THE ORIGIN OF THE BRIGHTEST CLUSTER GALAXIES

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ABSTRACT

Most clusters and groups of galaxies contain a giant elliptical galaxy in their centers that far outshines and outweighs normal ellipticals. The origin of these brightest cluster galaxies is intimately related to the collapse and formation of the cluster. Using an N-body simulation of a cluster of galaxies in a hierarchical cosmological model, we show that galaxy merging naturally produces a massive central galaxy with surface brightness and velocity dispersion profiles similar to those of observed BCGs. To enhance the resolution of the simulation, 100 dark halos at $z = 2$ are replaced with self-consistent disk + bulge + halo galaxy models following a Tully-Fisher relation using 100,000 particles for the 20 largest galaxies and 10,000 particles for the remaining ones. This technique allows us to analyze the stellar and dark-matter components independently. The central galaxy forms through the merger of several massive galaxies along a filament early in the cluster’s history. Galactic cannibalism of smaller galaxies through dynamical friction over a Hubble time only accounts for a small fraction of the accreted mass. The galaxy is a flattened, triaxial object whose long axis aligns with the primordial filament and the long axis of the cluster galaxy distribution, agreeing with observed trends for galaxy cluster alignment.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: interactions — galaxies: structure — methods: numerical

1. INTRODUCTION

The brightest cluster galaxies (BCGs) are the most luminous and massive galaxies in the universe. A typical BCG is located near the center of its parent cluster and is well aligned with the cluster galaxy distribution, suggesting that it lies at the bottom of the cluster’s gravitational potential well. The general impression that stars have settled to the bottom of a pit suggests that the origin of BCGs is closely related to the collapse and formation of the cluster. BCGs are elliptical galaxies that are much brighter and much more massive than the average, with luminosities $\sim 10L_\odot (L_\odot = 1.0 \times 10^{10} h^2 L_\odot$; e.g., Sandage & Hardy 1973; Schombert 1986; Brown 1997), central velocity dispersions in the range $\sigma \sim 300$–$400$ km s$^{-1}$ (e.g., Dressler 1979; Carter et al. 1985; Fisher, Illingworth, & Franx 1995), and very little rotational support. Like other ellipticals, their light profile is well described by a de Vaucouleurs surface brightness law, $\mu(r) \propto r^{1/4}$, over a large range in radii (de Vaucouleurs 1948). The BCGs are variously classified as giant ellipticals (gE), as D galaxies that have somewhat shallower light profiles than Es, and with the final classification of cD for D galaxies with an extended envelope of excess light over and above a de Vaucouleurs law fitted to the inner regions (Kormendy 1989). Also, cD galaxies are only found in the centers of clusters and groups, so their extended envelope is probably associated with the formation of the cluster.

The following hypotheses have been proposed to explain the origin of BCGs: (i) star formation from cooling flows expected in the high-density, rapidly cooling centers of cluster X-ray halos (Fabian 1994); (ii) galactic cannibalism or the accretion of the existing galaxy population through dynamical friction and tidal stripping (Ostriker & Tremaine 1975; Richstone 1976; Ostriker & Hausman 1977); and (iii) galaxy merging in the early history of the formation of the cluster as expected in hierarchical cosmological models (Merritt 1985; Tremaine 1990). The cooling-flow theory implies the creation of a large number of new stars, but generally there is weak evidence for this population (McNamara & O’Connell 1989). The galactic cannibalism picture fails when worked out in detail, since the dynamical friction timescales are generally too long, and so the expected amount of accreted luminosity falls short by an order of magnitude for making up a BCG’s luminosity (Merritt 1985; Lauer 1985; Tremaine 1990). The failure of this model implies that BCGs must have an earlier origin, and that galaxy merging within the cluster during collapse in a cosmological hierarchy is a possible alternative. The strong tendency for BCGs to align with their cluster population (Sastry 1968; Carter & Metcalfe 1980; Binggeli 1982; West 1994) also implies an origin coinciding with cluster collapse.

Most of the work on the formation of giant ellipticals has been based on studies of merging groups of several disk galaxies (Barnes 1989; Weil & Hernquist 1996) or small virialized clusters of spherical galaxies (Funato, Makino, & Ebisuzaki 1993; Bode et al. 1994; Garijo, Athanassoula, & Garcia-Gomez 1997). These simulations reveal the high efficiency of dynamical friction in driving galaxy merging and the general tendency to produce remnants resembling elliptical galaxies. However, they are phenomenological studies that are still considerably detached from the context of hierarchical collapse in which elliptical galaxies and BCGs probably form. In this paper we explore galaxy merging in a detailed cosmological simulation of cluster collapse including a realistic distribution of disk galaxies embedded in dark halos and show that it produces a consistent and quantitative picture for the origin of BCGs.

