. Now the values fall in the observed regime.

If the additional disk becomes too massive, the absolute values for $H_3$ are larger than observed and the surface brightness profiles change from de Vaucouleurs to exponential profiles, which is again not in agreement with observations. We therefore conclude that the existence of an additional stellar disk component with 10%–20% the luminosity of the spheroid and a scale length on the order of $r_{\text{eff}}$ can explain the observed correlation between $H_3$ and $v/\sigma$ in elliptical galaxies.

The same procedure for the corotating equal mass merger remnant (A) requires an additional disk component with similar size as in the unequal mass case. Interestingly, the galaxy that was anisotropic and slowly rotating with boxy isophotes now can appear both disky and fast rotating or boxy and slowly rotating depending on the projection. The kinematics of the counterrotating equal mass remnant (B) is consistent with observations and needs no additional component. If, however, we add a disk, the result is qualitatively the same as for model A.

We tested two possible caveats of the model: the thickening and the stability of the disk and the disk-spheroid interaction. First, we evolved model C with the best-fitting disk model for eight dynamical times. As a second test, we started with a massless disk and increased the total mass of the disk at a rate of $10^7 M_\odot$ Myr$^{-1}$ up to 15% of the spheroid mass to test the possible dynamical response of the remnant. In both cases, the disk tilted and thickened but kept its disklike structure. Both effects did not have a significant effect on the projected properties of the remnants and did not change our conclusions.

6. DISCUSSION AND CONCLUSIONS

Our simulations indicate that models of pure collisionless mergers in general fail to reproduce LOSVDs of observed elliptical galaxies. All simulated profiles locally have the wrong sign of $H_3$ with respect to $v/\sigma$, compared with the observations.
A similar result has been reported by Bendo & Barnes (2000). They, however, did not investigate projection effects. A detailed investigation of local properties of the LOSVDs and projection effects shows that the presence of an additional stellar disk component added to the stellar body after the merger is complete could solve the problem.

One possible origin for such a disk is gas that must have been present during the formation epoch of massive elliptical galaxies and that formed a disk after the major merger event was completed. In order to fit the observed profiles, the amount of gas that settled into the equatorial plane must have been significant. It is puzzling why the gas did not turn into stars prior to its infall onto the equatorial plane and how the gas could keep its angular momentum required for the disk to have a scale length equal to the effective radius of the spheroid.

Barnes & Hernquist (1996) do find gaseous disklike components in their equal mass merger models. Tidal torques lead, however, to efficient angular momentum loss in the gaseous component, resulting in gas infall to the center. Only 20% of the initial gas mass (which was 10% of the initial disk mass), and by this less than 2% of the stellar mass, settled into an extended disklike component. In this case, the disk would not be massive enough to change the LOSVD of the system significantly. Equal mass mergers of very gas-rich disks (more than 50% gas) could, however, lead to the formation of more massive disklike components in the end.

First simulations by Naab & Burkert (2001) have shown that for unequal mass mergers of gas-rich galaxies that lead to disky, fast rotating elliptical galaxies due to the stronger centrifugal support, a large fraction of the gas settles into extended disks after the merger is complete, if star formation is suppressed. This seems to be an attractive scenario to explain the existence of large disks in disky elliptical galaxies. The origin of large stellar disks in massive boxy elliptical galaxies with a small but significant amount of rotation that form presumably from equal mass mergers is, however, still unclear.

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