A possible mechanism for the mass ratio limitation in early type galaxies

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Abstract. There is an interesting correlation between the central objects and their host galaxies in recent high resolution HST photometry of early type galaxies and Near-IR images of nearby quasar hosts. It has been shown that a) the hosts of these very luminous quasars are likely to be early type galaxies and that b) the mass ratio of central black holes (BHs) and their host spheroidal components ($M_{\rm bh}/M_{\rm spheroid}$) is ~ 0.002 within a factor of three. Using the hierarchical galaxy evolution scheme for the formation of early-type galaxies, we present here a general viscous accretion disk model to trace the star formation and central engine evolution before and after mergers. In our model, starbursts and AGN coexist; these two activities compete for the gas supply, interact with each other, probably feed back on each other and lock into a final status. They thus constrain the ratio of central black hole mass and its host spheroidal mass to a universal value of order 10^{-3}.

Key words: galaxies: nuclei – galaxies: evolution – galaxies: formation – galaxies: starburst – galaxies: elliptical and lenticular, cD

1. Introduction

The main discussion about the formation of early-type galaxies centers on a 'nature' versus 'nurture' dichotomy. Sandage, Freeman & Stokes (1970) explained the 'nature' scheme as follows: A disk or a spheroidal configuration is produced by the collapse of a rapidly rotating or slowly rotating primordial gas cloud. The 'nurture' hypothesis, also referred to as the hierarchical scheme (Toomre 1977, Kauffmann 1996, Baugh et al. 1996, Mihos & Hernquist 1996, Walker et al. 1996) is: Mergers between disk galaxies where their mass ratio ($M_{companion}/M_{host}$) exceeds a value (of order ~ 0.3 in some simulations, but almost certainly a function of orbital parameters) form ellipticals or bulges in spiral galaxies; starbursts and nuclear activity can be triggered probably by the merger event (Fritze-v. Alvensleben & Gerhard 1994).

It seems that the 'nurture' scheme, which models the observed properties of ellipticals/bulges in a scenario where they

are formed by the merging of disk galaxies in a hierarchical universe, is more supported by recent numerical simulations and observations (Barnes 1988, Kauffman et al. 1993), and it also, for the first time, placed the theory of the formation and evolution of elliptical galaxies in a proper cosmological context.

Massive compact objects appear to be ubiquitous components of galactic nuclei. Particularly attractive is the possibility that we are observing the black holes (BHs) that once powered quasars and that still provide the energy source of Active Galactic Nuclei (AGN). This hypothesis is at least crudely consistent with the observed properties of quasars and AGN. Current black hole candidates have masses ranging from $\sim 10^{6.3} M_{\odot}$ in the case of Milky Way to $10^{9.5} M_{\odot}$ in the case of M87 (Kormendy & Richstone 1995). The compelling AGN theory is that these massive BHs are fuelled by gaseous accretion disks (Lüst 1952, Lynden-Bell 1969, Shakura & Sunyaev 1973, Rees 1984).

Starbursts and AGN are two fascinating phenomena after a merger. They are usually treated as independent activities in numerical simulations (Sargent et al. 1991, Barnes 1992). Recent observations of Ultraluminous Infrared Galaxies (ULIGs) by Very Long Baseline Interferometry (VLBI), the Very Large Array (VLA), infrared and optical wavelengths start to allow to consider a comprehensive picture for a starburst-AGN coexistence scenario (Smith et al. 1997, Heckman 1997). Also, HST photometry of ellipticals and spiral bulges, and Near-IR images of quasar hosts shows us that the central properties strongly depend on their host galaxies. A 'nuclear luminosity/host-mass limitation' in the most luminous quasars probably represents a physical limit on the mass of a black hole that can exist in a given galaxy spheroid mass. A mass ratio constraint of black hole mass and its host spheroid mass ~ 0.002 within a factor of three has been deduced from these observations and dynamical models (Faber et al. 1997, McLeod & Rieke 1994a,1994b, 1995a,1995b, Magorrian et al. 1996, Kormendy & Richstone 1995). The interesting point is whether this correlation is due to a statistical sampling bias, or a substantial evolutionary result.

In this paper, we try to use a simplified model to describe the steps of the elliptical/bulge formation, starburst and the central engine evolution in a hierarchical scheme by assuming that star formation and central object evolution are coexistent, and fed by a viscous accretion disk. In our scheme a disk galaxy is entirely

modelled as an accretion disk. Mergers can trigger a starburst in the central region, and induce more turbulence there. They thus drive turbulent accretion to feed both the AGN and starburst, grow a massive BH (Linden et al. 1993, Tacconi et al. 1994). The competition and feedback interaction between these two activities can lead to a constraint, and limit the ratio of BH mass and its spheroidal stellar mass ($M_{BH}/M_{spheroid}$) to a certain range of values.

2. Model

2.1. Formation of early-type galaxies, star formation and black hole evolution in a hierarchical universe

We consider a hierarchical universe. In this scenario, an elliptical/bulge does not form in a single collapse and burst of star formation at high redshift. Instead, in our model, gas cools and condenses at the center of a virialized halo of dark matter, and forms a centrifugally-supported gas disk there; star formation takes place mainly in the disk at a modest rate and gas is accreted inwards to the central object at the same time; a stellar disk and a central black hole may finally develop. If two disk galaxies merge at some time, the violent interaction between the two galaxies will smash the original stellar disks completely, and form the spheroidal component of the new early type galaxy. Meanwhile, the activity drives the outer cold gas to the central region of the newly formed galaxy and sets up a new molecular disk there; the triggered starburst and central AGN will put their kinetic energy into the ISM and induce turbulent viscous accretion in the central region.

