Merging of galaxies with central black holes

I. Hierarchical mergings of equal-mass galaxies

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ABSTRACT

We investigated the merging of galaxies with central massive black holes. We performed simulation of hierarchical mergings, in which the merger remnant of one simulation was 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 HST result which suggest most of large ellipticals have shallow density cusps. This shallow cusp gives almost constant surface density. The radius of this shallow cusp (core) roughly doubles at each merging event. This expansion of the core was supported by the energy production from the black hole binary. As a result, the ratio between the core radius and the half mass radius was kept roughly constant. This result is again in good agreement with the observed positive correlation between the core radius and the effective radius of elliptical galaxies. In previous simulations of galaxy merging, the role of the central black holes was neglected. In these simulations, the half mass radius increased but the core radius did not increase, showing a clear disagreement with observations. Our result implies that the existence of the central black holes naturally explains the structure and size of the cores of bright ellipticals, though other explanations (*e.g.*, by anisotropy) are not ruled out.

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 is explained by a simple argument that the distribution function in the energy space, $N(E)$, is smooth at $E = 0$ (Jaffe 1983, Makino *et al.* 1990). Second, the velocity dispersion of the merger remnant is slightly larger than that of progenitors, being consistent with the Faber-Jackson relation (Farouki *et al.* 1983; Okumura *et al.* 1991).

Third, the distribution of the ratio between the maximum rotation 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 $V_{\max}/\sigma$ of 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 merging 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 core of the elliptical galaxies has 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 the merging. He argued that it was impossible to form a 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 and Hernquist 1992, Hernquist 1992, Hernquist *et al.* 1993) confirmed Carlberg's argument that merging of two stellar disks cannot form the core of an elliptical. However, the central phase space density of the bulge of a spiral galaxy is much higher 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 ellipticals is lower than that of faint ellipticals. Though the central phase space density can decrease in the collisionless process, merging 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 rather weak, as seen in the Faber-Jackson relation (Faber and Jackson 1976). On the other hand, r_c is roughly proportional to L (*e.g.*, Lauer 1985). Therefore the central phase space density is roughly proportional to L^{-2}.

The core radii of simulated mergers remained nearly same as, or became slightly smaller than, the core radii of the progenitors, though 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 size of all elliptical galaxies would be similar.

The central phase space density can decrease if sufficient amount of vacuum is mixed into the core. However, the "violent relaxation" in the central region is not violent enough to mix in sufficient amount of vacuum. Thus 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 becomes even higher.

Recent observations by 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 of large ellipticals have "cores" which cannot be represented by an isothermal model. This difference has been suggested by ground-based observations (Lauer 1985, Kormendy and Djorgovski 1989), but Observations with HST have vastly improved the accuracy. Lauer *et al.*(1995) and Richstone (1996) argued that the deprojected "cores" are actually very shallow central density cusps ($\rho \sim r^{-1}$). Such a shallow cusp poses a serious problem to almost any scenario of the formation of the ellipticals. If these ellipticals do not have central BH, we are faced with very strange structure with the velocity dispersion decreasing inward. Neither dissipationless/dissipational collapse nor merging have been able to make such a density distribution.

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

The standard scenario of the formation of the central BH is the adiabatic growth by accretion. In this case, the central density would show the cusp of $\rho \sim r^{-3/2}$ (Young 1980, Quinlan *et al.* 1995), which is ruled out by the observation.

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

Ebisuzaki, Makino and Okumura (1991; hereafter EMO) pointed out that the heating by the central BHs can make the core larger. If both progenitor galaxies have central massive BHs, these BHs sink down to the center of the merger remnant because of the dynamical friction from field particles and form a BH binary. This BH binary heats up the core in the same way as the binaries in the core of the globular clusters heat the core. EMO performed N-body simulation of the merging of spherical galaxies containing central BHs, and found that the core actually expands. They also gave 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 ellipticals.

The result of numerical simulations by EMO, however, suffered two limitations. First, it is not clear what happens if the merger remnant again merged with the 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 (e.g. Begelman, Blandford and Rees 1980), leaving the core without central BH. Thus, it is necessary to determine what is the typical lifetime of the BH binary. We made a preliminary study of this problem (Makino *et al.* 1993), where 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 and Ebisuzaki 1995).

