Formation of Elliptical and S0 Galaxies by Close Encounters

Thorsten Naab and Andreas Burkert

Max-Planck-Institut für Astronomie, Heidelberg, Germany

Abstract. We study a possible formation mechanism for elliptical/S0 galaxies using N-body simulations with GRAPE. A close galaxy encounter which does not lead to a merger can induce a strong bar in an initially axisymmetric disk. This bar is unstable to bending oscillations and loses angular momentum to the dark halo. After 6 Gyrs the remnant is spheroidal with a de Vaucouleurs-type surface density profile and has ellipticities and rotation properties comparable to observed elliptical/S0 galaxies: the system rotates fast ($v/\sigma \approx 1$) and has disky isophotes.

1. Introduction

Most massive elliptical galaxies can be divided into two groups with different physical properties. Bright ellipticals are slow anisotropic rotators, have boxy distorted isophotes, are radio-loud, and are surrounded by gaseous X-ray halos (Bender et al., 1989). Faint elliptical galaxies are preferentially oblate isotropic rotators with disky isophotes. In contrast to boxy ellipticals they are radio-quiet and show no X-ray emission in excess to their discrete source contribution. Gravitational N-body simulations, starting with the work by Toomre & Toomre (1972,1977) using a restricted three-body approximation, and continued by others (e.g.: Barnes, 1988) using a hierarchical tree algorithm, have shown that mergers of equal mass disk-galaxies can produce slowly-rotating remnants with a de Vaucouleurs-like surface-brightness profile and disky or boxy isophotes depending on the viewing angle (Heyl et al., 1994). It is generally believed that merger remnants are supposed to have properties resembling observed boxy elliptical galaxies, such as slow figure rotation, kinematically distinct cores, so the question of how disky and fast rotating ellipticals have formed is still unanswered. Here we study a possible formation mechanism for disky elliptical galaxies in an encounter scenario. An approximated massive galaxy perturbs an equal mass disk galaxy and flies away. We analyze the triaxial shape, the rotation properties and the isophotal shape of the remnant.

1.1. The model

The initial conditions for our simulations were derived following Hernquist (1993) as described briefly below. The N-body model consists of an exponential disk surrounded by a dark halo. The thickness of the disk is determined by the velocity dispersion which is a function of radius. The halo is initially spherical and has an isothermal density profile with a core and a cutoff-radius to reduce
Figure 1. Snapshots of the simulation at different time steps seen face-on and edge-on. Only the distribution of the luminous matter is shown.

the computational costs. Velocities are initialized by taking moments of the collisionless Boltzmann equation and approximating the distribution function in phase space by Gaussians. This produces stable models that are nearly in
equilibrium. The Toomre Q-parameter is normalized to the value of 1.5 at a radius similar to the Solar neighborhood. The mass and size of the disk is scaled to physical values of the Milky Way, i.e. scale length \( h = 3.5 \) kpc and disk mass \( M_d = 5.6 \times 10^{10} \odot \). For the perturbing galaxy, we used an equal mass particle realization of a profile approximating a dark halo. At the beginning of the simulation the perturber is on a prograde hyperbolic orbit with an impact parameter of 63 kpc, and a relative velocity of 343 km/s.

The simulation was performed with a direct N-body code using the special hardware device GRAPE (Sugimoto et al., 1990). We followed the simulation for 6 Gyrs. The simulation presented here has 50,000 disk particles, 100,000 halo particles, and 20,000 particles representing the perturber.

1.2. Results

Figure 1 shows a sequence of snapshots for our simulation. The encounter induces a strong bar in the disk, although the disk is stable against bar formation if simulated in isolation. This bar becomes unstable to bending oscillations (Raha et al. 1991, Merritt & Sellwood, 1994) due to an increase of the velocity dispersion in radial direction. As a result of this instability the initially disklike system becomes spheroidal.

To estimate the three-dimensional shape of the remnant we computed the axis ratios of the distribution of disk particles from the eigenvalues of the moment-of-inertia tensor. For the 60% most tightly bound particles the triaxiality parameter \( T \equiv (a^2 - b^2)/(a^2 - c^2) \) is 0.88. The effective Hubble types for projections along the three principal axes are E5.7, E7.3 and E4 respectively.

The surface density follows a de Vaucouleurs-like profile over a large radial interval and is comparable to the remnants of merger simulations. After the strong rotating bar has formed, its dynamical friction with the live halo component leads to an effective transport of angular momentum to the halo. The rotation velocity in the inner parts decreases rapidly. Figure 2 shows the rotation properties of the system after 6 Gyrs. We have plotted \( v_m/\sigma \) (\( v_m \): maximum rotation velocity, \( \sigma \): central velocity dispersion) against the ellipticity. The points show the values for the same remnant in different projections. One can see that some projections follow the line for oblate rotators, but we also have anisotropic remnants and those with very high rotation velocities at low ellipticities. This effect can be influenced by the determination of the ellipticity; some observers see the same effect in their data (see Nieto et al., 1988).

We also investigated the deviations of the isophotes from pure ellipses applying the method described by Bender el al. (1988) after binning the particle distribution and convolving it with a Gaussian with a FWHM comparable to the seeing conditions of the observations.

We find that the remnant has disky isophotes (positive \( a4/a \)) for almost all projections. The value of \( a4 \) is higher for remnants with higher ellipticity (Figure 2). With increasing radius the \( a4 \) coefficient shows basically two global features: either a disky inner part changing to boxy in the outer parts, or a continuously rising positive \( a4 \). Those features could be explained as suggested before (Nieto et al., 1991) by a faint disk surrounded by a spheroidal component or, in the case of rising \( a4 \), tidal extensions of a round inner part. In our simulation the shape of the profile just depends on the projection angle.
Figure 2. Left: The isophote-shape parameter $a(4)/a$ against ellipticities for 100 randomly chosen projections (positive $a(4)/a$: disky, negative $a(4)/a$: boxy). Right: $v_m/\sigma$ against ellipticity.

Future simulations will show how sensitive our results are to the resolution and different initial conditions.

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