In the following, we describe the background for our model, and then the model itself.

1) In the early universe, tidal torques spin up both the dark matter and the baryonic matter in some region of space; when the region becomes overdense, it will eventually collapse into a galaxy. This process together with the cooling can finally form a primordial gas disk, possibly with a seed black hole in the center, surrounded by a dark halo.

2) When this primordial gas disk is formed, the viscosity can start to transfer angular momentum to the outside and accrete material into the central region of a galaxy, while at the same time, star formation is taking place in the disk. The two activities, accreting material inwards i) to feed the central object and ii) to form a stellar disk, occur together and outline a picture of evolution of the disk galaxy.

3) With the hierarchical galaxy formation model, the violent merger of two disk galaxies will destroy the original stellar disks completely. All the stars in the disks are transferred to the bulge or spheroidal component of the new galaxy (Baugh et al. 1996, Kauffmann et al. 1993, Kauffmann 1995b, 1996), and thus form ellipticals/bulges.

4) During or after the violent mergers, the fate of the gas component is very uncertain. Some gas may be shock-heated by collisions between galaxies and injected back into the intergalactic medium. Alternatively, a large fraction of the gas may lose its orbital angular momentum, decrease its orbital radius, and be driven to the center (Toomre & Toomre, 1972). We propose here that most of the gas contained within the central kiloparsec or so is in the form of dense clouds which are on more or less circular orbits; self-gravity may play a critical role in the subsequent evolution of this molecular gas disk.

5) Both the concentration of molecular clouds towards the merger nucleus and an increased efficiency of star formation due to cloud-cloud collisions (Scoville et al. 1986) will result in the appearance of a nuclear 'starburst'. This merger triggered starburst probably can stir up turbulent accretion in the new molecular disk by heating or shocking the ISM from supernovae (SN), and thus help to grow a quasar black hole in a very short time. The possible fate of cool gas could be to form stars in a starburst, to feed a quasar black hole by turbulent accretion, or to be blown out of the disk by a wind.

There are several key concepts and basic assumptions in our model:

1) By the disk formation scenario in the early universe (Dalcanton et al. 1997), we basically assume that gas and baryons from a protogalactic halo cool, collapse or settle into a rapidly rotating gas disk on a time scale, that is much shorter than the star formation time scale t_* and the angular momentum transport time scale due to spiral density waves etc. (Zhang 1996, Gnedin et al. 1995, Olivier et al. 1991). Nevertheless, this assumption does not restrict our results here. Because, even if there is still some gas in a hot phase when the merger takes place, this gas could cool and together with the cool molecular gas from the outer disk set up the new molecular disk in the central region of the elliptical. This can change the total mass of the newly formed molecular disk, increase both star formation and accretion to the central black hole, but it will not affect the final mass ratio of the black hole and its stellar component.

2) We basically assume that the first merger event between two disk galaxies which possibly form the elliptical/bulge happens around $10^9 yr$ or later after the gas and baryons from a protogalactic halo cool, collapse and initially set up a gaseous disk. At this later evolution stage, the drastic disk evolution has already quieted down, or in other words, a stellar disk has already been well developed (Rieke et al. 1980, Kronberg et al. 1985). This merger time scale fits also the cosmological pattern of the merger event and the formation history of ellipticals/bulges near $z \approx 1$ (Baugh et al. 1996), but we can see in Fig. 5 that the final mass ratio limitation does not depend on the exact merger time.

3) With the basic assumption that t_* is proportional to t_{acc} (i.e. $t_* = \alpha t_{acc}, \alpha \simeq 1$), Lin & Pringle (1987) got a nice fit for the exponential stellar disk evolution in a spiral galaxy. We will adopt the same assumption for our disk evolution and also for the starburst and AGN stage after the merger. We found that the final mass ratio limitation ~ 0.006 strongly depends on this assumption of equal time scales (see Fig. 10).

4) As for the uncertainty of the detailed physical interaction between starburst and AGN, the purpose of this paper is just to sketch out an indicative picture for these activities; we will basically imitate the coexistent 'starburst' and the subsequent AGN evolution with the starburst time scale and the turbulent accretion time scale much shorter than their normal time scales before mergers (Mihos & Hernquist 1994).

5) We adopt the notion that accretion onto the central BH is restricted to a rate at which the Eddington luminosity is reached. In our calculation, we assume that the central BH is a seed BH ($\sim 5 M_\odot$) at the outset, the growth of this seed BH is limited by the Eddington limit. The extra gas supply to the center can form gas clouds there shrouding the central BH, or be blown away by a wind.

According to the scenario sketched here, disk evolution including the star formation in the gas disk and a viscous accretion to the central region will start in a protogalaxy before the merger, thus develop a stellar disk and a black hole in the center. We will show the BH evolution, stellar mass evolution and mass ratio evolution for a normal disk galaxy in Fig. 1 and Fig. 2 (line). By our model, we assume, at a certain time, after the disk evolution quiets down, two disk galaxies merge, firstly, destroy the original stellar disks and form the spheroidal component, secondly, drive the cool gas left to the center, redistribute a molecular disk there. A starburst can be triggered in this newly formed molecular disk by the violent interaction, and it probably will induce a turbulent viscous accretion to feed both the central AGN and starburst there. These two activities will grow together rapidly, compete for the gas supply and drain the gas in the molecular disk in a very short time, thus restrict the growth of the black hole to a certain ratio relative to the newly formed stellar component. We will show that the mass ratio of these two components ($M_{bh}/M_{spheroid}$) converges to a limited range of value ~ 0.006 from our calculation in Fig. 2 (dashed line).

