On the formation of compact ellipticals

A. Burkert
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching bei München, Germany

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ABSTRACT
A model for the formation of compact elliptical galaxies as satellites of massive galaxies is presented. It is assumed that compact ellipticals formed through a starburst and the subsequent violent collapse of the stellar system. Numerical N-body experiments show that one can understand the peculiar structure of compacts if they were produced as a result of the relaxation of initially cold stellar systems which were disturbed by the tidal field of a bright galaxy. The observed differences between compact ellipticals and low-mass giant ellipticals might therefore result from the fact that the compacts formed within the potential well of another galaxy whereas the giant ellipticals evolved as isolated systems.

Constraints on the internal rotation and on the orientation of the major and minor axes with respect to the orbital plane of the compacts are derived. These results can be used to deproject the observed surface brightness and velocity profiles of compact ellipticals, and to calculate their orbital parameters.

Additional N-body experiments of collapsing, initially clumpy protogalaxies indicate that compact ellipticals might be the remnants of those clumps that did not merge, but gained energy and angular momentum and formed separate satellite systems. Thus the compacts might provide important information on the building blocks of giant galaxies as well as on the physical conditions of the protogalactic environment in which they evolved.

Key words: galaxies: compact – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: interactions.

1 INTRODUCTION
At absolute blue magnitudes fainter than $M_B = -18$ mag, two types of ellipsoidal galaxies are observed: compact ellipticals (cEs) and dwarf ellipticals (dEs). Dwarf ellipticals are characterized by low surface brightnesses, which decrease exponentially with radius, and low mean metallicities $[\text{Fe/H}] < 0.1$ (Binggeli, Sandage & Tarenghi 1984; Kormendy 1985). They are anisotropic with an anisotropy parameter

\[
\frac{v}{\sigma} = \frac{v/\sigma}{\sqrt{1-e}} \leq 0.5
\]

(Bender & Nieto 1990), where $v$ is the observed rotational velocity and $\sigma$ and $e$ are the mean velocity dispersion and ellipticity, respectively.

In contrast to dEs, the rare compact ellipticals cover a small range in $M_B$ of $-18$ mag $\leq M_B \leq -14$ mag. They show a truncated de Vaucouleurs profile (see e.g. Nieto & Prugniel 1987) and follow the colour–luminosity relation of giant ellipticals (gEs). Their effective surface brightnesses are orders of magnitude larger than those of dEs, even sometimes exceeding those of gEs. Like low-mass gEs they seem to have solar-like or even higher metallicities (Freedman 1989) and are supported by rotation.

Due to these similarities, Wirth & Gallagher (1984) proposed that cEs actually represent the low-mass extension of gEs. New observations have, however, shown some interesting differences between cEs and gEs which might justify a classification of these galaxies into two different groups with different formation histories. For example, some cEs have surface brightnesses that are an order of magnitude higher than those of low-mass gEs, and they have very shallow metallicity gradients, in contrast to the giant ellipticals (de Vaucouleurs 1961; Peletier 1993). Their mean ellipticities are $\langle e \rangle \approx 0.2$, and their outer regions are significantly less elliptical than the inner parts. The gEs have $\langle e \rangle \approx 0.4$ and also exhibit radially varying ellipticity. Their averaged $\epsilon(r)$ for a composite of many systems is, however, roughly constant (Franx, Illingworth & Heckmann 1989). Finally, if cEs...
represent a low-mass extension of gEs we would expect them to have rotational parameters \( v/\sigma \approx 1 \). Observations, however, indicate that they are more anisotropic, with \( v/\sigma = 0.6 \) and rotational velocities of \( v = 40 \text{ km s}^{-1} \) (Bender \& Nieto 1990).

With respect to their formation and evolution, it might be important to note that compact ellipticals exist almost exclusively as satellites of bright galaxies. Faber (1973) concluded that they might actually represent the inner regions of low-mass giant ellipticals, the outer diffuse parts of which were stripped during the encounter. Nieto (1990) proposed another scenario wherein a cE is the bulge of a low-mass S0 galaxy that lost its disc during the interaction with the bright galaxy. These models can explain the larger average surface brightnesses that cEs possess. It seems, however, more difficult to understand the anisotropy, the lack of a metallicity gradient and the peculiar ellipticity profiles of cEs.

Here we will adopt a somewhat different approach. As in some earlier models we assume that cEs had an internal evolution similar to that of gEs, with the exception that this evolution took place close to a bright galaxy. cEs therefore evolved under the influence of a tidal field. It will be shown that this scenario can explain the observed differences between cEs and isolated gEs. Section 2 presents a model for the formation of gEs and demonstrates how compact ellipticals could have formed as isolated satellites around bright galaxies. Section 3 studies the dynamical evolution of cEs in greater detail and compares the theoretical results with the observations. Conclusions follow in Section 4.