Secondly, the initial galaxy model used in EMO had a rather large core, because of the limited computing resources then available. They argued that the core mass would become comparable the BH mass, if the core radius is determined solely by the energy input from the BH binary. However, they used a Plummer model as the initial galaxy model, and the ratio of the core mass and the BH mass is initially about 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: How 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 the simulation of the hierarchical mergings. The merger remnant of one simulation is used as the progenitor for the next simulation in the way similar to Farouki *et al.* (1983), who did the simulation of hierarchical merging without taking into account the effect of the central BHs. The progenitor for the first simulation is constructed in the way same as that in EMO. At the end of each simulation, we artificially replaced the BH binary by one particle. We used about 16,000 particles for each galaxy and the mass of a BH was 1/16 to 1/64 of the total mass of a galaxy. The total number of particles in the present simulation is 8 times larger than that used in EMO. We repeated the merging simulation four or five times, both with and without the central BH. In order to see the dependence on the initial condition, we tried three different initial galaxy models and three different BH masses.

For merging without central BHs, our result is essentially same as that of Farouki et al. (1983), who observed the core size relative to the half mass radius shrinks after each merging event. For the merging with central BH, 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 slight increase inward. This result nicely explains the resent observation of large ellipticals with HST (Lauer *et al.* 1995, Richstone *et al.* 1996), which found a number of ellipticals with such shallow cusps. They called this shallow cusp "core".

The ratio r_c/r_h converges to 0.1, for simulations from three different initial galaxy models with same BH of 1/32 of the total mass of the galaxy. Thus, it it 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 mass and smaller for smaller BH mass, as naturally expected. Therefore we can conclude that the merging of galaxies with central BHs succeeded to reproduce the observed correlation between the core radius and the luminosity.

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

2. NUMERICAL METHOD AND INITIAL CONDITION

2.1. NUMERICAL METHOD

The calculation code we used is NBODY1 (Aarseth 1985) modified to be used with GRAPE-4 special purpose computer for gravitational N-body simulation (Taiji *et al.* 1996). The time integration scheme is changed to the Hermite scheme (Makino and Aarseth 1992) to take advantage of the GRAPE-4 hardware. We neglect 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 the softening of $1/128$ for the force between field particles, and pure $1/r$ potential for forces to and from BH particles. The relative accuracy of the force calculated on GRAPE-4 is about 7 digits (IEEE single precision), which is more than enough for forces from field particles but might cause problem for the force from BH particles. In the present code, the force from field stars are calculated on GRAPE-4, while that from BH particles are calculated on the host computer in full double precision.

For merging without central BHs, we used a simple leap frog integrator with a constant timestep. The size of the timestep was $1/256$.

Calculations are performed on one cluster of GRAPE-4 system with the theoretical peak of 270 Gflops. Actual sustained speed was around 50 Gflops. One simulation took 10-20 hours, depending on the structure of the galaxy.

2.2. Initial Conditions

We performed the merging simulation of two identical spherical galaxies from a parabolic orbit. We used three different initial galaxy models, namely King models with the nondimensional central potential W_c of 5, 7, and 9. Initial galaxy is created so that the total mass M_g is one and the total energy E_g is $-1/4$ in the system of units where gravitational constant G is one (the standard unit, Heggie and Mathieu 1986). The number of particles is 16384. In this unit the half mass radius of the initial galaxy model is about 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 one, we scale the mass of each particle by a factor $(1 - M_{BH})/1$, and placed a point particle with mass M_{BH} at the center of the cluster. In this case initial galaxy has a density cusp around BH. In the second case, we removed $N \times M_{BH}$ particles closest to the center of the galaxy and put the BH particle at the center. In this case, the galaxy do not have the central cusp. We compared the structure of the merger remnant for the case of

$W_c = 7$ and $M_{BH} = 1/32$, and found no difference. However, the calculation time is about 3 times longer for the first procedure, since it has an initial central density cusp. For other initial conditions, we adopted the second procedure described above.

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 $M_{BH} = 1/32$ only.