2.2. Fundamental equations and viscosity

We take the gas surface density Σ, to be the sum of HI and H$_2$ surface density (plus the small amount of heavy elements). The evolution of $\Sigma(R,t)$, is governed by the standard viscous accretion disk equations of continuity and conservation of angular momentum (Lüst 1952, Pringle 1981), with a sink term due to the conversion of gas to stars (Σ/t_*). The basic equations are

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{R}\frac{\partial}{\partial R}\left(\Sigma R V_R\right) = -\frac{\Sigma}{t_*}\left(1 - R_e\right) \tag{1}$$

$$\frac{\partial}{\partial t}\left(\Sigma R^2 \Omega\right) + \frac{1}{R}\frac{\partial}{\partial R}\left(\Sigma R^3 \Omega V_R\right) = \frac{1}{R}\frac{\partial}{\partial R}\left(\nu \Sigma R^3 \frac{\partial \Omega}{\partial R}\right)$$
$$-\frac{R^2 \Omega \Sigma}{t_*}\left(1 - R_e\right) \tag{2}$$

If we assume $\dot{\Omega} = 0$ for a stable accretion, and replace the radial velocity V_R from Eqs. (1) and (2), we get,

$$\frac{\partial \Sigma}{\partial t} = -\frac{1}{R}\frac{\partial}{\partial R}\left\{\left[\frac{\partial(R^2\Omega)}{\partial R}\right]^{-1}\frac{\partial}{\partial R}\left(\nu \Sigma R^3 \frac{\partial \Omega}{\partial R}\right)\right\}$$
$$-\frac{\Sigma}{t_*}\left(1 - R_e\right) \tag{3}$$

Where R_e is the mass return of gas through mass loss from stars. In our calculation, we take $R_e \cong 0.3$ (Tinsley 1974), but

we show in Fig. 6 how sensitive the mass ratio limitation is to this fraction. Ω is the angular velocity, and t_* is the star formation time scale. As for the viscosity ν, we will take a new viscosity prescription $\nu = \beta_1 v_\phi r$ (Duschl et al. 1997) for our Keplerian selfgravitating molecular disk. In this case, the accretion time scale $t_{acc} = r^2/\nu = r/\beta_1 v_\phi$ (Pringle 1981).

In our model, we basically assume that t_* is proportional to t_{acc}, i.e. $t_* = \alpha t_{acc} = \beta_2 r/v_\phi$ for the disk evolution stage before merger and also the starburst & AGN stage after a merger. In this case, with a flat rotation law, we get the star formation rate as: $\frac{\partial \Sigma_*}{\partial t} \propto \Sigma \Omega$, which is exactly the observed star formation law for disk galaxies (Dopita et al. 1994). We will show in Fig. 10 that the relationship of these two time scales $t_{acc}/t_* = (\beta 1\beta 2)^{-1}$ is a key parameter for the final mass ratio limitation.

The evolution of the stellar surface density $\partial \Sigma_*/\partial t$ and the central black hole $\partial M_{BH}/\partial t$ are given by the prescriptions as below:

$$\frac{\partial \Sigma_*}{\partial t} = \Sigma/t_* \tag{4}$$

$$\frac{\partial M_{bh}}{\partial t} = -2\pi \beta_1 V_0 \left[2R\Sigma + R^2 \frac{\partial \Sigma}{\partial R}\right]_{R=R_{in}} \tag{5}$$

Where R_{in} is the inner boundary radius of the molecular disk. We basically choose $R_{in} \cong 0.1 pc$ in our calculation, a value which we adopt for the inner edge of the molecular disk (Moran et al. 1995, Barvainis 1995). We will show in Fig. 7 that the final mass ratio limitation weakly depends on this radius. $V_0 = 100 km/s$ is a standard velocity in our calculation, with the relationship $v_\phi \propto V_0$.

The stars are assumed to be on approximately circular orbits and to stay at the radii at which they are formed, so they are effectively frozen out of the viscous evolution. For that gas left still in the disk, it will continue the viscous accretion process.

As for most disk galaxies, their rotation curves are usually quite flat outside the parsec scale, which corresponds well to the region of our interests (Linden et al. 1993, Yoshiaki et al. 1989, de Blok et al. 1996, Genzel et al. 1987, 1994). Our own galaxy shows rather well, that a flat rotation is a fair approximation in the inner region. Also, the recent HST work by Faber et al. (1997) shows that even the general class of "core galaxies" with an inner surface brightness law of a powerlaw in radius with an index 0. to -0.3 still give a rather shallow radius dependence of their circular velocity with $v_\phi \sim r^{0.5..0.35}$, which corresponds to an angular velocity law of $\Omega \sim r^{-0.5..-0.65}$, still far from rigid rotation. The other class of "power law galaxies" all have an inner rotation law which is quite flat. So, we adopt the approximation of a flat rotation curve in our calculation, and solve the Eqs. (3), (4) and (5) by a standard first-order explicit finite difference method.

