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MERGING OF GALAXIES WITH CENTRAL BLACK HOLES. I. HIERARCHICAL MERGINGS OF EQUAL-MASS GALAXIES

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ABSTRACT

We have investigated the merging of galaxies with central, massive black holes. We performed simulations of hierarchical mergings, in which the merger remnant of one simulation is used as the progenitor for the next simulation. Our main results are the following: First, the central part of the merger has a very shallow density cusp ($\rho \propto r^{-\alpha}$, with $\alpha \lesssim 1$). This result is in good agreement with recent *Hubble Space Telescope* results that suggest most large elliptical galaxies have shallow density cusps. This shallow cusp yields an almost constant surface density. The radius of this shallow cusp (core) roughly doubles at each merger event. This expansion of the core is supported by the energy production from the black hole binary. As a result, the ratio between the core radius and the half-mass radius remains roughly constant. This result is, again, in good agreement with the observed positive correlation between the core radius and effective radius of elliptical galaxies. In previous simulations of galactic mergers, the role of the central black holes was neglected. In these simulations, the half-mass radius increased but the core radius did not, in clear disagreement with observations. Our results imply that the existence of central black holes naturally explains the structure and size of the cores of bright elliptical galaxies, though other explanations (e.g., anisotropy) are not ruled out.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

The "merger hypothesis" (Toomre 1977) has been quite successful in explaining many global properties of elliptical galaxies. First, the density profiles of the simulated merger remnants are well described by the $r^{1/4}$ profile (Toomre 1977; Barnes 1988). This fact can be explained by a simple argument that the distribution function in energy space, $N(E)$, is smooth at $E = 0$ (Jaffe 1983; Makino, Akiyama, & Sugimoto 1990). Second, the velocity dispersion of the merger remnant is slightly larger than that of the progenitors, consistent with the Faber-Jackson relation (Farouki, Shapiro, & Duncan 1983; Okumura, Makino, & Ebisuzaki 1991). Third, the distribution of the ratio between the maximum rotational velocity $V_{\max}$ and the central velocity dispersion σ of elliptical galaxies is explained naturally by the merger hypothesis (Okumura et al. 1991). The observed distribution of $V_{\max}/\sigma$ in elliptical galaxies shows a sharp cutoff at $V_{\max}/\sigma \simeq 0.6$. There are very few large ellipticals that rotate more rapidly.

Okumura et al. (1991) performed a series of merger simulations with various initial orbital angular momenta. They found that the merging of two spherical galaxies cannot produce a merger remnant with $V_{\max}/\sigma > 0.6$. If the initial orbital angular momentum is very large, two galaxies first form a binary, and the angular momentum is carried away by escaping particles until the orbital separation becomes a few times the half-mass radius. As a result, the merger remnant cannot rotate very rapidly.

However, the properties of the cores of elliptical galaxies have been thought to be difficult to reproduce by merger simulations. Carlberg (1986) pointed out that the central phase-space density cannot increase through a collisionless process such as merging. He argued that it was impossible to form the core of an elliptical galaxy from the merging of two disk galaxies, since the central phase-space density of a disk is much lower than that of the core of an elliptical galaxy. Recent detailed simulations of the merging of disk galaxies (Barnes & Hernquist 1992; Hernquist 1992; Hernquist, Spergel, & Heyl 1993) have confirmed Carlberg's argument that the merging of two stellar disks cannot form the core of an elliptical galaxy. However, the central phase-space density of the bulge of a spiral galaxy is much greater than that of its disk. Therefore, mergings of bulge-disk galaxies form remnants with sufficiently small cores (Hernquist 1993).

Carlberg (1986) also pointed out that the central phase-space density of bright elliptical galaxies is lower than that of faint ellipticals. Though the central phase-space density can decrease in the collisionless process, merger simulations have shown that it does not (Farouki et al. 1983; Okumura et al. 1991). Thus, mergings of small ellipticals cannot produce bright ellipticals.

The central phase-space density, f_c, is expressed as

$$f_c \propto v_c^{-3} r_c^{-2} , \tag{1}$$

where v_c is the central velocity dispersion and r_c is the core radius. The relation between v_c and the total luminosity L is

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rather weak, as seen from the Faber-Jackson relation (Faber & Jackson 1976). On the other hand, r_c is roughly proportional to L (see, e.g., Lauer 1985). Therefore, the central phase-space density is roughly proportional to L^{-2}.

The core radii of simulated mergers remain nearly the same as or become slightly smaller than the core radii of the progenitors, although the half-mass radius becomes roughly twice as large (Farouki et al. 1983; Okumura et al. 1991). If bright ellipticals were formed by the merging of smaller ellipticals, the core sizes of all elliptical galaxies would be similar.

The central phase-space density can decrease if a sufficient amount of vacuum is mixed into the core. However, the "violent relaxation" in the central region is not violent enough to mix in a sufficient amount of vacuum. Therefore, the core radius does not increase by merging. If the dissipative process and star formation are taken into account, the core of the merger remnant would become even smaller and the central density even greater.

