Evidence for Large Stellar Disks in Elliptical Galaxies.

Andreas Burkert and Thorsten Naab
Max-Planck-Institut für Astronomie, D-69242 Heidelberg, Germany

Abstract. High-resolution numerical simulations of galaxy mergers are analysed. The global structure and isophotal shapes of the merger remnants are in good agreement with the observations. Whereas equal-mass mergers lead to anisotropic, boxy ellipticals, unequal-mass mergers result in disky and isotropic systems. The line-of-sight velocity distributions show small deviations from a Gaussian distribution. In all cases we find that the retrograde wings are steeper and that the prograde wings are broader than a Gaussian distribution. This is in contradiction with the observations which show broader retrograde and steeper prograde wings in all ellipticals. This fundamental difference between observation and theory can be explained if all ellipticals, even anisotropic boxy ones, contain extended stellar disk components with luminosities of order 10% to 20% the total luminosity and scale radii of order the effective radii of the spheroids.

1 Introduction

Elliptical galaxies are believed to form by major mergers of spiral galaxies [12]. Numerous numerical simulations have indeed demonstrated that mergers lead to spheroidal stellar systems with surface brightness profiles that are in good agreement with the observations of elliptical galaxies (e.g. [1, 9, 10, 2]). During the merging epoch the systems are far from dynamical equilibrium, resulting in bursts of star formation [13], the formation of massive star clusters and the infall of gas into the central regions and the formation and feeding of massive central black holes. When the merger remnants have settled into dynamical equilibrium, phase mixing and violent relaxation will erase the information about the initial conditions. However, as violent relaxation is incomplete, ellipticals should still show fine structure in their isophotal shape and velocity distribution which provides insight on their formation.

This conclusion is confirmed by numerical simulations. Heyl et al. [14] showed that the line of sight velocity distributions contain information about the initial disk orientations. Naab et al. [14] and Bendo & Barnes [3] demonstrated that the isophotal shapes of the remnants are determined primarily by the initial mass ratio of the merging galaxies.

In this paper we focus on signatures for gas infall and star formation during the formation of ellipticals. We demonstrate that all ellipticals must contain a second disk-like substructure that most likely formed by gas infall with subsequent star formation from gas-rich progenitors.
Fig. 1. **Left panel:** Observed local correlation between $H_3$ and $v/\sigma$. Typical error bars are plotted in the upper right corner. The lines show model predictions for two-integral models. **Right panel:** Correlation between $H_3$ and $v/\sigma$ for a typical merger remnant.

## 2 The Line-of-Sight Velocity Distribution of Merger Models

We have performed very high-resolution N-body simulations with more than $10^5$ particles of spiral-spiral mergers with different mass ratios and orbital parameters. The spirals are constructed in dynamical equilibrium using the method described by [10]. Each galaxy consists of an exponential disk, a spherical, non-rotating bulge and a dark halo component. An analysis of the isophotal shapes and the global kinematical properties of the merger remnants is presented in [14]. We find a strong dependence on the initial mass ratio of the merging components. Whereas mergers with mass ratios $m_1 : m_2 \leq 2 : 1$ lead to boxy and anisotropic systems, unequal mass mergers with mass ratios $m_1 : m_2 > 2 : 1$ form disky and isotropic ellipticals.

Another interesting property is the line-of-sight velocity distribution and its deviations from a Gaussian. Following the procedure discussed by [5] we have placed slits with thickness 0.2 the effective radius along the apparent long axis of our projected merger remnants. The slit is subdivided into grid cells with length 0.15 the effective radius. All particles within a cell are binned in line-of-sight velocity. The resulting profile is parametrized using Gauss-Hermite functions [5] and the amplitude $H_3$ of the third-order basis function is determined by least squares fitting. In addition, in each grid cell the mean projected radial velocity $v$ and the radial velocity dispersion $\sigma$ of all particles is determined. In agreement with the observations, the deviations from Gaussians are small, of order a few percent.
Fig. 2. Values of disk masses $M_d$ versus disk scale lengths $r_d$ that have been added to a merger remnant. Big dots represent solutions that provide an excellent fit to the observed $H_3$ versus $v/\sigma$ relationship. Small dots show values that provide a reasonable fit. Minus signs show combinations that fail.