3. Calculations and discussion

3.1. The numerical scheme and boundary conditions

For computational convenience to solve the partial differential Eq. (3), we introduce here dimensionless variables, $r' = r/r_0$,
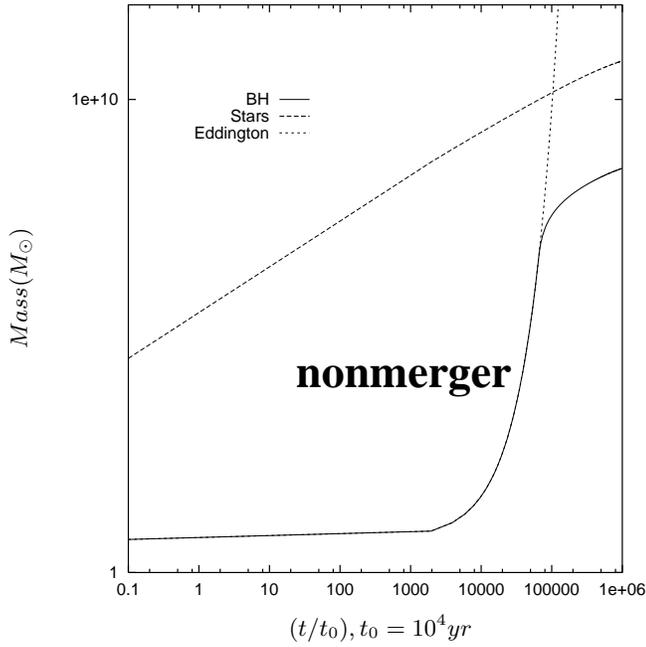
Fig. 1. The temporal evolution of the central black hole mass and the stellar mass in a normal disk galaxy (without any merger). The short dashed curve is the Eddington limitation for the growth of BH. We note that BH growth at the Eddington limit in a log-log plot of mass versus time is exponential.

Fig. 2. The time evolution of the mass ratio ($M_{\mathrm{bh}}/M_{\mathrm{spheroid}}$) in a normal disk galaxy (without any merger), and that with one merger. We note that both cases lead to a very similar final mass ratio.

$t' = t/t_0$, $\Sigma' = \Sigma/\Sigma_0$ with the scale $r_0 = 1\,\mathrm{pc}$, $t_0 \sim 10^4 yr$, the general boundary conditions as $lim_{r \to R_{out}}[\Sigma(r,t)] \longrightarrow 0$, and zero torque at the origin, $lim_{r \to R_{in}}[G(r,t)] = 0$, where R_{out} and R_{in} are the disk's outer radius and inner radius, and the viscous torque G as given by (Pringle 1981).

$$G(r,t) = 2\pi\nu\Sigma R^3 \frac{\partial\Omega}{\partial R}$$

This choice of boundary conditions guarantees zero viscous coupling between the disk and the central object, and so allows all mass reaching that point to flow freely inward. Evidently, the accretion to the central BH is still limited by the Eddington condition.

3.2. Initial conditions

The procedure of our calculation is at first to develop a disk galaxy, and after the merger, to continue the turbulent viscous accretion disk evolution in the newly formed molecular disk. For this purpose, we set up two reasonable initial density distributions for the gas disks before and after a merger. We will discuss these two initial conditions in paragraph 1) and 2) below.

1) The initial gas disk surface density for disk galaxy formation is dependent on the characteristics of the protogalactic halo and on the details of dissipative collapse of the gas to the rotationally supported disk. As for our disk evolution scenario, our disk is basically a Keplerian selfgravitating disk (Duschl et al., 1997), we will just use its stationary solution $\Sigma(R) \propto \sqrt{R_0 - R}/R$ as our initial gas disk surface density
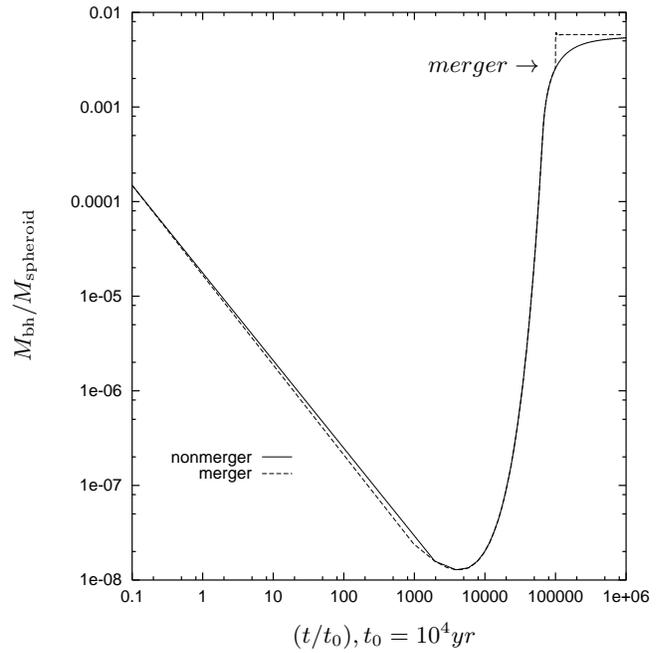
distribution for the disk evolution, where R_0 is the outer radius of our disk $\sim 20\,\mathrm{kpc}$.

2) In our calculation, we will assume the initial gas distribution of the molecular disk assembled after merger to be a power law $\Sigma(R) \propto 1/R$, as a good approximation to the equilibrium distribution of mass with a highly flattened axisymmetric, self-gravitating system (Toomre 1963). This law fits the observation result of the distribution of molecular gas in merger remnants, such as, ARP220 (Scoville et al. 1986), where more than 70% of the CO emission, corresponding to more than $\sim 10^{10}\,M_\odot$, is confined to a galactocentric radius smaller than 1 kpc.

3.3. Numerical calculation and discussion

In our model, we basically consider the case when a merger happens some time after the disk has already been well developed. This does not mean that it is a necessary condition for merger in real life, but it does really exclude the possibility that ellipticals or bulges form through a single collapse of a protogalaxy in high redshift.