2. MERGING AND THE FORMATION OF ELLIPTICAL GALAXIES

The formation histories of BCGs and ordinary elliptical galaxies are closely linked. Elliptical galaxies most likely

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form through the dissipationless merger of smaller spiral or elliptical galaxies (Toomre & Toomre 1972; Toomre 1977), while the spirals themselves form dissipatively as gas cools radiatively and sinks to the center of a dark halo (White & Rees 1978). When galaxies collide, dynamical friction combined with strong time-dependent mutual tidal forces redistribute the ordered orbital kinetic energy into random energy, allowing the galaxies to merge into an amorphous, triaxial system resembling an elliptical galaxy (Barnes 1988; Hernquist 1992, 1993; Barnes & Hernquist 1992a, 1992b).

In the various N-body studies of mergers of galaxy pairs, analysis of the merger remnants shows that they have light profiles and kinematics similar to those of observed ellipticals, although the match is not perfect. The simulation of the merger of groups of galaxies (Barnes 1989; Weil & Hernquist 1996), which is more closely related to the formation of BCGs, gives results generally similar to the merger of galaxy pairs. Simulated merger remnants generally have de Vaucouleurs profiles, although the cores can be less dense than real ellipticals when the progenitors are pure stellar disks without a bulge (Hernquist 1992). This problem probably arises from Liouville's theorem and the conservation of fine-grained phase-space density (Carlberg 1986). The central phase-space density of the remnant can be no greater than that of the progenitors, so pure disks with low central phase-space density cannot make ellipticals with a high central value. Disk galaxies with bulges can lead to denser cores (Hernquist 1993), but this only skirts the issue by including an elliptical component with a dense core in the progenitors. The solution to this problem is probably gaseous dissipation through radiative cooling, which can lead to higher central densities in merging galaxies with gas (Kormendy 1989b), although simulations with gas and stars formation seem to produce cores that are too dense (Mihos & Hernquist 1994). Despite the uncertainties in core properties, galaxy merging produces remnants with global structure and kinematics that are similar to real ellipticals and remains the most likely way that they form.

Galaxy clusters hold the key to understanding the formation of elliptical galaxies. While E galaxies only make up about 10% of all galaxies, they are much more abundant in regions of high galaxy density, especially in the centers of clusters of galaxies, where they make up most of the galaxy population (Dressler 1980, 1984). The high frequency of E galaxies in rich clusters has been viewed as a paradox and the central phase-space density of the remnant can be no greater than that of the progenitors, so pure disks with low central phase-space density cannot make ellipticals with a high central value. Disk galaxies with bulges can lead to denser cores (Hernquist 1993), but this only skirts the issue by including an elliptical component with a dense core in the progenitors. The solution to this problem is probably gaseous dissipation through radiative cooling, which can lead to higher central densities in merging galaxies with gas (Kormendy 1989b), although simulations with gas and stars formation seem to produce cores that are too dense (Mihos & Hernquist 1994). Despite the uncertainties in core properties, galaxy merging produces remnants with global structure and kinematics that are similar to real ellipticals and remains the most likely way that they form.

In this paper, we introduce a new approach to cluster simulation with a large enough dynamic range to resolve galaxies within a cluster and examine galaxy merging in a cosmological context. We simply assume that disk galaxies form instantly in the center of galactic-mass dark halos early on in the evolution of the dark matter cluster in a cosmological N-body simulation. At an early time, we replace galactic dark halos with equilibrium N-body galaxy models scaled to the appropriate mass and dimensions and resolved with 10–100 times as many particles. We assume that the first galaxies are disks embedded in dark halos with flat rotation curves similar to the Milky Way and other nearby galaxies (Kuijken & Dubinski 1995). To guarantee that the chosen galaxies end up in the final cluster, we use the following procedure:

1. A dark matter simulation of the cluster is run until the current epoch, $z = 0$.
2. The particles in the final virialized cluster are labeled and identified at the earlier epoch, $z = 2$.
3. From this subset of particles, all galactic dark halos are identified using the friends of friends linking method (Davis et al. 1985) and replaced by randomly oriented disk galaxy models of the same mass scale, placed on the same trajectories as the halos.
4. The simulation of the cluster is then rerun with the higher resolution galaxy population until the present epoch.