Recent observations by the *Hubble Space Telescope* (*HST*) (Ferrarese et al. 1994; Lauer et al. 1995; Richstone et al. 1996) have made the problem of the core size even more intriguing. They demonstrated that most large elliptical galaxies have "cores" that cannot be represented by an isothermal model. This difference had been suggested based upon ground-based observations (Lauer 1985; Kormendy & Djorgovski 1989), but observations with *HST* have vastly improved the accuracy. Lauer et al. (1995) and Richstone et al. (1996) have argued that the deprojected "cores" are actually very shallow central-density cusps ($\rho \sim r^{-1}$). Such a shallow cusp poses a serious problem for almost any scenario of the formation of elliptical galaxies. If these galaxies do not have central black holes (BHs), we are faced with a very strange structure, with the velocity dispersion decreasing inward. Neither dissipationless/dissipational collapse nor merging has been able to create such a density distribution.

There have been several claims that the halo formed by dissipationless collapse can be well fitted by a Hernquist (1990) or similar model that has asymptotic behavior of $\rho \sim 1/r$ at the center (e.g., Dubinski & Carlberg 1991; Navarro, Frenk, & White 1996). Indeed, these simulations resulted in halos with the power-law index smoothly changing from around -1 to -3 or -4 as the radius increases. However, the central structures of the halos obtained by these simulations are strongly affected by the softening used. The softening was 1.4 kpc in Dubinski & Carlberg (1991) and 1% of the virial radius in Navarro et al. (1996). The profiles obtained by these simulations show a rather rapid change in the power, from nearly zero at the softening radius to nearly -2 at a radius several times the softening. This is quite different from what is suggested by *HST* observations, which give a $1/r$ cusp for at least an order of magnitude in radius (Lauer et al. 1995). Warren et al. (1992) performed large-scale simulations with two different softenings (1 and 5 kpc). Their plots of rotation curves (Figs. 20 and 21) show that the density profiles in the inner 10 kpc are completely different.

The standard scenario for the formation of a central BH is adiabatic growth by accretion. In this case, the central density would show a $\rho \sim r^{-3/2}$ cusp (Young 1980; Quinlan, Hernquist, & Sigurdsson 1995), which is ruled out by the observations.

To summarize, we are faced with two problems: (1) the cores of large elliptical galaxies are too large to be formed by the merging of smaller galaxies, and (2) these "cores" are not real cores, with flat density, but very shallow cusps.

Ebisuzaki, Makino, & Okumura (1991, hereafter EMO) pointed out that heating by the central BHs can make the core larger. If both progenitor galaxies have central, massive BHs, these BHs sink to the center of the merger remnant as a result of the dynamical friction from field particles and form a BH binary. This binary heats the core in the same way as the binaries in the cores of globular clusters heat the core. EMO performed N-body simulations of the merging of spherical galaxies containing central BHs and found that the core actually expands. They also made a qualitative argument that the core mass would become several times larger than the BH mass, which nicely explains the linear proportionality between the core radius and the effective radius of the observed elliptical galaxies.

The results of the numerical simulations by EMO, however, suffer two limitations. First, it is not clear what happens if the merger remnant again merges with a third galaxy. If the BH binary has merged to form a single BH before the third BH comes by, we can apply the same scenario as described above. If the BH binary has not merged, however, the three-body interaction might eject all three BHs from the core (see, e.g., Begelman, Blandford, & Rees 1980), leaving the core without a central BH. Thus, it is necessary to determine the typical lifetime of the BH binary. We have made a preliminary study of this problem (Makino et al. 1993), in which we found that the lifetime of a BH binary is much shorter than the theoretical prediction of Begelman et al. (1980). Another possibility is that the slingshot predicted by Begelman et al. (1980) will not occur since the binary would merge by gravitational radiation during the three-body interaction or in the period that the binary and the third body are far apart (Makino & Ebisuzaki 1995).

Second, the initial galaxy model used in EMO had a rather large core because of the limited computing resources then available. It was argued that the core mass would become comparable the BH mass if the core radius were determined solely by the energy input from the BH binary. However, EMO used a Plummer model for the initial galaxy, and the ratio of the core mass to the BH mass was initially ~ 20. As a result, the core radius showed only marginal increase through a merging. Because of the rather small number of particles they could use, it was difficult for them to use a galaxy model with a realistic core radius, since the central two-body relaxation time would become too short.

In the present paper, we address the following problem: What does the core of the merger look like when the core parameter is determined solely by the energy input from the BH binary? In order to study the structure of the core, we performed simulations of hierarchical mergings. The merger remnant of one simulation is used as the progenitor for the next simulation, in a way similar to Farouki et al. (1983), who simulated hierarchical mergings without taking into account the effect of the central BHs. The progenitor for the first simulation is constructed in the same way as that in EMO. At the end of each simulation, we artificially replace the BH binary by one particle. We used $\sim 16{,}000$ particles for each galaxy, and the mass of a BH was 1/16–1/64 the total mass of a galaxy. The total number of particles in the present simulations is 8 times larger than that used in

EMO. We repeated the merger simulation four or five times, both with and without the central BH. In order to see the dependence on initial conditions, we tried three different initial galaxy models and three different BH masses.