In order to understand the merger effects, we first show in Fig. 1 and Fig. 2 (line) a normal disk evolution. We can see in Fig. 1 that after BH evolution starts from a seed BH ($\sim 5\,M_\odot$), it will grow a central BH $\sim 10^8\,M_\odot$ (for a protogalaxy of $10^{11}M_\odot$) after a full Eddington evolution of nearly 10^9 years. Because the gas was almost used up by the BH evolution and the star formation finally, both activities will quiet down, thus the ratio of the BH mass and the stellar mass will slowly approach a constant. We emphasize that no spheroid exists at all during this disk evolution stage.
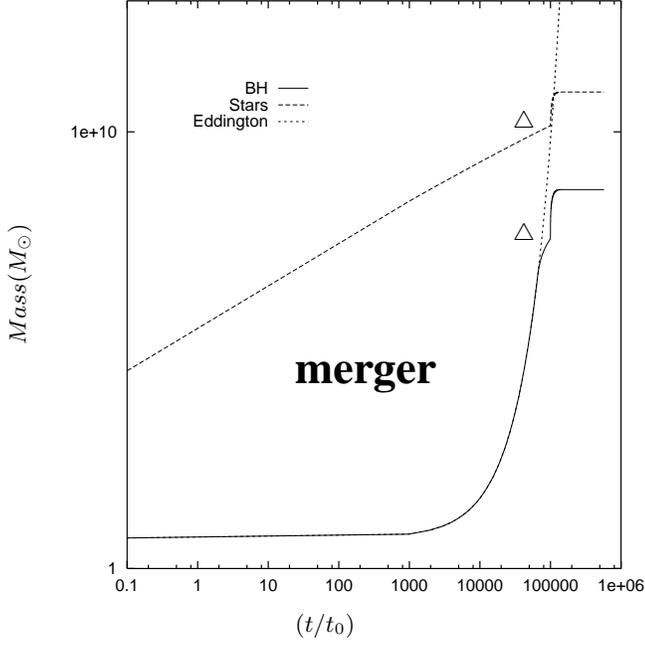
Fig. 3. The time evolution of the black hole mass, spheroidal component mass and the Eddington growth mass limitation with one major merger. The triangles indicate the merger event.
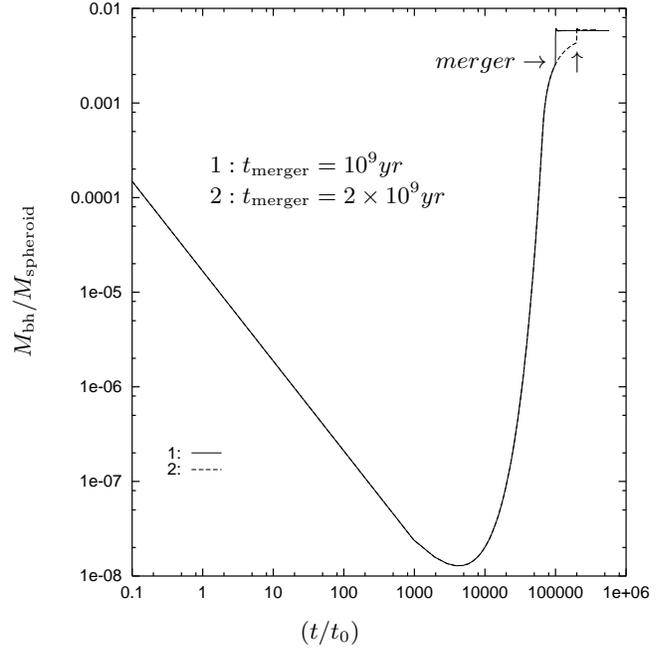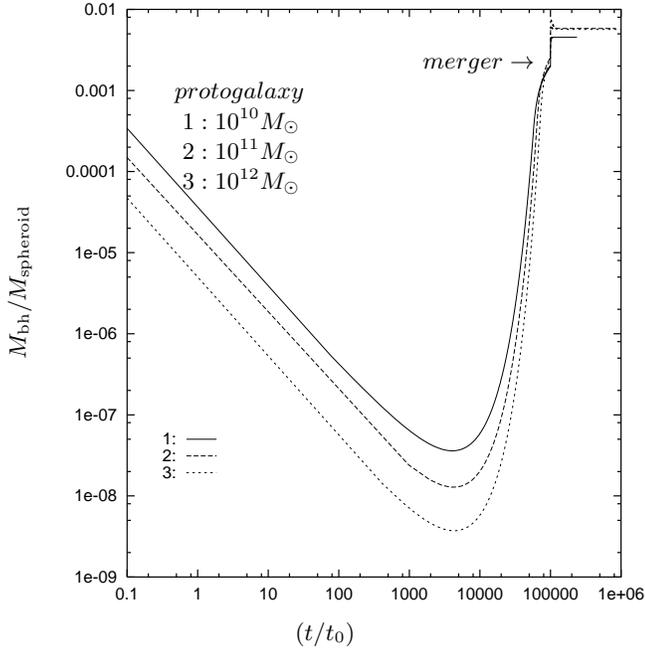

Fig. 4. The time evolution of mass ratio of the central black hole and its host spheroid for the protogalaxy mass ranges from $10^{10} M_\odot$ to $10^{12} M_\odot$. The curves coincide after the merger, and converge to the almost same mass ratio ~ 0.006.

According to our model, at a certain time after the disk evolution quiets down, if a violent merger happens between two well developed disk galaxies, it will smash the original stellar disks completely and form the spheroid of a new early type galaxy. Meanwhile, the merger can cause a severe perturbation

Fig. 5. The time evolution of the mass ratio ($M_{\rm bh}/M_{\rm spheroid}$) when the merger happens in different times.

in the central region and drive the gas inwards to concentrate in the central kiloparsec (Barnes 1992, Casoli et al. 1988). We simulate this effect by redistributing a certain amount of cool gas to that region, setting up a molecular disk, triggering a starburst and nuclear activity there. In the real universe, the violence of the merger to form an elliptical/bulge can have a variety of properties. So, the amount of gas redistributed in the center by the merger effect can be different also. In our simulation, we therefore redistribute the same amount of cool gas as the host galaxy's in its central region, to simulate the effect of a major merger between two disk galaxies with comparable mass, and half the amount of cool gas for the case of a minor merger. We find from our calculation that the amount of gas mass redistributed to the central region has no influence on the mass ratio limitation, but it does affect the final black hole mass.