Note that both the core radius and the mass of BH we used for our simulation are significantly larger than that of real ellipticals. 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 we described in the introduction, the purpose of the present paper is to investigate the structure of the core which is determined by the energy generation from the BH binary. If the mass of BH binary is too large, it might affect not only the structure of the core but also the structure of the whole 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 its 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 the dynamical equilibrium during the first approach. Initial periastron distance of the relative orbit was 1 and initial separation of two galaxies was 10. We simulated the evolution of the system for 60 time units.

We constructed the galaxy model for the second merging 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 mass of all particles so that the half mass radius of the system becomes 0.75.

The spin axe of two galaxies were set to anti-parallel. Both are perpendicular to the orbital plane of the relative orbit of galaxies. Farouki *et al.* (1983) randomized the spin axis before starting the simulation. 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 BH.

3. Results

3.1. The structure of the merger remnant

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

EDITOR: PLACE FIGURE 1 HERE.

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.

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

EDITOR: PLACE FIGURE 3 HERE.

If we compare the density profiles in figures 1a and 1b, the profiles in figure 1a show modest rise in the central region, while there is no such tendency for profiles in figure 1b. As shown in figure 3, density profiles of merger remnants from other initial conditions show 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 the introduction, resent HST observations suggest that what have been believed to be flat cores are actually a shallow density cusps with $\alpha \sim 1$. Thus, it seems the merging with central BH provides a plausible explanation for the observed structure of ellipticals.

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 single perturbation can make such a structure, if we fine-tune the initial density perturbation. However, it is extremely unlikely that most elliptical are actually formed from such fine-tuned initial perturbations. Dubinski and Carlberg (1991) and Navarro *et al.* (1995) claimed that the collisionless formation of halo under standard CDM model lead to $1/r$ cusp at the center. However, as we discussed in the introduction, their results were still limited by the size of softening they used and the index approaches to -1 only at the radius comparable to the softening size.

Dissipational process would create the cusp with $\alpha \simeq 2$, which is more appropriate as an explanation for small ellipticals with central cusps.

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

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

3.2. The core radius

In order to see the difference between the mergings with and without BHs quantitatively, we calculate the core radius for each models. Since the mergers with central BH do not have core with flat density, we must be careful what we are measuring. Fortunately, the standard method used to calculate the core radius (Casertano and Hut 1985) actually gives 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 BH show large increase in r_c, while runs without BH show only small increase. The non-BH run with $W_c = 9$ shows rather large increase in the core radius. This is because the core radius becomes comparable to the softening length. In figure 4, we plotted the core radius and half-mass radius that are scaled back to the original unit. As we described in section 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 round 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 BH and $W_c = 9$, r_c/r_h after the 5th merging was 0.0067. Thus the core size is smaller than twice the softening. The small increase of the core radius in the case of $W_c = 7$ is also explained as the 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 last merging.

EDITOR: PLACE FIGURE 4 HERE.

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 ration r_c/r_h on the BH mass is somewhat weaker than linear; r_c/r_h for runs with $M_{BH} = 1/16$ is $\sim 40\%$ larger than those for $M_{BH} = 1/32$. The relation between the runs with $M_{BH} = 1/32$ and 1/64 is similar.

A simple theory (EMO) would predict that $r_c/r_h \propto M_{BH}/M_g$. The reason why 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_{BH}. After the 4th merging, r_h is 34, 20 and 11 for runs with $M_{BH} = 1/16$, 1/32 and zero. Thus, the energy production from BH actually affects the structure of the whole galaxy. We expect that the relation between r_c/r_h and M_{BH} would approach to a linear one if we further decrease the BH mass.

EDITOR: PLACE FIGURE 5 HERE.

Figure 6 shows the relation between the effective radius and the core radius of observed elliptical galaxies. Data were 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 got ~ 0.09 while figure 6 gives 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 smaller core.

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

Ferrarese *et al.* (1994) measured the surface luminosity profiles of 14 ellipticals in Virgo cluster, in which 4 are classified as their Type I (non-thermal 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 ellipticals — their Type I, Type II and cDs, in a single plane. Since the number of samples they used is very small (only 4), we have to wait for better statistics based on larger number of samples to see whether their claim is valid or not. Note that even if their claim turned out to be true, we still have to explain the origin of large cores of cD galaxies.

EDITOR: PLACE FIGURE 6 HERE.