A similar method has been used in the study of galaxy harassment in clusters (Moore et al. 1996a). The idea is to...
enhance the resolution of the simulation selectively by using galaxy models as in phenomenological studies while retaining the cosmological character of the mass distribution and large-scale kinematics.

The experimental cluster is chosen from a cold dark matter (CDM) simulation of periodic cubic volume with \( L = 32 \) Mpc on a side, assuming \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and normalized to \( \sigma_8 = 0.7 \). With this normalization the CDM model is a good description of the clustering of galaxies for the scale that we are examining, although it is known to lack sufficient power on larger scales.

The initial conditions were generated by applying the Zel’dovich approximation to a random realization of a CDM density field generated with a 256\(^3\) Fourier transform. The simulation is first run at 64\(^3\) resolution to identify the site of cluster formation. A spherical volume of comoving radius \( R = 11 \) Mpc, associated with the virialized cluster, is identified in the initial conditions and then resampled at the full 256\(^3\) resolution. The tidal boundary of the collapsing cluster is adequately handled using two concentric shells in the radial ranges of \( 11 < R < 16 \) Mpc and \( 16 < R/L < 27 \) Mpc, sampled at 128\(^3\) and 64\(^3\) resolution, respectively. The simulation therefore contains a total of \( 4.3 \times 10^6 \) particles, of which about \( 10^6 \) end up in the virialized cluster halo. All of the simulations are run with a parallel N-body treecode adapted for both periodic and vacuum boundaries (Dubinski 1996).

The cluster has a virial radius of 1.2 Mpc, a mass of \( 1.0 \times 10^{14} \) M\(_\odot\) within this radius, and a spherically averaged, central line-of-sight velocity dispersion of 550 km s\(^{-1}\). This cluster would be classified as a poor cluster or a large group by observers. At \( z = 2 \), the 100 most massive dark halos associated with the cluster with masses in the range of \( 10^{10} \) to \( 5 \times 10^{12} \) M\(_\odot\) are identified and replaced with N-body galaxy models. The model used for each galaxy (with different scaling) is composed of an exponential disk, a truncated King model bulge, and King model dark halo with the potential and orbital distribution derived from a self-consistent distribution function (model B of Kuijken & Dubinski 1995). By design, the model has a flat rotation curve out to 10 exponential scale lengths and declines beyond that distance.

The 20 most massive halos are replaced with "high"-resolution galaxy models including 50,000 disk particles, 10,000 bulge particles, and 40,000 dark halo particles, with a softening length of 0.32 kpc for the stars and 0.64 kpc for the dark halo particles. The remaining 80 halos are sampled at "low" resolution with 1/10 as many particles as above in the same ratios and a softening length twice as large. The remaining cluster dark matter is retained with a softening length of 3.2 kpc.

The models are scaled according to the value of the circular velocity and mass of the halos in the dark matter simulation at about \( 1/2 \) the virial radius. The scale lengths \( h \) of the disks are determined by the measured mass and velocity (\( h \propto GM/v^2 \)) and fall in the range of observed disks. The 100 galaxies roughly follow a Tully-Fisher relation (Tully & Fisher 1977) in their circular velocity versus mass profiles with \( v_c \sim M^{0.28} \) (Fig. 1). The disk scale lengths also vary according to observed laws with \( h \sim M^{0.45} \) (again cf. \( h \sim L^{0.5} \); Freeman 1970; Fig. 2). The mass function also has a Schechter form, with \( z \approx -1.5 \), and \( M_\ast = 5 \times 10^{11} \) M\(_\odot\) (stellar mass), similar to the observed local galaxy luminosity functions, but perhaps somewhat steeper (Loveday et al. 1992). The simulation is run for 10.5 Gyr with a single leapfrog time step \( \Delta t = 2.3 \) Myr for a total of 4700 steps. This time step allows the resolution of structures down to about 0.5 kpc.

One problematic feature of the distribution is that the three most massive galaxies have unusually large circular velocities for normal disk galaxies, with \( v_c > 400 \) km s\(^{-1}\). These galaxies are probably ellipticals rather than disks at the time they are selected. Their exact morphology probably makes little difference to the final outcome, since they quickly merge at the outset. The simulation should eventually be rerun with elliptical galaxies to check for possible discrepancies. However, the remaining galaxies follow a realistic mass distribution having properties similar to the observed high-surface brightness disks.