We show in Fig. 2 (dashed line) and Fig. 3 the evolution of the mass ratio ($M_{\rm bh}/M_{\rm spheroid}$), BH mass and the stellar component mass for the case when a major merger happens near 10^9yr. We can see that black hole grows in full Eddington evolution at the beginning, until some time later, the gas in the disk is drained off by star formation and BH evolution, both activities quiet down, thus constrain the mass ratio firstly around a limited value of ~ 0.006. If a merger happens afterwards, it can reawaken these two activities, with the appearance of a starburst and central AGN. The extreme starburst and BH growth last only for a short time, then the gas in the central region will be used up by these two activities, or some of it is blown away by the wind; till this stage, we see the normal ellipticals/bulges with the mass ratio limited. From Fig. 2 and Fig. 3, we see that a merger dramatically shortens the convergence time scale and grows a massive BH in the center quickly.
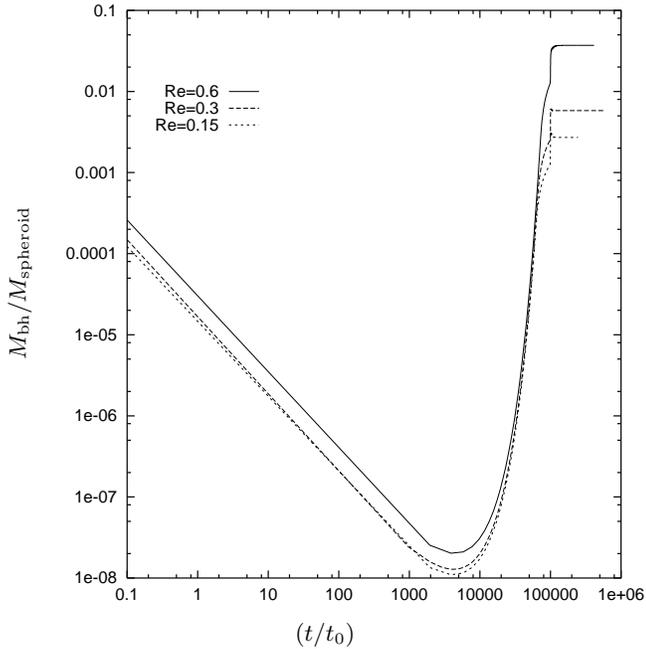
Fig. 6. The time evolution of the mass ratio of the central black hole and its host spheroid for the mass return rate $R_e = 0.6, 0.3, 0.15$. A standard value for this parameter is 0.3 (Tinsley 1974), but various common IMFs can give other values. Varying this parameter by a substantial factor does influence the resulting mass ratio $M_{bh}/M_{spheroid}$. It appears as if this final ratio depends on R_e approximately as $(1 - R_e)^{-3.4}$. This means that our results depend on the assumption that the universal spread of this parameter is less than about two.

In our model, the prescriptions of the star formation time scale and the accretion time scale are $t_* = \beta_2 r/v_\phi$, and $t_{acc} = r/\beta_1 v_\phi$. Considering a reasonable accretion time scale ($10^9 \sim 10^{10} yr$) and the star formation rate for a normal galaxy (Dalcanton et al. 1997), we choose $\beta_1 = 0.005, \beta_2 = 200$ for the normal disk evolution phase. We simulate the starburst and central engine activity by taking $\beta_1 = 0.5, \beta_2 = 2$, thus shorten both time scales by a factor of 100. So it will dramatically increase the star formation rate to nearly two orders of magnitude in ultraluminous starburst galaxies; it also fits the starburst time scale about $10^7 \sim 10^8 yr$ (Rieke et al. 1980, Kronberg et al. 1985, Mihos & Hernquist 1994, Smith et al. 1996). We will show in Fig. 9 and Fig. 10 that the mass ratio is not very sensitive to the exact number of β_1 and β_2, but clearly sensitive to their correlation. We will discuss this in detail below.

We show the mass ratio evolution in Fig. 4, for the case that protogalaxy mass ranges from $\sim 10^{10} M_\odot$ to $\sim 10^{12} M_\odot$; and in Fig. 5, the case when merger happens at a different time after the disk quiets down. We see from our results that the final mass ratio limitation does not depend on these two parameters.