2 THE FORMATION OF GIANT ELLIPTICALS

If we assume that compact ellipticals had a star formation history similar to that of giant ellipticals, we first have to construct a model for the formation of giant ellipticals. Until we can focus on the more complex gEs. It is generally assumed that the distribution of the stars in gEs formed through a short, violent starburst (Sandage 1985; Matteucci 1992). The star formation time-scale \( t_{\text{ff}} \) exceeded the dissipation time-scale \( t_{\text{diss}} \) of the gaseous protogalaxy, enabling the system to dissipate its internal kinetic and thermal energy and start a violent collapse phase. During the collapse a starburst converted most of the gas into stars on such a short time-scale that the interstellar medium had no time to settle into the equatorial plane and form a galactic disc (Thies, Burkert \& Hensler 1992). The inward-falling stellar component crossed the galactic centre and the equatorial plane without dissipative collisions, and the system re-expanded and formed a spheroidal elliptical galaxy. According to this picture the presently observed structure of gEs should be a result of the relaxation and phase-mixing of a violently collapsing stellar system. In fact, numerical N-body simulations have shown that collisionless-particle systems with initially small virial coefficients

\[
\eta_{\text{vir}} = \frac{2E_{\text{kin}}}{E_{\text{pot}}} < 0.1
\]

reach a final macroscopic equilibrium state within a few dynamical time-scales, which is in good agreement with the observations of gEs (see e.g. van Albada 1982; May \& van Albada 1984; Merritt \& Aguilar 1985; Burkert 1990; Cannizzo \& Hollister 1992). In equation (2), \( E_{\text{kin}} \) and \( E_{\text{pot}} \) are the kinetic and potential energies, respectively.

As a standard model for the formation of typical giant ellipticals we analyse the evolution and final equilibrium state of a stellar system that started with clumpy initial conditions and a small virial coefficient. Such inhomogeneous initial conditions are predicted from cosmological models (see e.g. Norman \& Silk 1980). They also seem to be required in order to achieve better agreements with the observed de Vaucouleurs profile of gEs (de Vaucouleurs 1948) after collisionless relaxation (van Albada 1982; May \& van Albada 1984; see, however, Aguilar \& Merritt 1990).

We adopt the same initial conditions as in model C3 of van Albada (1982): 20 spheres of radius 0.4 are placed randomly into a volume of radius \( R = 1 \). The isotropic velocity distribution of the subunits is chosen such that the initial virial coefficient is \( \eta_{\text{vir}} = 0.1 \). The clumps are filled homogeneously with stars moving collectively with the assigned clump velocity.

The dynamical evolution of the system is studied with 50 000 test particles. This provides a resolution that is 10 times as high as in van Albada's calculations. We use a vectorized version of the Barnes–Hut TREECODE (Barnes \& Hut 1986). The program was written and kindly made available by Lars Hernquist (Hernquist 1987). The code parameters (Hernquist 1988) are set as follows: smoothing length \( \epsilon = 0.05R \); tolerance parameter \( \theta = 0.5 \); force computation with quadruple terms; and time-step \( \Delta t = 0.01 \tau_{t} \). In all the calculations discussed here, the total energy was conserved to better than 0.2 per cent, and the total angular momentum was conserved to better than 1 per cent.

Fig. 1 shows the initial positions of the test particles, projected onto the \( x \)-\( y \) plane. The radii of the clumps are chosen such that the subunits overlap and no large empty spaces are created. The mass of the clumps is distributed uniformly between 0 and 0.2. Following van Albada (1982), the gravitational constant is set to \( G = 4.497 \), defining a typical unit of \( t_{\odot} = 10^{10} \text{ yr} \) and a dynamical time-scale of \( t_{\text{dyn}} = 0.37 t_{\odot} = 4 \times 10^{7} \text{ yr} \).

The final, prolate equilibrium state of this N-body experiment at a time \( t = 6 = 16 t_{\text{dyn}} \) is plotted in Fig. 2. Here and in the following discussion the long axis of the ellipsoid is chosen as the \( x \)-axis. The virial coefficient is now \( \eta_{\text{vir}} = 1 \) and the macroscopic structure of the stellar system has become time-independent. The ellipticity profile \( \epsilon(r) \) of the surface density distribution, projected on to the \( x \)-\( y \) plane, is approximately constant with a mean ellipticity \( \langle \epsilon \rangle = 0.4 \), in good agreement with the observed ellipticities of gEs. In agreement with van Albada's calculations, the surface density distribution can be approximated over many orders of magnitude by a de Vaucouleurs profile

\[
\Sigma \sim \exp(-r^2/\epsilon)
\]

and the system is anisotropic with the radial velocity dispersion \( \sigma_r \), being larger than the tangential velocity dispersion \( \sigma_\theta \), especially in the outer regions where the stars are moving preferentially on radial orbits.