For mergings without central BHs, our result is essentially the same as that of Farouki et al. (1983), who observed that the core size relative to the half-mass radius shrinks after each merger event. In the mergers with central BHs, the central density of the remnant shows a shallow cusp with the profile $\rho \propto r^{-\alpha}$, with $\alpha \lesssim 1$. In the projected density profile, this cusp has nearly constant density, with a slight increase inward. This result nicely explains the recent *HST* observations of large elliptical galaxies of Lauer et al. (1995) and Richstone et al. (1996), which found a number of ellipticals with such shallow cusps. They called this shallow cusp the "core."

The ratio r_c/r_h converges to 0.1 for simulations from three different initial galaxy models with the same BH of 1/32 the total mass of the galaxy. Thus, it is clear that the radius of this "core" is determined by the BH mass and not by the initial density profile. This radius is larger for larger BH masses and smaller for smaller BH masses, as naturally expected. We can therefore conclude that the merging of galaxies with central BHs succeeds at reproducing the observed correlation between core radius and luminosity.

In the next section, we describe the numerical method we used. In § 3, we describe the results. Section 4 is devoted to discussion and summary.

2. NUMERICAL METHOD AND INITIAL CONDITIONS

2.1. *Numerical Method*

We used the NBODY1 calculation code (Aarseth 1985), modified for use with the GRAPE-4 special-purpose computer for gravitational *N*-body simulations (see Taiji et al. 1996). The time-integration scheme was changed to the Hermite scheme (Makino & Aarseth 1992) to take advantage of the GRAPE-4 hardware. We neglected relativistic effects and treated BH particles as massive Newtonian particles. This treatment is good as long as the periastron distance of the BH pair does not become very small. We used a softened potential with softening of 1/128 for the force between field particles, and a pure $1/r$ potential for forces to and from BH particles. The relative accuracy of the force calculated on GRAPE-4 is ~ 7 digits (IEEE single precision), which is more than enough for forces from field particles but might cause problems for the force from BH particles. In the present code, the force from field stars is calculated on GRAPE-4 while that from BH particles is calculated on the host computer in full double precision. For mergings without central BHs, we used a simple leapfrog integrator with a constant time step of size 1/256.

Calculations were performed on one cluster of the GRAPE-4 system, with a theoretical peak of 270 GFLOPS. The actual sustained speed was ~ 50 GFLOPS. One simulation took 10–20 hr, depending on the structure of the galaxy.

2.2. *Initial Conditions*

We performed the merger simulation of two identical, spherical galaxies from a parabolic orbit. We used three different initial galaxy models, namely, King models with nondimensional central potentials W_c of 5, 7, and 9. The initial galaxy was created so that the total mass $M_g = 1$ and the total energy $E_g = -\frac{1}{4}$ in the system of units in which the gravitational constant $G = 1$ (the standard unit; Heggie & Mathieu 1986). The number of particles was 16,384. In this unit, the half-mass radius of the initial galaxy model is ~ 0.75 and the half-mass crossing time is $2\sqrt{2}$. To place the central BH, we tried following two procedures. In the first, we scaled the mass of each particle by a factor $1 - M_{\rm BH}$ and placed a point particle with mass $M_{\rm BH}$ at the center of the cluster. In this case the initial galaxy has a density cusp around the BH. In the second case, we removed $NM_{\rm BH}$ particles closest to the center of the galaxy and put the BH particle at the center. In this case the galaxy does not have the central cusp. We compared the structure of the merger remnant for the case of $W_c = 7$ and $M_{\rm BH} = 1/32$ and found no difference. However, the calculation time is ~ 3 times longer for the first procedure since it has an initial central-density cusp. For other initial conditions, we adopted the second procedure.

We tried three different BH masses (1/16, 1/32, and 1/64) for runs with $W_c = 7$. For other values of W_c, we tried $M_{\rm BH} = 1/32$ only.

Note that both the core radius and the BH mass that we used for our simulations are significantly larger than those of real elliptical galaxies. To reduce the BH mass, one has to increase the total number of particles so that the mass ratio between the BH particle and field particles is large enough. With the calculation scheme we used, it is rather difficult to use more than 10^5 particles.

As described in § 1, the purpose of the present paper is to investigate the structure of the core as determined by the energy generation from the BH binary. If the mass of the binary is too large, it might affect not only the structure of the core but also the structure of the entire galaxy. Thus, the mass of BH particle must be small enough so that the effect on the galaxy as a whole is small. On the other hand, if the effect on the galaxy as a whole is small, it is not necessary to make the BH mass smaller. We tried different BH masses to see their effect on the structure of the remnant.