In our calculation, we basically choose the star formation mass return rate $R_e = 0.3$ (Tinsley 1974), and the inner radius for the molecular disk $R_{in} = 0.1 pc$ (Moran et al. 1995, Barvainis 1995). In Fig. 6 and Fig. 7, we see that the mass ratio limitation will vary moderately if we vary R_e by a factor of two and R_{in} by a factor of 12.
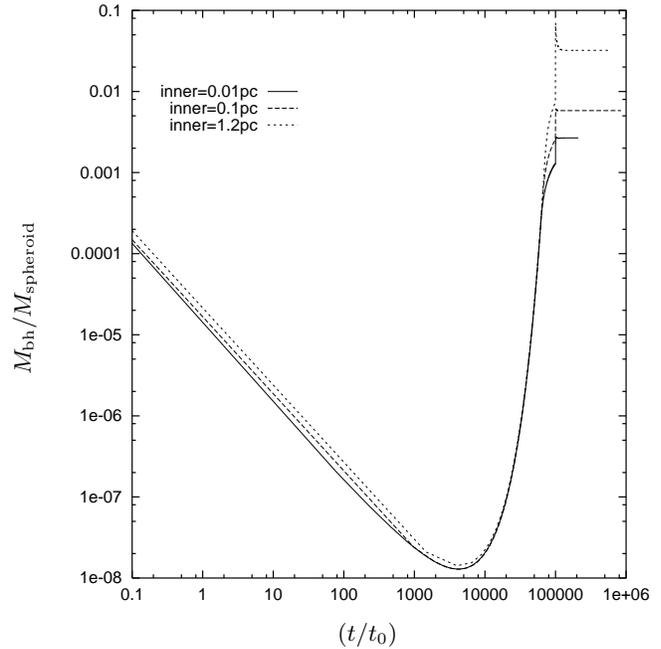
Fig. 7. The time evolution of mass ratio of central black hole and its host spheroid when the inner boundary radius of the molecular disk shifts with a factor of 12, i.e. $R_{in} = 0.1pc, 1.2pc$. We see in the graph that the mass ratio converges to a constant quickly after the merger. The final ratio $M_{bh}/M_{spheroid}$ varies by a factor of 5 for the variation of R_{in} by a factor of 12. This shows a soft dependence.

From our calculation, we see that the mass ratio of the central black hole and its host spheroid is very sensitive to the ratio of the starburst time scale and the turbulent accretion time scale after a merger (see Fig. 10). The mass ratio converges to the value ~ 0.006 only when the turbulent accretion time scale approximately equals the starburst time scale (i.e. $\beta_1 * \beta_2 \cong 1$). This probably hints at a physical reality, which is, a merger will drive a large amount of cold gas inwards to the central region, the increased molecular cloud collisions can trigger a starburst in the central region, the kinetic energy output from these young massive stars and the shocks from supernovae will heat and disturb the ISM locally, thus probably induce turbulent viscous accretion to feed both the AGN and starburst in the central region. These two activities, starburst and central AGN, will interact with each other, feedback, drain the gas in the molecular disk in a short time, thus grow a massive BH quickly there. To some degree, it probably can start a strong wind from the center, blow off the leftover gas in the disk, stop the starburst and the accretion process in the central region. It seems that this evolution scenario can help to explain the observed limited mass ratio region ~ 0.002 within a factor of three. In order to see the sensitivity of this mass ratio limitation to the equal time scale assumption, we show the results in Fig. 10 for different ratios of the starburst time scale and the turbulent accretion time scale; we can see the dramatic divergence of the mass ratio when $t_{acc}/t_* = 0.1, 1, 10$.

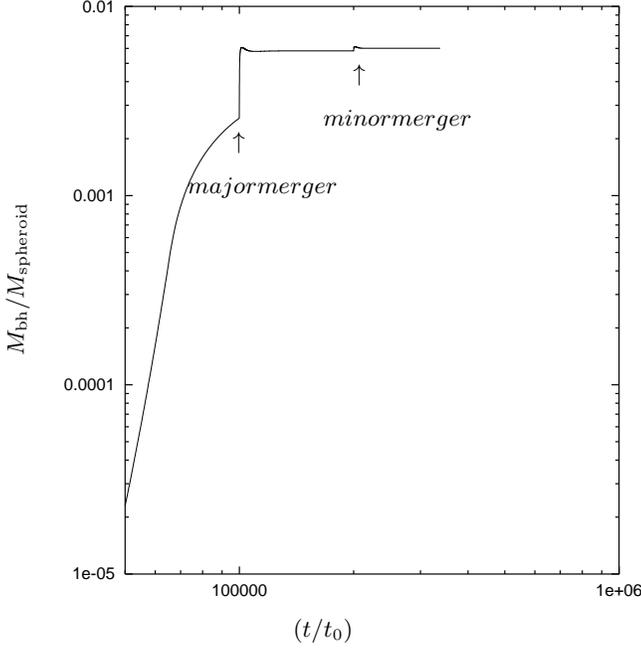All we discussed above is the case where only one major merger happens between two disk galaxies to form an elliptical

Fig. 8. The time evolution of the mass ratio of the central black hole and its host spheroid with one major merger and another minor merger.
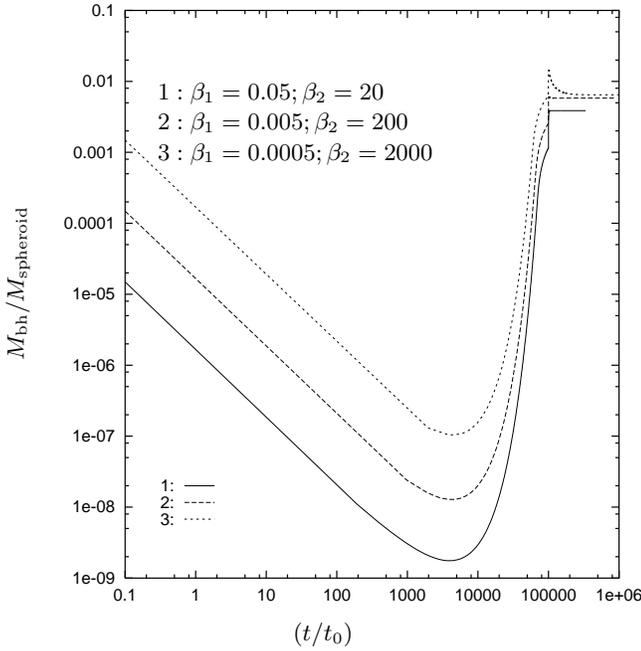

Fig. 9. The time evolution of the mass ratio of the central black hole and its host spheroid when the parameters β_1, β_2 vary with a factor of 10. We see in the graph that the final mass ratio limitation does not strongly depend on the exact value of these parameters, as long as $\beta_1 * \beta_2 \cong 1$.