Fig. 3 shows the rotation curve along the major axis. Due to the fact that we started with only 20 randomly distributed clumps, we end with a non-zero net angular momentum (i.e. some rotation is generated). The anisotropy parameters (equation 1) that we derive for the equilibrium state with
Figure 1. The initial particle distribution of the clumpy gE-model, projected on to the x-y plane.

Figure 2. The final triaxial particle distribution of the gE-model at a time $t = 16 \tau$, projected on to the x-y plane. The long axis of the ellipsoid is defined as the x-axis of the coordinate system.
$v = 0.4, \sigma = 5$ and $e = 0.4$ is small: $(v/\sigma)^* = 0.1$. This result is in good agreement with the observations of high-mass ellipticals. It is interesting that, although the ellipticity is not a result of rotational flattening, the minor axis of the system is parallel to the rotation axis. This indicates that rotation, even if it does not determine the final ellipticity, can still affect the orientation of the system.

The normalized binding energy $(E/W)(r)$ as a function of the radial distance $r$ from the centre of the galaxy is shown in Fig. 4. Inside $r \approx 2$ the deep potential well of the giant galaxy is visible. Outside $r \approx 2$ one can recognize two additional gravitational centres located at $r = 8.2$ and $r = 14$. These self-gravitating objects formed from clumps that gained energy and angular momentum during the violent collapse phase and did not merge with the central galaxy. They evolved separately, then collapsed and relaxed to form self-gravitating, isolated star clusters. The system at $r \approx 8$ has a negative mean energy and therefore represents a bound satellite galaxy. It has a high surface density and a mass that is a factor of 50 smaller than that of the giant galaxy. We can therefore identify this object as being a compact elliptical galaxy.

3 THE FORMATION OF COMPACT ELLIPTICALS

In the last paragraph it was shown that isolated, self-gravitating satellites can form in the vicinity of evolving, bright galaxies. Let us now assume that compact ellipticals formed in this way through a starburst and subsequent dissipationless, violent collapse close to a giant galaxy. In order to study the effect of the tidal field on the evolution we place a satellite system with an initially small internal virial coefficient in the vicinity of a massive galaxy with a dark halo component. The violent relaxation of the stars is again studied with the hierarchical TREECODE and 50 000 test particles.

3.1 Initial conditions

As a standard model we choose a stellar system with a total mass $M = 1$, outer radius $R = 1$, constant density $\rho(r) = \rho_0 = 0.239$ and a free-fall time $\tau_f = 1.11$. The gravitational constant is set to $G = 1$. The test particles are distributed randomly so as to produce a velocity distribution function

$$f(r, v) = \frac{\rho}{(2\pi \sigma^2)^{3/2}} \exp \left(-0.5 \frac{v^2}{\sigma^2}\right).$$

(4)

The velocity dispersion $\sigma$ is determined by the initial virial coefficient $\eta_{\text{vir}}$ (Burkert 1990), which in this model is $\eta_{\text{vir}} = 0.1$.

The system is placed on a circular orbit with radius $D$ around the massive dark halo of a bright galaxy, which generates a force field

$$f(r) = -\frac{Gm(r)}{r^3}r$$

(5)

and

$$m(r) = \begin{cases} 
(M_d/R_d)r & \text{if } r \leq R_d, \\
M_d & \text{otherwise.}
\end{cases}$$

(6)
$M_d$ is the total mass of the dark halo inside its outer radius $R_d$ and $r$ is the radius vector with respect to the centre of the dark halo.

Here we adopt $D = 11$, $M_d = 100$ and $R_d = 10$. The tidal radius of the satellite (Keenan & Innanen 1975) is then

$$R_t = \left[ \frac{M}{2m(D)} \right]^{1/3} D = 1.64.$$  \hspace{1cm} (7)

In order to start on a circular orbit, a streaming velocity $v = \vec{\Omega} \times \vec{r}$ is added to the random velocity of the stars with

$$|\vec{\Omega}| = \Omega = \sqrt{\frac{GM(D)}{D^3}} = 0.274.$$  \hspace{1cm} (8)

The correction (8) also generates an internal spin of the satellite with a small angular velocity $\vec{\Omega}$. This one-to-one spin-orbit coupling is a probable initial condition if the stellar system formed from a gas cloud that was already moving on a circular orbit around the giant galaxy.