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, however, expect that the dependence is not very large. The binding energy of BH binary can easily become larger than the total energy of the whole galaxy, provided 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 the energy generated from BH binary would be rather weak, because of the reason we described above.

4. DISCUSSION AND SUMMARY

In this paper, we investigated the structure of the merger remnant formed by the merging of galaxies each containing massive central BHs. We performed simulations of hierarchical merging, in which a merger remnant merges again with the 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 the recent observation of large ellipticals. 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 to 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 about 0.1 for the case of $M_{BH}/M_g = 1/32$. In the case of the merging of galaxies without central BH, the ratio between the core radius and the half mass radius decreases through merging. The merging scenario with central massive BH 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 result implies 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 *et al.* (1995) performed simulations similar to that by EMO, but with several different galaxy models. They found that if the galaxies have extremely large cores, the timescale for the formation of BH binary can be as long as 10 half-mass crossing time. They used King models with $W_c = 1, 3, 7$ as initial model galaxies, and found that for runs where galaxies with different values of W_c are used, it tool very long time for BHs to sink into the center. As they stated in their paper, this is naturally explained by the fact that 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 timescale only for runs with extremely large cores ($r_c \sim 0.5 r_h$) and small BH mass compared to the core mass ($M_{BH} < 0.1 M_c$). In practice, r_c would be less than $0.1 r_h$ and $M_{BH} \sim M_c$

It should be noted that the range of the initial condition we covered is still rather limited. In particular, we have not yet investigated the merging of galaxies with different masses. In the case of merging without central BH, if two galaxies with different sizes merge, the core with higher density is likely to survive (Barcells and Quinn 1990). If we assume that the initial density profiles are similar, *i.e.*, the values of r_c/r_h are similar for two progenitors, the core of the merger will have the size close to that of the smaller one. Thus, if we consider the merging without BH, either the hierarchical mergings or accretion of small galaxies to a big one cannot create observed large "cores". In the forthcoming paper we will investigate the merging of galaxies with different masses.

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Figure Captions

Fig. 1.— The density profiles of merger remnants. Solid curves represent 1st mergings, dotted curves 2nd, short-dashed curves 3rd, and long-dashed curves 4th mergings, (a) mergings with BH, $M_{BH} = 1/32$, $W_c = 7$; (b) mergings without BH, $W_c = 7$.

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

Fig. 3.— Same as figure 1 but for final mergers from different initial conditions, (a) results for different initial galaxy models, (b) results for different BH masses.

Fig. 4.— Relation between the half mass radius r_h and the core radius r_c for the 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.

Fig. 5.— Same as figure 4 but for result of runs with different M_{BH}. King model with $W_c = 7$ is used as the initial model for all runs. Triangles, squares and hexagons represent the BH mass of 1/16, 1/32 and 1/64, respectively.