We set the initial separation of two galaxies large enough so that the inner core had sufficient time to establish dynamical equilibrium during the first approach. The initial periastron distance of the relative orbit was 1, and the initial separation of the galaxies was 10. We simulated the evolution of the system for 60 time units.

We constructed the galaxy model for the second merger simulation from the final merger product of the first simulation. First, we removed the particles with positive binding energy. Then we replaced the two heavy particles (BHs) by their center of mass and selected half of the field particles with odd indices. Then we scaled the positions, velocities, and masses of all particles so that the half-mass radius of the system became 0.75.

The spin axes of the two galaxies were set to be antiparallel. Both are perpendicular to the orbital plane of the relative orbit of the galaxies. Farouki et al. (1983) randomized the spin axis before starting their simulations. We adopted the above-described configuration to avoid additional complications. For comparison, we performed the same simulation for the same King model but without central BHs.

3. RESULTS

3.1. *Structure of the Merger Remnant*

Figure 1 shows the density profiles of the merger remnant for the run with $M_{\rm BH} = 1/32$ and $W_c = 7$ as well as the run without BHs, using the same W_c. It is clear that the merger without central BHs results in a quick increase in the central density, as observed by Farouki et al. (1983). On the other hand, for the run with the central BHs, the density profile is almost unchanged.

Figure 2 shows the projected density profile averaged over the projection angle. We can see the same tendency as in Figure 1, but more clearly since the projected density is less noisy than the volume density.

Note that we rescaled the radius and mass of the merger remnant after each merging. In the original unit, the half-mass radius of the merger is roughly twice that of the progenitors. Therefore, the core size of the merger with central BHs also roughly doubles, while the core of the merger without central BHs remains roughly unchanged.

If we compare the density profiles in Figures 1*a* and 1*b*, the profiles in Figure 1*a* show a modest rise in the central region while there is no such tendency for the profiles in Figure 1*b*. As shown in Figure 3, density profiles of merger remnants from other initial conditions show a similar tendency. Roughly speaking, if we approximate the inner region by a power law of the form $\rho \propto r^{-\alpha}$, the index α is between 0.5 and 1.

As we mentioned in § 1, recent *HST* observations suggest that what have been believed to be flat cores are actually shallow density cusps with $\alpha \sim 1$. Thus it seems that merg-

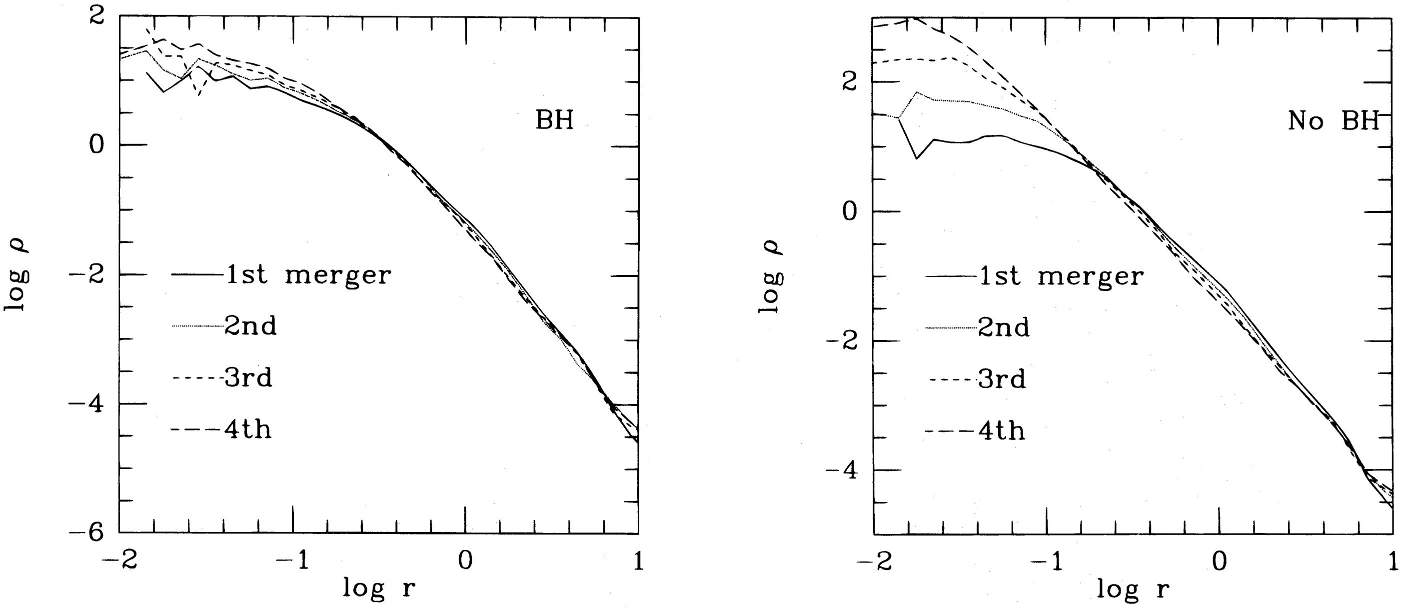

FIG. 1*a* FIG. 1*b*

FIG. 1.—Density profiles of merger remnants. Solid curves represent first mergings, dotted curves second, short-dashed curves third, and long-dashed curves fourth mergings. (*a*) Mergings with BHs, $M_{\rm BH} = 1/32$, $W_c = 7$; (*b*) mergings without BHs, $W_c = 7$.