If the physical parameters of the dark halo are chosen to be $M_d = 10^{12} M_\odot$ and $R_d = 100$ kpc, the physical units of the protocompact elliptical will be $M = 10^{10} M_\odot$, $R = 10$ kpc, orbital period $T_{\text{orb}} = 3.4 \times 10^9$ yr and internal free-fall time $t_f = 1.7 \times 10^8$ yr.

### 3.2 Evolution of the standard cE model

Fig. 5 shows the orbits of a small sample of test particles projected on to the orbital plane (the $x$-$y$ plane) as well as the evolutionary state of the standard model at time intervals of 4 initial free-fall times. Starting from an extended, spheroidal initial state, the system collapses while moving on a circular orbit around the massive galaxy. After the violent collapse phase, the subsequent expansion lifts 30 per cent of the stars on to orbits with high energies. These stars achieve velocities in excess of the escape velocity for the cE and are thrown out of the system. The bound stars mix in phase space and a macroscopic equilibrium state is reached after a few $t_f$.

After the violent relaxation phase a centrally condensed, ellipsoidal equilibrium state appears with the long axis rotat-
ing fast in the orbital plane. The system is triaxial, with the long axis being parallel to the orbital plane. This is evident from Fig. 6, which shows a contour plot of the projected surface density perpendicular to the orbital plane. The system has a large ellipticity inside the effective radius \( r_e = 0.1 \) (Fig. 7) and becomes more spheroidal in the outer region. There exists a well-defined relationship between ellipticity and radius with \( e = 0.4 \) in the core and \( e \) decreasing systematically with increasing radius, leading to a mean ellipticity of only \( \langle e \rangle = 0.2 \), in very good agreement with the observations of compact ellipticals. As in the isolated collapse model, the surface density profile \( \Sigma(r) \) can be described by a de Vaucouleurs profile (equation 3), but now with a cut-off at large radii due to the external tidal field. In the outer regions the system is slightly anisotropic. The rotational velocity of \( v = 0.4 \) corresponds to a rotation in physical units (see Section 3.1) of order 30 km s\(^{-1}\). Adopting a central velocity dispersion of \( \sigma = 1.6 \), a mean ellipticity of \( e = 0.2 \) and a rotation of \( v = 0.4 \), we find an anisotropy parameter \( (v/\sigma^*) = 0.5 \).

In summary, the cE-model can well reproduce the observed structure of compact ellipticals. The ellipticity, the surface density profile, the rotational velocity and the anisotropy parameter are in very good agreement with the observations.

The observation that cEs generally have surface densities that are an order of magnitude higher than those of typical gEs is explained in this scenario by the fact that satellite galaxies can only survive as separate entities if they form from density fluctuations larger than the underlying 1\( \sigma \) to 3\( \sigma \) density fluctuation that formed the bright galaxy. Let us assume, for example, that the giant galaxy formed from a density perturbation of baryonic mass \( M_{\text{g}} \), radius \( R_\text{g} \), and dark-halo mass \( M_\text{d} \) inside \( R_\text{d} \). In order for a cE to survive near the giant galaxy at a distance \( R_\text{c} \), its internal radius \( R_\text{c,E} \) must have been smaller than its tidal radius \( R_\text{t} \) (equation 7). This implies a mean initial density of the cE of

\[
\rho_{\text{c,E}} > 3 \rho_\text{b} \frac{M_\text{d}}{M_\text{b}}
\]

with \( \rho_\text{b} \) representing the mean density of the proto-giant galaxy. As \( M_\text{d}/M_\text{b} = 10 \), the compacts must have formed from fluctuations with initial densities an order of magnitude larger than those of giant galaxies. If cEs and gEs had similar collapse factors, one must expect the final surface densities of the compacts also to be an order of magnitude higher than in typical giant ellipticals, in agreement with the observations.

3.3 The dependence of the equilibrium state on free parameters

In order to explore the parameter space, several test calculations with different initial virial coefficients \( \eta_{\text{vir}} \), dark

![Figure 6. Contour plot of the surface density distribution of the cE-model in the equilibrium state. The system is projected on to a plane which is perpendicular to the orbital plane and parallel to the long axis of the ellipsoid. The density contours are spaced logarithmically at intervals of \( \Delta \log \rho = 0.15 \).](https://academic.oup.com/mnras/article-abstract/266/4/877/982695)
matter halo masses $M_0$, distances $D$ and initial density gradients $\rho \sim r^{-\nu}$ of the collapsing stellar systems were performed. All models with initial radii $R \leq R_0$ and initial spins as described in Section 3.1 (equation 8) produce an equilibrium state that is very similar to that of the standard model.