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

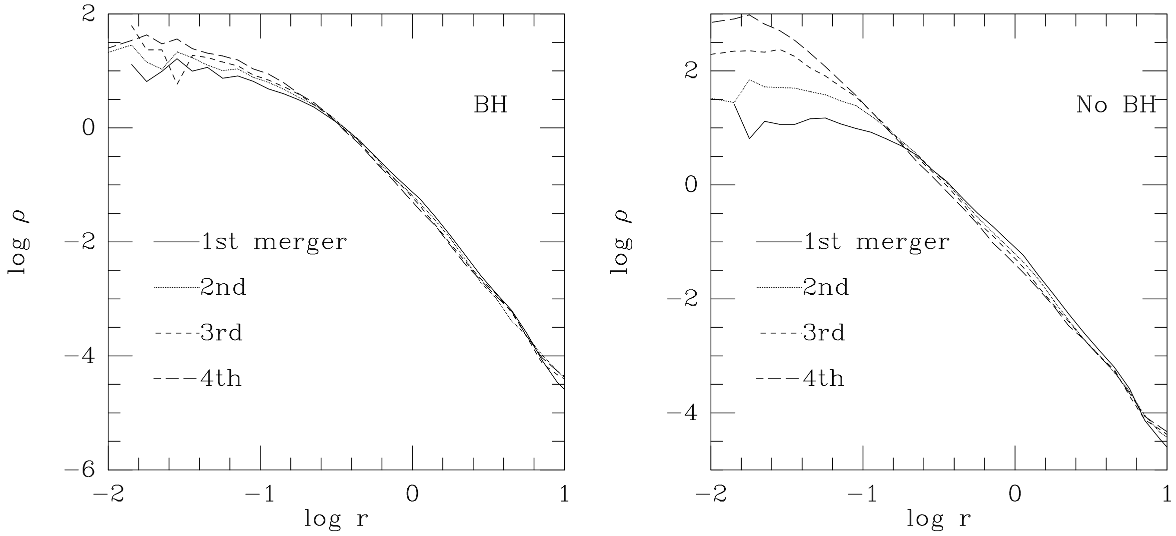