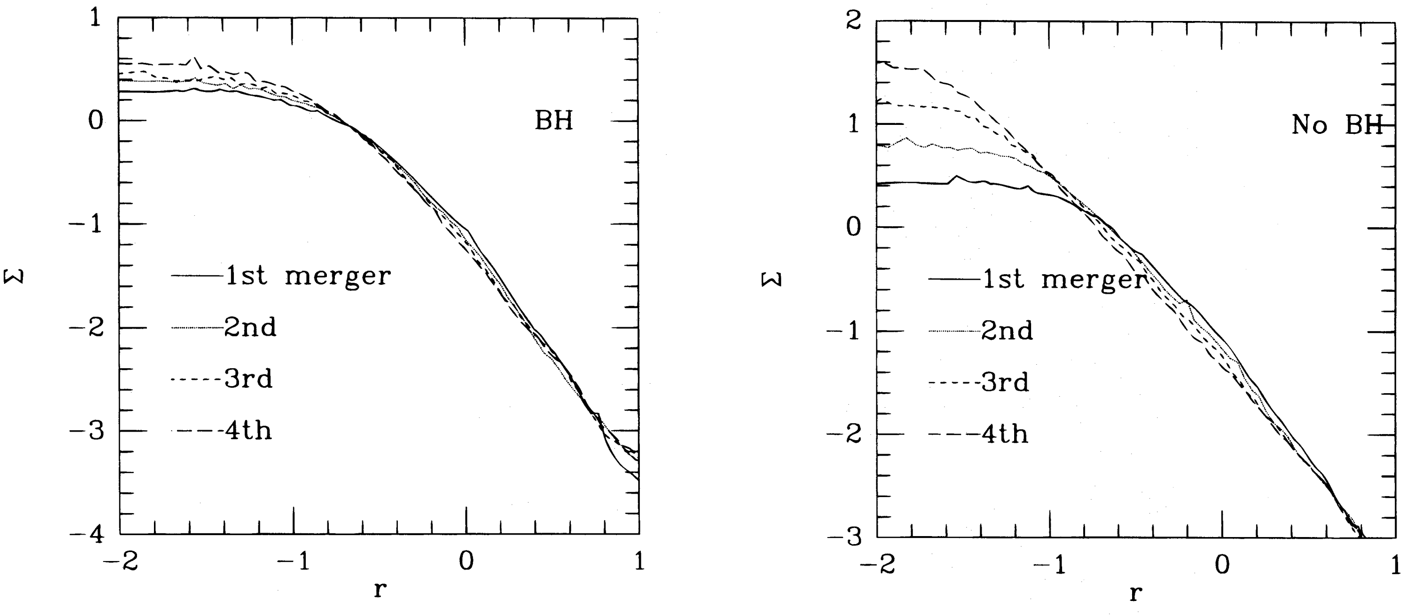

FIG. 2*a* FIG. 2*b*

FIG. 2.—Same as Fig. 1, but for projected density profiles

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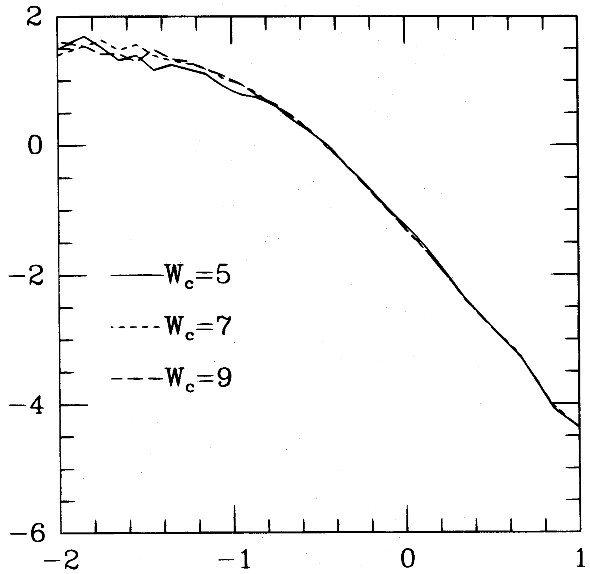