Fig. 10. The time evolution of the mass ratio of the central black hole and its host spheroid with different correlation between starburst time scale and the turbulent accretion time scale. We calculate the cases: $t_{acc}/t_* = 0.1, 1, 10$. We see that the variation of the final value $M_{bh}/M_{spheroid}$ is almost a factor of 10^4 for a variation of time scale ratio by a factor of 10^2. This shows that the correlation between these two time scales deeply dominates the final mass ratio limitation. It seems also that the mass ratio can finally converge to a limited region ~ 0.006 only when the starburst time scale and the turbulent accretion time scale are almost equal.

is followed by another minor merger. We show our result in Fig. 8, and it seems that the multimerger will not change this universal ratio.

4. Summary

In this paper, we presented an *ab initio* model of formation and evolution of early-type galaxies by combination of the viscous accretion disk model, the star formation and nuclear activity within the hierarchical galaxy formation scheme.

The basic ideas are:

1) An elliptical/bulge is formed by the merger of two disk galaxies in a hierarchical universe.

2) Star formation and AGN evolution coexist in the disk evolution stage (pre-merger) and also post-merger stage. They compete for the gas supply and interact with each other.

3) The violent interaction between two disk galaxies by a merger can not only form the spheroidal component of the elliptical or bulge, but also drive the cool outer gas to the center, trigger a starburst and a central AGN there. The merger triggered starburst probably can stir up a turbulent accretion to feed both the starburst and AGN in the center. These two activities interact with each other, feedback, thus speed up the BH growth,

or the bulge of a spiral. In a real hierarchical universe, multiple minor mergers would also probably occur after the major merger. These could bring in more cool gas to the central region and start another evolution cycle. In order to imitate our universe closely, we also calculated the case that one major merger
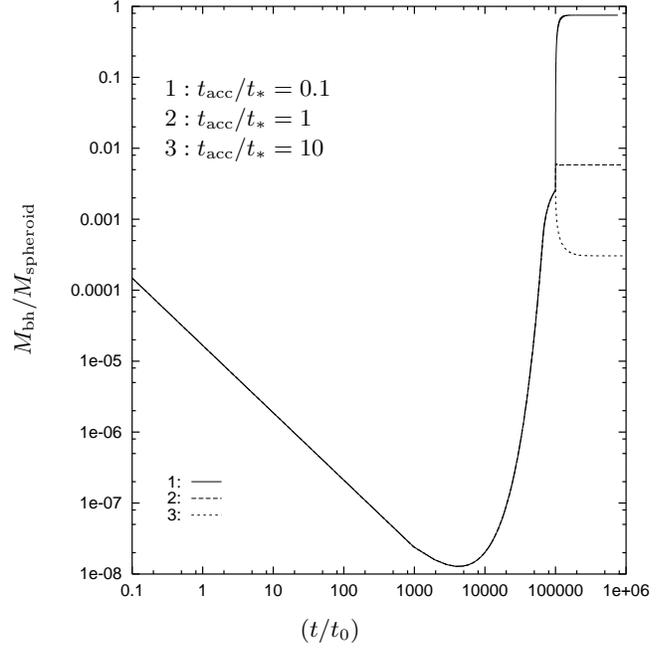
drain the gas in the molecular disk quickly and constrain the final mass ratio $M_{bh}/M_{spheroid} \sim 10^{-3}$.

From our calculation, we found:

1) Mergers can help to grow a massive BH in a very short time, and shorten the convergence time for the mass ratio $(M_{bh}/M_{spheroid})$ to a limited region.

2) The final mass ratio limitation does not depend on the mass of the protogalaxy.

3) The exact time, when the merger happens after the disk evolution quiets down, will not influence the mass ratio limitation.

4) Whether the ellipticals/bulges are formed by the major mergers or minor mergers between two disk galaxies, or by multimergers is not very critical for our final result.

5) The final mass ratio limitation does depend moderately on the inner radius of the molecular disk R_{in}, and the mass return rate R_e from star formation.

6) The exact number of the parameters β_1, β_2 for the star formation and accretion time scale has no influence on the final mass ratio limitation, but it is obvious that the correlation of these two time scales (or β_1, β_2) is very critical to the final mass ratio limitation. It seems that the mass ratio $(M_{bh}/M_{spheroid})$ can finally converge to a limited region near 0.006 only when the starburst time scale and the turbulent accretion time scale can be approximately equal.

The conclusion 6) probably indicates a physical relationship between starburst and central AGN as we discussed already in the previous section. In the hierarchical universe, mergers will destroy the quiescent disk galaxies, transfer the stars in the disks completely to form a spheroidal component. At the same time, it will also drive a large amount of gas into the central region and trigger a starburst. The kinetic energy input to the ISM from the young massive stars and supernovae can heat and shock the ISM, and probably induce turbulent viscous accretion there. This turbulent viscous accretion can feed both the starburst and central AGN, and grow a massive BH very quickly. The two activities, starburst and central AGN can drain the gas in the disk in a very short time, and also when the power of the central engine reaches some degree, it probably can start a wind and help the starburst to blow out the hot gas completely out of the disk, thus stop the accretion and star formation there.

In this paper, we did not include the kinetic energy term in our viscosity directly, but from this simple model and calculation, it seems that the feedback relationship between the starburst and central engine can be a very interesting physical process. To do this, we need more elaborated physical models and more numerical work.

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