Figure 1

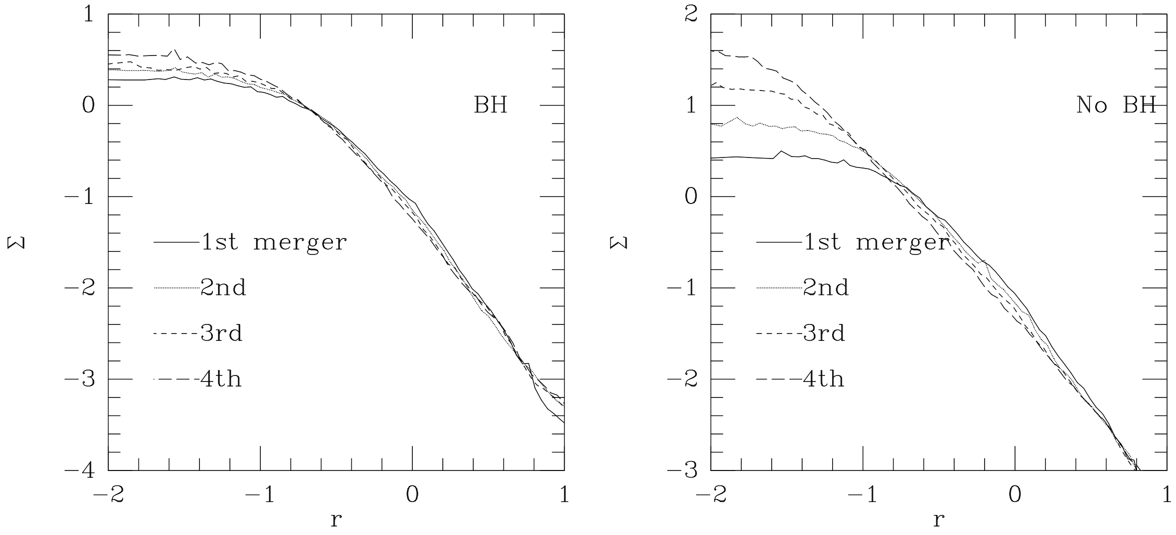

Figure 2

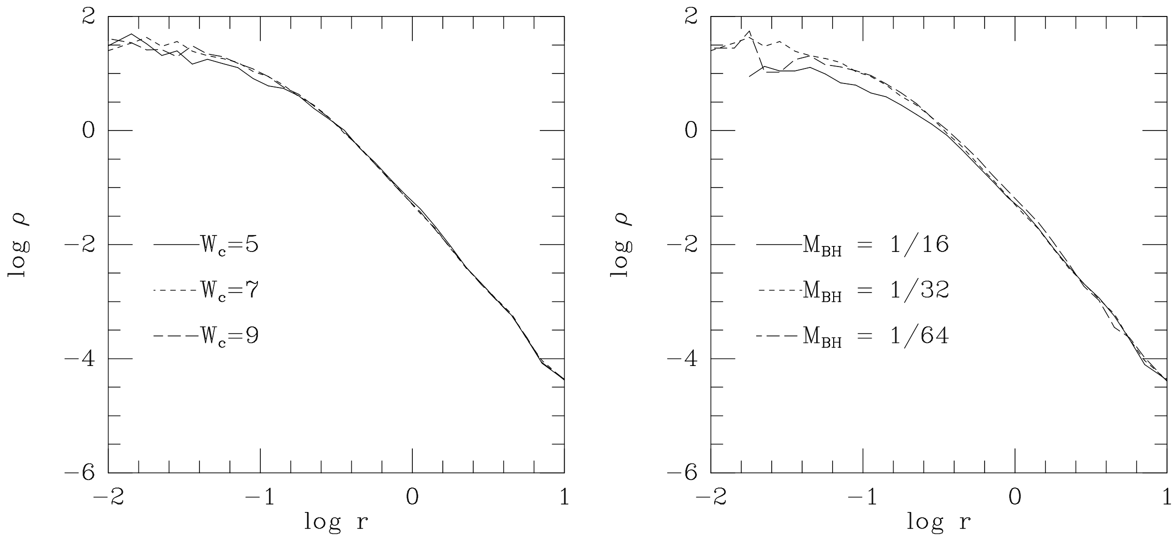