FIG. 3*a*

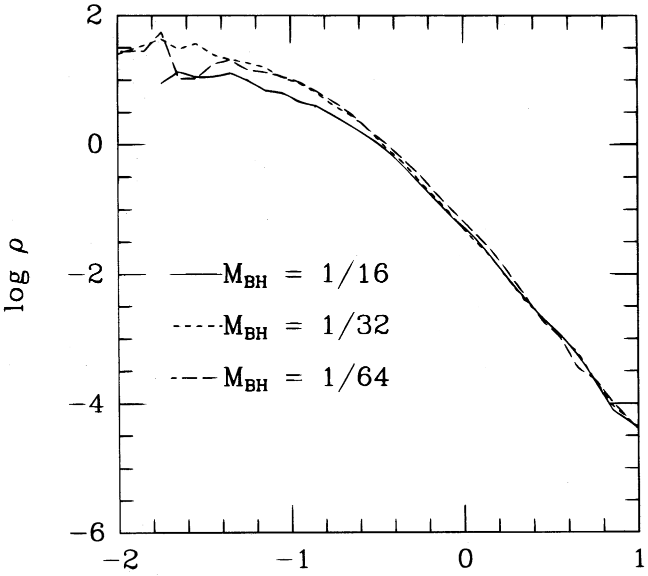

FIG. 3*b*

FIG. 3.—Density profiles of merger remnants for final mergers from different initial conditions. (*a*) Results for different initial galaxy models; (*b*) results for different BH masses.

ings with central BHs provide a plausible explanation for the observed structure of elliptical galaxies.

It is very difficult to construct an $\alpha = 1$ cusp by a dissipationless process. Merging of smaller clusters would form a small, flat core with a nearly isothermal halo, as our simulation without central BH showed. In principle, a dissipationless collapse from a single perturbation can make such a structure, if we fine-tune the initial density perturbation. However, it is extremely unlikely that most elliptical galaxies were actually formed from such finely tuned initial perturbations. Dubinski & Carlberg (1991) and Navarro et al. (1996) claimed that the collisionless halo formation under the standard CDM models leads to a $1/r$ cusp at the center. However, as we discussed in § 1, their results were limited by the size of the softening they used, and the index approaches -1 only at a radius comparable to the softening size. A dissipational process would create cusps with $\alpha \simeq 2$, which is more appropriate as an explanation for small elliptical galaxies with central cusps.

If the central BH is formed after the elliptical is formed, the structure of the central region will not resemble an $\alpha \simeq 1$ cusp. Both theory (Young 1980) and large-scale N-body simulations (Quinlan et al. 1995) show that $\alpha = 3/2$ if the BH grows slowly at the center of the galaxy. If two-body relaxation is important, α will become 7/4 (Bahcall & Wolf 1976). Both scenarios predict a cusp that is much steeper than what is observed.

At present, we do not understand the mechanism that resulted in the $\alpha = 1$ cusp in our merger simulation. Therefore, there is some possibility that this result is a numerical artifact caused by, for example, relaxation effect. However, since the relaxation process is known to yield a different power, we think this is rather unlikely.

3.2. *Core Radius*

In order to see the difference between the mergings with and without BHs quantitatively, we calculated the core radius for each model. Since the mergers with central BHs do not have cores with flat density, we must be careful of what we are measuring. Fortunately, the standard method used to calculate the core radius (Casertano & Hut 1985) actually gives the correct size of the "core," since it gives the radius of the region with $\alpha \leq 3/2$. So, we used the standard definition without modification.

Figure 4 shows the relation between the core radius r_c and half-mass radius r_h for runs with $M_{BH} = 1/32$ and runs without BHs. All runs with central BHs show a large increase in r_c, while runs without BHs show only a small increase. The non-BH run with $W_c = 9$ shows a rather large increase in the core radius. This is because the core radius

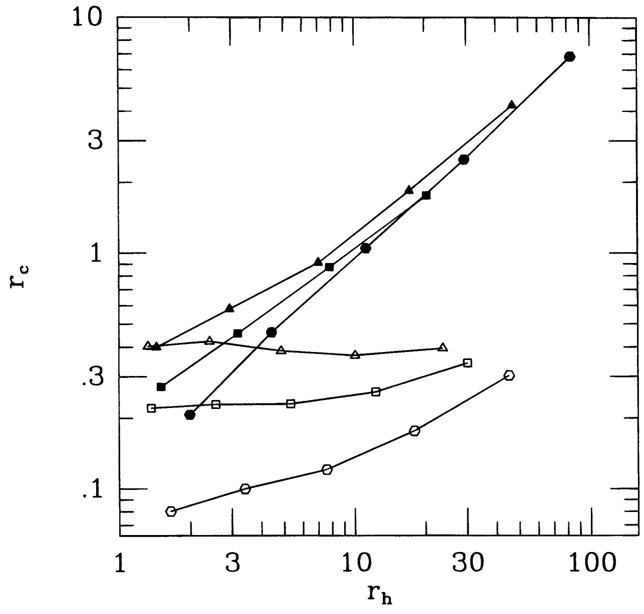

FIG. 4.—Relation between the half-mass radius r_h and core radius r_c for hierarchical merging with central BHs (*filled symbols*) and without central BHs (*open symbols*), in the original units. Triangles, squares, and hexagons represent the initial models with W_c = 5, 7, and 9, respectively.

becomes comparable to the softening length. In Figure 4, we plotted the core radius and half-mass radius scaled back to the original unit. As described in § 2, we rescaled the merger remnant before starting the next simulation in order to simplify the simulation procedure. As a result, the ratio between the softening length and the half-mass radius of the remnant is kept roughly constant. The half-mass radius of the merger remnant is ~1.8 in the unit used in the simulation, and the softening is 1/128. Thus, it is impossible for the core size to become smaller than 0.4% of the half-mass radius. In the run without BHs and with $W_c = 9$, the value of r_c/r_h after the fifth merging was 0.0067. The core size is thus smaller than twice the softening. The small increase of the core radius in the case of $W_c = 7$ is also explained as an effect of the softening.