4. RESULTS

4.1. The Formation of a Giant Elliptical Galaxy

Within 3 Gyr of the start of the simulation (by \( z = 0.8 \)), the four most massive galaxies merge to form a central

\[ V = 294 \left( \frac{M}{10^{11} \, M_\odot} \right)^{0.28} \text{ km/s} \]

\[ \log \frac{\text{M}_{\text{stars}}}{[10^{11} \, M_\odot]} \]

\[ \log R_{\ast} [\text{kpc}] \]

\[ 1 = 1.2 \left( \frac{\text{M}_{\text{stars}}}{10^{11} \, M_\odot} \right)^{0.45} \text{ kpc} \]

Fig. 1.—Relation between mass and circular velocity for the initial galaxy population. The relation is similar to the Tully-Fisher relation.

Fig. 2.—Relation between mass and exponential scale length for the initial galaxy population. The relation follows the prediction of Freeman’s (1970) law for exponential disks.
object resembling an elliptical galaxy. As we describe below, its measured surface brightness and velocity dispersion profile are very similar to real giant ellipticals. Three of the galaxies fall down a line that can be identified with the primordial filament apparent in the early formation of the dark matter cluster. The fourth galaxy comes from a different direction, but the infall of material generally follows the line of the filament (Fig. 3). Over the next 5 Gyr (ending around $z = 0.4$), nine more galaxies are accreted (some as merged products themselves); of the total of 13 merging to form the elliptical, seven are galaxies with circular velocities greater than 200 km $s^{-1}$ while the remaining six are smaller galaxies with circular velocities $\sim 100$ km $s^{-1}$. The epoch around $z = 0.4$ is marked by a period of intense activity, in which many of the galaxies are merging and experiencing strong tidal perturbations resulting in tidal tails from close passes with the cluster center. This epoch is an illustration of the galaxy harassment process (Moore et al. 1996b). From $z = 0.4$ to the present, there are no more large mergers with the BCG. At the end of the simulation only 59 galaxies can be identified orbiting in the cluster. Of the 41 “missing” galaxies, 13 have merged to form the central massive elliptical galaxy. The remaining 28 have been incorporated into other galaxies through mergers. The group simulated here is too small to allow detection of the density-morphology effect (Dressler 1984). However, the few ellipticals created are close to the cluster center ($R < 500$ kpc) and on eccentric orbits that are measureably decaying by dynamical friction.

4.2. Analysis of the Merger Remnant

Is the merger remnant in the center of the cluster a giant elliptical or cD galaxy? We measured the shape of the central galaxy, the surface density, and velocity dispersion profiles along different lines of sight to answer this question. We also measured the three-dimensional structure and kinematics of the stars and dark matter for comparison to interpretations of the projected data.

4.2.1. Shape

The central elliptical is a triaxial object with principal axis ratios of $b/a = 0.66$, and $c/a = 0.47$, where $a$, $b$, and $c$ are the major, middle, and minor axes, respectively (Fig. 5). The surface density contours (isophotes) are nearly perfect ellipses in the inner regions with very little signal of “boxiness” or “diskiness” seen in smaller ellipticals. The regularity of the isophotes is consistent with a relaxed galaxy that has suffered no recent mergers, which is indeed the case.

4.2.2. Density

The surface density profiles from three different lines of sight along each of the principal axes are measured by fitting elliptical contours to the observed density map. Figure 6 shows the log surface density $\mu$ plotted versus $r^{1/4}$. Another axis is included, showing the equivalent surface brightness assuming $M_\odot/L_\odot = 10$ for the stars. The nearly linear dependence on $r^{1/4}$ from 3–100 kpc reveals that the

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2 See www.cita.utoronto.ca/~dubinski/bigcluster.html for mpeg animations.
The galaxy follows a de Vaucouleurs light profile. The profile is similar to measured profiles of giant ellipticals (gE) rather than cD galaxies, which show an excess of light at large radii. De Vaucouleurs profiles are fitted for the effective radius $r_e$ and the total mass. The effective radii [calculated as $(ab)^{1/2}$] is between 18–22 kpc, depending on the projection. The fitted total mass is $2.6 \times 10^{12} M_\odot$, corresponding to a total luminosity of $6L_\odot$ (assuming $M_\odot/L_\odot = 10$, and $L_\odot = 1.0 \times 10^{10}h^{-2} L_\odot$). The regularity of the isophotes and the measured scales and luminosities of the merger remnant are consistent with observations of giant elliptical galaxies.