Figure 3

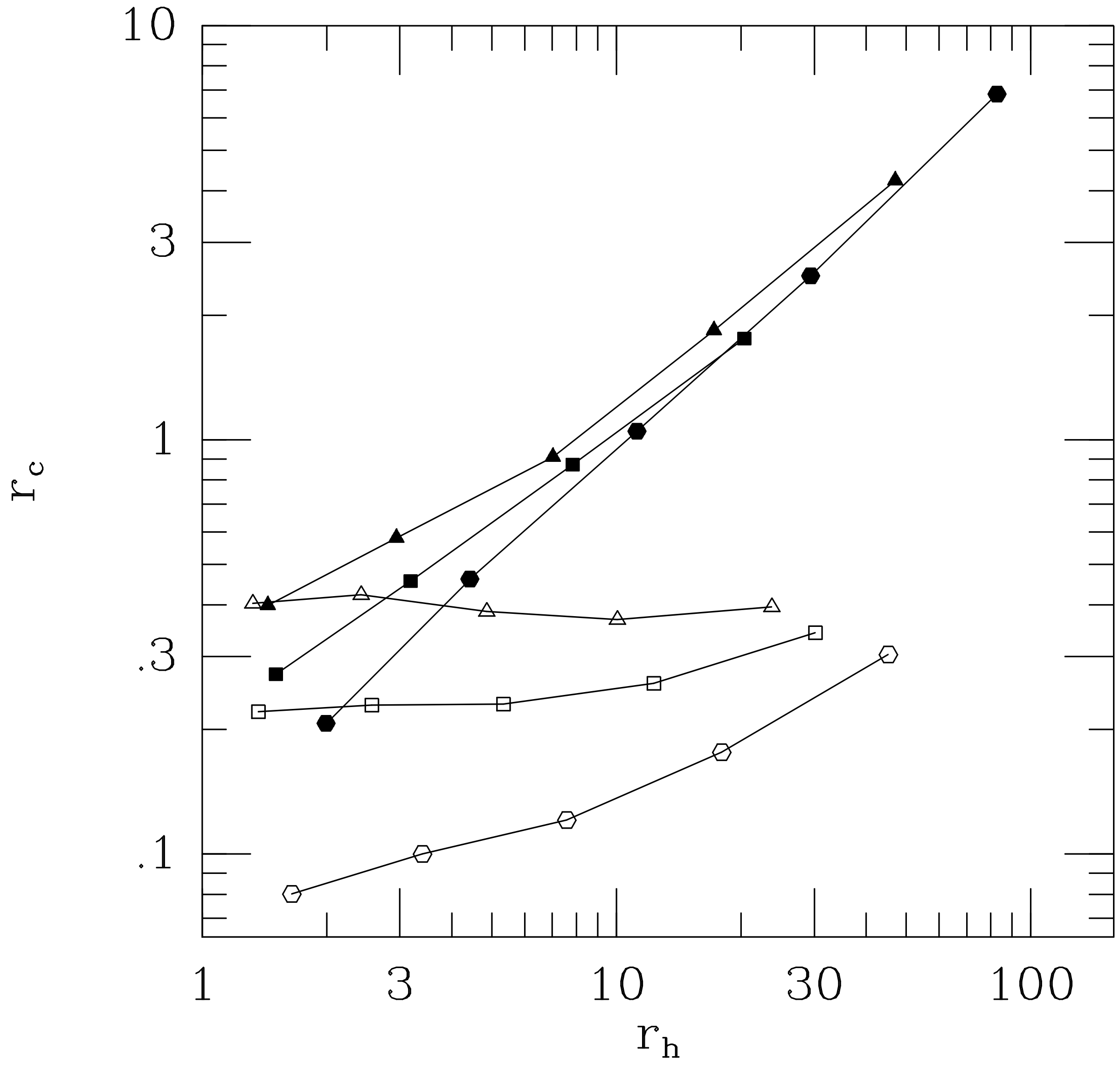

Figure 4