If we compare the results of runs with BHs started from different galaxy models, it is clear that the ratio r_c/r_h converges to one value. In this case, $r_c/r_h \sim 0.09$ for all galaxy models after the last merging.

Figure 5 shows the relation between the core radius r_c and half-mass radius r_h for runs with different BH masses. The core size is larger for larger BH mass. The dependence of the ratio r_c/r_h on the BH mass is somewhat weaker than linear; r_c/r_h for runs with $M_{\rm BH} = 1/16$ is ~40% larger than those for $M_{\rm BH} = 1/32$. The relation between the runs with $M_{\rm BH} = 1/32$ and 1/64 is similar.

A simple theory (EMO) would predict that $r_c/r_h \propto M_{\rm BH}/M_g$. The reason the dependence is weaker than the theoretical prediction of linear dependence is that the BH mass is still too large. In Figure 5, we can see that the half-mass radius grows more rapidly for runs with larger $M_{\rm BH}$. After the fourth merging, r_h is 34, 20, and 11 for runs with $M_{\rm BH} = 1/16, 1/32$, and 0, respectively. Thus, the energy production from the BHs actually affects the structure of the whole galaxy. We expect that the relation between r_c/r_h and $M_{\rm BH}$ would approach linear if we further decreased the BH mass.

Figure 6 shows the relation between the effective radius and the core radius of observed elliptical galaxies, with data taken from Lauer (1985). It is clear that the merging with central BHs nicely reproduces the observed correlation. If one compares the absolute values of r_c/r_h in our simulation with r_c/r_e in Figure 6, our result is somewhat larger since we obtained ~0.09 while Figure 6 yields 0.04–0.05. This is purely because our BH mass of 1/32 is still too large. As shown in Figure 5, smaller BH mass produces a smaller core.

On the other hand, mergings without central BHs fail to reproduce the observations, since r_c stays almost constant (note that the increase in r_c for $W_c = 9$ is a numerical artifact due to softening). Galaxies with $r_c = 500$ pc cannot be formed by the merging of galaxies with $r_c = 100$ pc without central BHs.

Ferrarese et al. (1994) measured the surface luminosity profiles of 14 elliptical galaxies in the Virgo Cluster, of which four were classified as their type I (nonthermal core). Based on these four samples, they suggested that the correlation between r_c and r_h might be the result of showing three different types of elliptical galaxies—their types I and II and cDs—in a single plane. Since the number of samples they used was very small (only four), we have to wait for better statistics based on a larger number of samples to see whether their claim is valid. Note that, even if their claim turns out to be true, we still have to explain the origin of the large cores of cD galaxies.

The size of the core would be determined by the amount of energy input from the BH binary to the core relative to the total binding energy of the merger. Therefore, the final core radius obtained in our simulation should depend on the binding energy of BH binary when we stopped the simulation.

We expect, however, that the dependence is not very large. The binding energy of a BH binary can easily become larger than the total energy of the whole galaxy provided

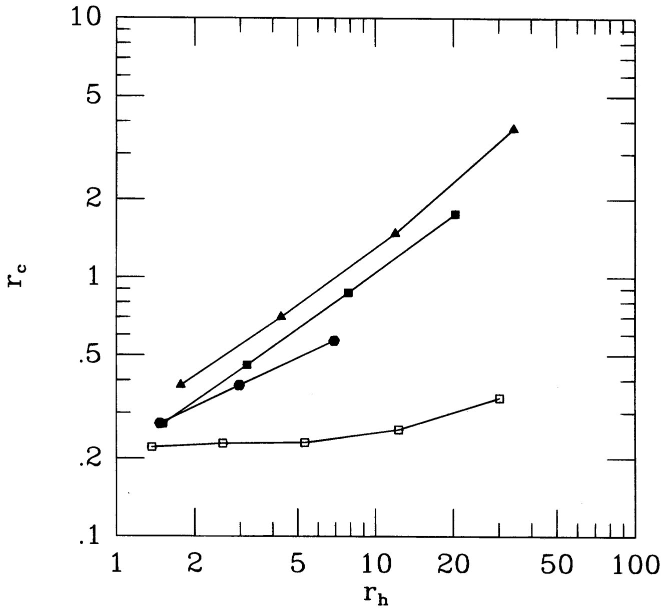

FIG. 5.—Same as Fig. 4, but for results of runs with different $M_{\rm BH}$. A King model with $W_c = 7$ was used as the initial model for all runs. Triangles, squares, and hexagons represent BH masses of 1/16, 1/32, and 1/64, respectively.