The three-dimensional density profile of the merger remnant reveals the relative distribution of stars and dark matter in an elliptical galaxy (Fig. 7). The Hernquist density profile (Hernquist 1990),

$$\rho(r) = \frac{Ma}{2\pi r(a + r)^3},$$

provides convenient model fits to both the stellar and dark matter profiles. The fitted masses and scale radii are $M_*=3.3 \times 10^{12} M_\odot$ and $a_*=19$ kpc for the stars, and $M_d=1.6 \times 10^{14} M_\odot$ and $a_d=250$ kpc for the dark matter, as shown in Figure 7. Stellar mass dominates within $r < 10$ kpc ($0.5r_e$), although the stellar density is only about 3 times the dark matter density at the center. The stellar and dark matter density are equal in the range of 10–20 kpc [(0.5–1.0)$r_e$] while beyond 40 kpc ($2r_e$) the dark matter density is at least 10 times the stellar density. The merging process tends to enhance the ratio of dark mass to luminous mass within the central regions. In the initial population of disk + bulge galaxies, the dark to luminous mass ratio at the half-light radius is 0.4, while the giant elliptical has a ratio of about 1.0 at a nominal effective radius of 20 kpc, a factor of 2.5 enhancement. The most likely reason for this enhancement is the tendency for disk stars to be heated more effectively than the dark matter particles. The same resonant interactions that create tidal tails during mergers add energy more effectively to disk stars than to dark matter particles with the same initial binding energy. The dark matter density may then be enhanced slightly with respect to the stars in the merger remnant, in comparison with the initial disks.

The overall trend for increasing dark-to-luminous mass ratio is shown in Figure 8. Stars dominate the central density, and the dark-to-luminous mass ratio is only about 0.3. At $r = 0.5r_e$, the ratio starts to grow linearly, reaching 1.0 at $r = r_e$, continuing to rise to 3.3 at $r = 3r_e$. These mass ratios and general behavior are in accord with recent models of the dark matter in ellipticals derived from combining surface brightness and kinematical information (e.g., Saglia, Bertin, & Stiavelli 1992; Saglia et al. 1993; Rix et al. 1997).

### 4.2.3. Kinematics

The velocity dispersion profiles of the galaxies are also measured using a method faithful to current observational techniques. A slit of 3.2 kpc in width is laid along the apparent major axis in three independent directions. This corresponds observationally to a 1.5 slit laid across a galaxy at a distance of 100 Mpc. Particles are binned in squares 3.2 kpc on a side, and the mean line-of-sight velocity and velocity
dispersion are measured in each bin. Like real ellipticals, the galaxy rotates slowly about its minor axis with $v_{rot} \sim 50 \text{ km s}^{-1}$ (Franx, Illingworth, & Heckman 1989). Figure 9 shows the velocity dispersion profile along the apparent major axis for the three lines of sight down each of the principal axes. The central value peaks between 300 and 450 km s$^{-1}$.
Fig. 8.—Ratio of dark to luminous mass in the BCG over 5$r_e$. Dark mass still represents about 30% of the mass at the center in this model. The ratio grows almost linearly with radius.

Fig. 9.—Velocity dispersion profile measured along a slit laid on the major axis for the three principal-axis projections of the galaxy. The velocity dispersion declines slowly with distance from the center. There is no sign of an upturn at large distances.

Fig. 10.—Spherically averaged radial velocity dispersion profile compared to anisotropic spherical model predictions from the fitted density profile. Each line is labeled with the anisotropy parameter used in the model. The anisotropy of the model rises from about 0.2 in the center to 0.5 at 100 kpc ($5r_e$). The dashed line represents a best-fit model with $\beta(r)$ growing monotonically from 0.0 to 0.5 from the center to 100 kpc.

4.2.4. Comparison with Other Merger Remnants

The properties of the merger remnant in this experiment are rather different from those found in other simulations of merging groups. The Weil & Hernquist (1996) simulations depending on the line of sight. The large value of 450 km s$^{-1}$ occurs when looking exactly down the long axis of the galaxy, showing the anisotropy of the velocity ellipsoid in this flattened triaxial stellar system. These central values again are in accord with real giant ellipticals, although the value of 450 km s$^{-1}$ might be considered too large (Fisher et al. 1995). The velocity dispersion only declines gradually out to 60 kpc (about 3 effective radii), again in similar fashion to many elliptical galaxies. There is no sign of an upturn in the velocity dispersion at large radii, as seen in the exceptional case of the cD galaxy in A2029 (Dressler 1979).