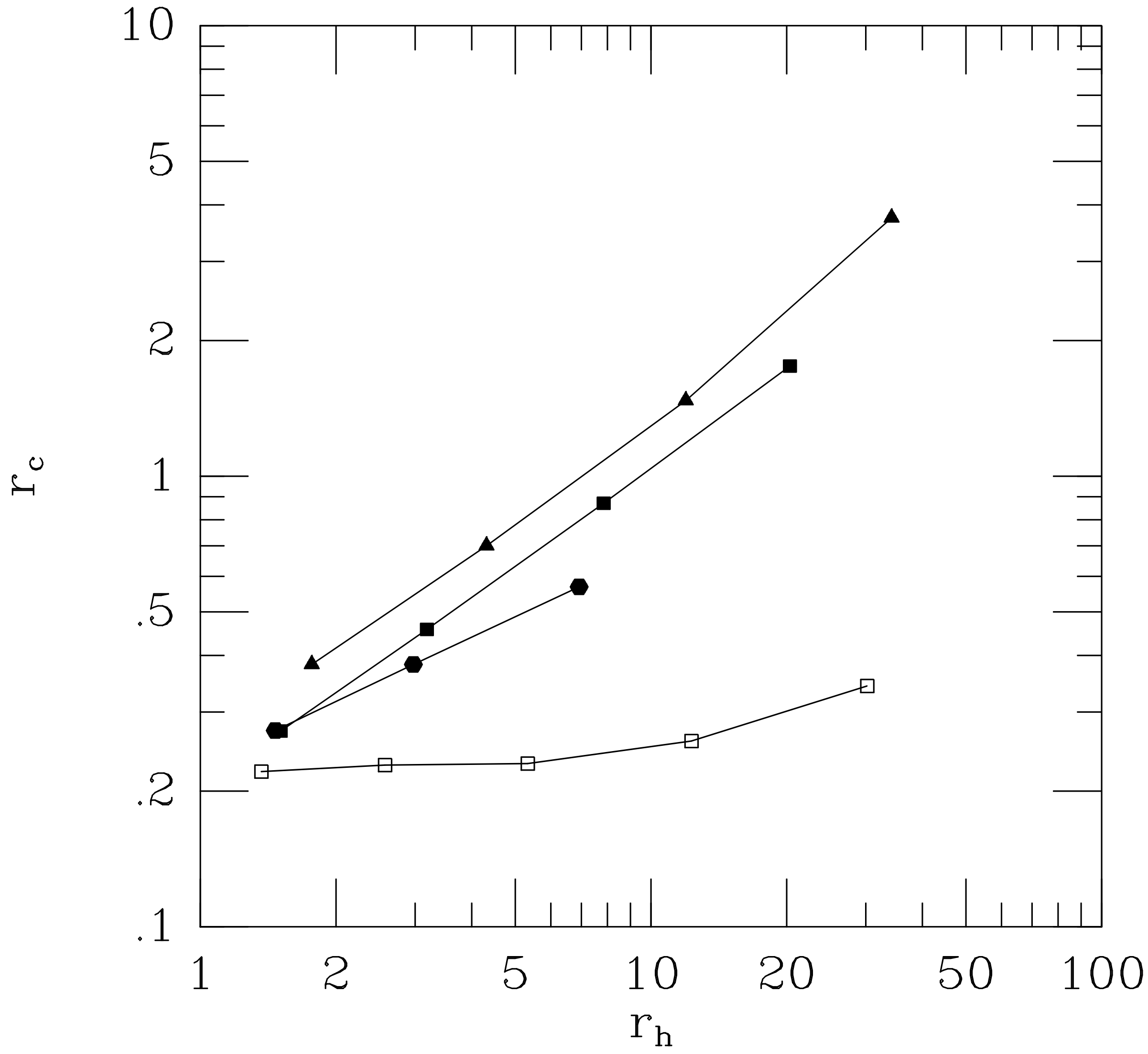

Figure 5

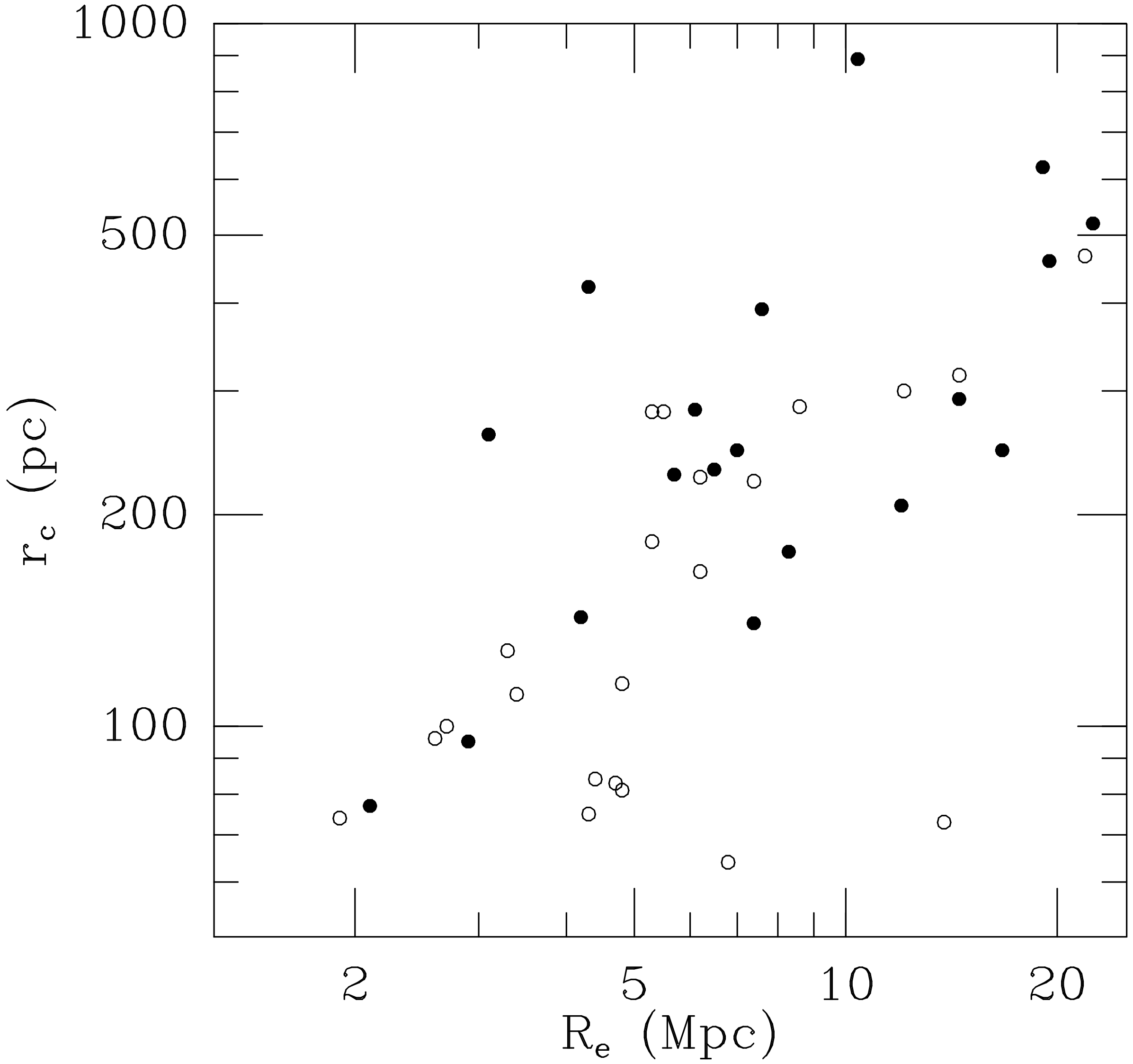

Figure 6