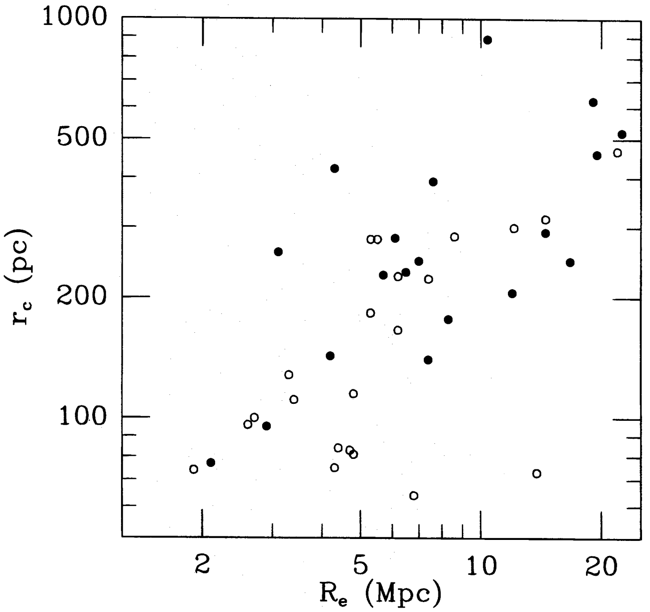

FIG. 6.—Relation between the core radius (*vertical axis*) and effective radius (*horizontal axis*) of observed elliptical galaxies. Data are taken from Lauer (1985). Filled circles indicate the galaxies of resolution classes I and II in Lauer (1985), and open circles denote those of class III.

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that the loss-cone depletion is not very effective. However, if the BH binary becomes sufficiently hard, most of the energy is not deposited to the core, since the particle that interacted with the binary is likely to be ejected from the core. Therefore, most of the energy released from the binary is not used to heat the core. In fact, we found that the core radius does not change very much after the BH binary is formed, even though the energy released from the BH binary is comparable to the total energy of the galaxy. Also, in real mergers, the dependence of the core radius on the amount of energy generated from the BH binary would be rather weak, because of the reason described above.

4. DISCUSSION AND SUMMARY

In this paper we investigated the structure of the merger remnant formed by the merging of galaxies that contain massive central black holes. We performed simulations of hierarchical merging, in which a merger remnant merges again with a galaxy of the same mass and size. We found that the merger remnant has a shallow cusp in the center, which is in good agreement with recent observations of large elliptical galaxies. If we regard this shallow cusp as the core (since it gives essentially flat projected density), the ratio between the core radius and the half-mass radius approaches a constant value determined by the mass ratio between the BH binary and the whole galaxy. In our simulations, the final value for r_c/r_h was ~ 0.1 for the case of $M_{\rm BH}/M_g = 1/32$. In the case of the merging of galaxies without central BHs, the ratio between the core radius and the half-mass radius decreases through merging. The merger scenario with central massive BHs well explains the observed positive correlation between the core size and the effective radius. It also solves the problem of the central phase-space density posed by Carlberg (1986).

Our results imply that most bright elliptical galaxies with finite core radius are likely to contain massive black holes, or at least some compact objects with comparable masses, since otherwise their core size would be much smaller. In addition, it would be difficult to explain the existence of the shallow cusp.

Governato, Colpi, & Maraschi (1994) performed simulations similar to those by EMO, but with several different galaxy models. They found that if the galaxies have extremely large cores, the timescale for the formation of the BH binary can be as long as 10 half-mass crossing times. They used King models with $W_c = 1$, 3, and 7 as initial model galaxies and found that, for runs in which galaxies with different values of W_c were used, it took a very long time for the BHs to sink to the center. As they stated, this is naturally explained by the fact that the less concentrated galaxy was disrupted in the early stage of merging, leaving the BH far away from the center. Their result has little practical significance, since they found long timescales only for runs with extremely large cores ($r_c \sim 0.5 r_h$) and small BH mass compared to the core mass ($M_{\rm BH} < 0.1 M_c$). In practice, r_c would be less than $0.1 r_h$ and $M_{\rm BH} \sim M_c$.

It should be noted that the range of initial conditions we have covered is still rather limited. In particular, we have not yet investigated the merging of galaxies with different masses. In the case of mergings without central BHs, if two galaxies of different sizes merge, the core with higher density is likely to survive (Balcells & Quinn 1990). If we assume that the initial density profiles are similar, i.e., the values of r_c/r_h are similar for the two progenitors, then the core of the merger will have a size close to that of the smaller one. Thus, if we consider merging without BHs, neither hierarchical mergings nor accretion of small galaxies to a large one can create the observed large "cores." In a forthcoming paper we will investigate the merging of galaxies with different masses.

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