In three dimensions the measured velocity dispersion is nearly isotropic to the center, but becomes radial anisotropic with a radial anisotropy parameter (Binney & Tremaine 1987) $\beta = 0.5$ at 3$r_e$. The density profiles of Figure 7 for the dark matter and stars were fitted with Hernquist (1990) models and used to solve the spherical Jeans equations for the velocity dispersion profile of the stars, using constant values for the anisotropy parameter $\beta$. Figure 10 shows that the velocity profile is consistent with the mass model for values of $\beta < 0.3$ within $r < 20$ kpc ($r < r_e$). The best-fit spherical Jeans model in Figure 10 is one in which the anisotropy grows monotonically from the center with $\beta = 0.0$ to $\beta = 0.5$ at 3$r_e$. 

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The properties of the merger remnant in this experiment are rather different from those found in other simulations of merging groups. The Weil & Hernquist (1996) simulations
produced remnants that are nearly oblate with a small flattening. They also have a modest amount of rotational support about their minor axes. These results contrast with the prolate, nearly nonrotating object in the cluster simulation. The differences can be attributed to initial conditions. The group simulations start with galaxies on random trajectories selected from an isotropic distribution, while the cosmological mergers are strongly anisotropic because of the initial filamentary structure. The initial isotropy leads to a rounder oblate remnant, while collapse down a filament appears to lead to a prolate, elongated object.

4.3. Fossil Alignments

BCGs are often well aligned with the distribution of the cluster galaxies (Sastry 1968; Carter & Metcalfe 1980; Porter, Schneider, & Hoessel 1991), as well as more extended large-scale clustering features (Binggeli 1982), and it has been suggested that this results from filamentary collapse expected in hierarchical structure formed from Gaussian random noise (e.g., Rhee & Roos 1990; West 1994; Bond, Kolman, & Pogosyan 1996). The alignment of the central galaxy is seen as the consequence of an anisotropic collapse that is remembered from the initial random density field. Filamentary collapse leads to nearly head-on collisions of galaxies, which create prolate merger remnants aligned with the initial collision trajectory (Villumsen 1982).

The simulated BCG examined here shows the alignment effect as seen in previous work. The shape and orientation of the BCG is indeed nearly congruent with the galaxy distribution in the cluster. The angle between the long axis of the central galaxy and the cluster galaxy population as measured by its moments is only 15°. Furthermore, the orientation of the BCG is closely aligned with the primordial filament delineated by the three large galaxies that make up most of the mass of the BCG. We should emphasize that this alignment effect only works for the central giant elliptical, for which the kinematics and morphology are dependent on the large-scale convergence of the flow of matter into the cluster’s forming potential well. Other galaxies falling into the cluster that avoid merging with the BCG will have random alignments, dependent on their merging history and tidal interactions with the cluster core and other galaxies. This simulation strongly supports the hypothesis that the shape and orientation of the central galaxy are fossils of the filamentary initial conditions of the cluster collapse, although further simulations should be done to confirm this result.

5. CONCLUSIONS

In summary, when a population of disk galaxies with an observed distribution of masses falls in a collapsing cluster in a cosmological setting, a central, giant elliptical galaxy will form in the cluster center. The galaxy forms through the merger of many smaller galaxies that converge on the cluster center along the filamentary structure originating in the initial density field. The one simulation presented here agrees quantitatively in its structure and kinematics with many BCGs, but there are still many open questions, in particular: What is the origin of the envelope in the cD galaxies in rich clusters? Perhaps the driving mechanism is tidal stripping (Richstone 1976) and harassment (Moore et al. 1996a), which only occurs in more massive clusters than examined here. Why does BCG central velocity dispersion correlate poorly with the cluster velocity dispersion? Are multiple nuclei in BCGs ongoing mergers, or are they the result of chance projections? How do the properties and the timing of formation of BCGs depend upon different cosmological models? If there is a strong dependence, the observation of their evolution may constrain cosmological models. A modest sample of simulations covering different mass scales and cosmological models can answer these questions quantitatively.

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