Even if we start with no internal spin the satellite begins to rotate as a result of its tidal interaction with the external gravitational field. The spin axis in all calculations is parallel to the short axis and is perpendicular to the orbital plane. In the outer regions, the system ultimately achieves synchronous rotation with an angular velocity similar to the orbital angular velocity.

As an example, Fig. 8 shows the equilibrium state of a model that was started with no initial internal rotation and the following parameters: $M = 1$, $R = 0.8$, $D = 5$, $\nu = 0.04$, $M_0 = 100$, $R_0 = 10$, $n = 0.5$. The final prolate structure of this system is very similar to the observed structure of the compact elliptical galaxy M32 (Bender & Nieto 1990; Peletier 1993; Tonry 1984, 1987). Like M32 it shows a rapidly rotating, flattened core and a high central surface density which leads to a central peak in the velocity dispersion. This core is a result of the degeneracy of the stellar system due to its small initial virial coefficient, as discussed in Burkert (1990). The outer regions rotate with an angular velocity $\omega = 0.5$, which is similar to the orbital angular velocity $\Omega = 0.6$. The system shows again the characteristic properties of typical cEs: a high surface density, an outwardly decreasing ellipticity profile and an anisotropy parameter in the outer regions of $(\nu/\sigma)^* \approx 0.6$.

3.4 The importance of an external tidal field
The tidal field of the parent galaxy has an important effect on the final equilibrium structure of the satellite galaxy. In order to demonstrate this, a test calculation with the same initial
conditions as in the standard model (see Section 3.1), but now without an external tidal field, was performed. In this calculation the equilibrium state is similar to the observed structure of gEs and does not show the peculiar properties of cEs. Again, a prolate object is formed. Now, however, the mean ellipticity is large \( (\epsilon = 0.3) \) and approximately independent of radius (Fig. 7). The anisotropy parameter \( (v/a)^{1/2} = 0.3 \) and the surface density profile follows the \( r^{1/4} \) law in the outer region without truncation.

We also have to confront the observation that cEs have no metallicity gradients, whereas such a gradient exists in gEs. Figs 9(a) and (b) compare the final versus the initial binding energies of the stars for the standard cE-model and the isolated test case, respectively. In the isolated case the stars that are loosely bound initially are also loosely bound at the end. Thus any initial metallicity gradient would not have been smeared out completely during the violent collapse phase. In contrast, violent relaxation is much more complete.
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4 CONCLUSIONS

We have investigated a scenario in which compact elliptical galaxies experienced an initial starburst and a subsequent violent collapse phase in the tidal field of a massive galaxy. This model explains why cEs have a global equilibrium structure that is similar to that of giant ellipticals; both stellar systems formed from cold initial conditions. It can also account for the peculiar properties of cEs which distinguish them from low-mass gEs as being due to the external tidal field, which affects the evolution of these systems. The compacts become more spherical in the outer regions, their surface density profiles are truncated, and any metallicity gradients are smeared out effectively during the violent collapse phase. The high surface density of cEs results from the fact that these objects could only survive as separate systems if they formed from clumps with initial densities that were approximately an order of magnitude higher than the underlying 1σ to 3σ density fluctuation that formed the massive galaxy. The observed central density cusp in some compact ellipticals might represent a degenerate core which is expected to form if the system collapsed from very cold initial conditions with small initial density gradients.

If a cE obtained its internal spin through interaction with the tidal field, we expect its rotation axis to be parallel to its minor axis and to be oriented perpendicularly to the orbital plane. Compacts should also rotate in the same sense as they rotate around the massive galaxy. These results might provide important constraints on deriving the true shapes and orbital parameters of observed cEs. Test calculations show that, even if some satellites did not gain their internal rotation from the tidal interaction with the massive galaxy, they would still show the peculiar structure that is observed in cEs. Their orbital parameters would not, however, correlate with the internal spin parameters.

If giant ellipticals formed from clumpy initial conditions, one must expect that a few clumps could survive the merging process and form satellites which revolve around the bright galaxy. If the cEs formed in this way, we have to conclude that they or their progenitors were much more frequent at the epoch of galaxy formation than they are today. Most of them merged with the parent galaxy during the initial collapse and relaxation phase of the bright galaxy, and only the least tightly bound objects with large orbital angular momentum survived as separate satellites. These systems might therefore provide important information on the initial building blocks of giant galaxies and on the hot interstellar environment in which these objects evolved.

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REFERENCES

Barnes J., Hut P., 1986, Nat, 324, 446