3 Comparison with Observations

Figure 1 (left panel) shows the local correlation between $H_3$ and $v/\sigma$ as measured by [5] for their observed sample of galaxies. In all cases $H_3$ and $v/\sigma$ have opposite signs, that is the prograde wings of the line-of-sight velocity distributions are always steeper than the retrograde wings. This result holds not only for ellipticals in low-density environments studied by [5] but also for ellipticals in the Coma cluster [12]. The right panel of Figure 1 shows the result of a representative merger simulation, an unequal mass merger which leads to a disky, isotropic elliptical. The correlation between $v/\sigma$ and $H_3$ is opposite to the observed one. The profiles have broad prograde wings and narrow retrograde wings. The same signature is found in all remnants, independent of whether they are disky or boxy, isotropic or anisotropic. The only exception are equal mass mergers of counter-rotating disks which lead to very anisotropic ellipticals with no signature of rotation.
4 Disk-like Subcomponents in Elliptical Galaxies

One possible solution is the existence of a second disk component. In order to test this assumption we have placed stellar disks in the equatorial plane of the merger remnants. The disks rotate in centrifugal equilibrium with the total gravitational potential. Adopting an exponential disk surface brightness profile, the only free parameters are the ratio of disk mass to spheroid mass and the scale length of the disk, normalized to the scale radius of the spheroid. The results are summarized in Figure 2. Disks with small masses or radii do not change the line-of-sight velocity distribution of the stellar component, especially in the outer regions where \( v/\sigma \) is large. Disks with mass ratios and radii in the region shown by the filled dots in Figure 2, on the other hand, lead to a significant change in the line profiles. The prograde wings become steeper than the retrograde ones also at an effective radius and beyond, in very good agreement with the observations. If the disks become too massive, the surface brightness profiles of the spheroids change from de Vaucouleurs profiles to exponential profiles which is again not in agreement with the observations. We therefore can conclude that disks with 10% to 20% the luminosity of the spheroids and scale lengths of order the effective radii of the spheroids can explain the observed correlation between \( H_3 \) and \( v/\sigma \) in ellipticals.

The origin of extended disk components in ellipticals is not understood up to now. Bekki discussed the formation of nuclear disks in mergers which however have scale lengths that are small compared to the length scales of the spheroids. We recently started a new set of merger simulations of very gas-rich spiral galaxies. For unequal mass mergers, which lead to disky ellipticals, the gas settles indeed into extended disks if star-formation is suppressed during the early merging phase. However, in the case of equal-mass mergers, which produce boxy ellipticals, tidal torques lead to efficient angular momentum loss in the gaseous component, resulting in gas infall into the center and the formation and growth of central massive black holes. No extended gaseous disks are formed in this case. The origin of large stellar disks in boxy ellipticals is therefore still unclear.

References

1. J.E. Barnes: ApJ 331, 699 (1988)
2. K. Bekki: ApJ 502, L133 (1998)
3. K. Bekki: ApJ 545, 753 (2000)
4. K. Bekki: ApJ 546, 189 (2001)
5. R. Bender, R.P. Saglia, O.E. Gerhard: MNRAS 269, 785 (1994)
6. G.J. Bendo, J.E. Barnes: MNRAS 316, 315 (2000)
7. W. Dehnen, O.E. Gerhard: MNRAS 261, 311 (1993)
8. W. Dehnen, O.E. Gerhard: MNRAS 268, 1019 (1994)
9. L. Hernquist: ApJ 400, 460 (1992)
10. L. Hernquist: ApJ 409, 548 (1993)
11. J.S. Heyl, L. Hernquist, D.N. Spergel: ApJ 463, 69 (1996)
12. D. Mehlert, R.P. Saglia, R. Bender, G. Wegner: A&A 141, 449 (2000)
13. J.C. Mihos, L. Hernquist: ApJ 464, 641 (1996)
14. T. Naab, A. Burkert, L. Hernquist: ApJ 523, L133 (1999)
15. A. Toomre, J. Toomre: ApJ 178, 623 (1972)