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Evolution of Galaxies in Clusters

Yoko Funato

General Systems Studies, Graduate Division of International and Interdisciplinary Studies, University of Tokyo, Komaba, Meguro-ku, Tokyo, 153, Japan

Abstract. In this paper I show recent results of our studies on the evolution of an isolated cluster of galaxies using N-body simulations. In Sensui, Funato & Makino (1999) only one initial cluster model are investigated. In the present study, we varied the initial model of galaxies and clusters, and studied the dependence of evolution on initial conditions. We found that the mass of galactic halos are stripped and a common halo develops for any cluster models. Using result of scattering experiments of two halo-halo encounters, we show that the growth rate of the common halo (and complimentarily decrease rate of average mass of galactic halos) can be explained as a result of stripping due to cumulative encounters between two galactic halos.

We also found that the galaxies evolved so as to satisfy the relation between the masses of galaxies $m_{\rm gx}$ and their velocity dispersion $\sigma_{\rm gx}$ expressed as $m_{\rm gx} \propto \sigma_{\rm gx}^{3\sim4}$ for all galaxy models as a consequence of their dynamical evolution through galaxy–galaxy interactions. We discuss the relation between our result and the observed Faber–Jackson relation.

1. Introduction

In recent years, observations of structures of galaxies in clusters at high-z ($z \sim 1$) have become possible due to the advances in telescopes, related instruments and methods of analysis. Such observations of high-z clusters allow us to study the evolution of clusters and galaxies in clusters by comparing high- and low-z clusters. Using an I-band magnitude-selected sample of 81 confirmed cluster members covered by HST WFPC2, (van Dokkum, et al. 1999) reported that the fraction of mergers in clusters is high in high-z region and the fraction drops quickly in low-z clusters. In the field, merger fraction seems to drop more slowly than that in clusters. Their result suggests that mergings of galaxies take place mainly in the formation epoch of a cluster. After the cluster virialized, or, in the region where the galaxies have virialized, mergings of galaxies become rare.

However, merging is not the only way for galaxies in clusters to evolve. Ellipticals and S0 galaxies are much more abundant in clusters than those in the field. They are more abundant in clusters in low-z than in high-z (e.g., Couch, et al. 1998) and, especially, in central high density regions in such clusters (density-morphology relation, Dressler, 1980). These observations suggest that galaxies dynamically evolve after their parent cluster virialized.

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Dynamical evolution in cluster environment is, however, more complex than that appearing in formation epoch of the cluster. In a cluster environment, even from the point of view of dynamics, there are many processes, such as mass stripping, merging, dynamical friction, tidal disruption due to the mean field of the parent clusters and so on, take place. And there are only a few studies on each subject yet, though they should be investigated. For example overmerging problem may be solved by taking the dynamical evolution after formation of a cluster into account, since there are several process which can reduce mass and number of galaxies.

In this paper, we show the result of our study on how clusters of galaxies and their member galaxies evolve themselves after the formation of clusters. We performed N-body simulations of interaction between halos and dynamical evolution of isolated model clusters.

In our study we set the initial condition of cluster models so that the effect of galaxy–galaxy interaction is clearly visible since interactions seem to be the dominant mechanism for the dynamical evolution of clusters of galaxies.

We also performed systematic numerical experiments of encounters of two halo models in order to clarify the effect of encounters between halos quantitatively. Combining these results, we obtained quantitative understanding on how the mass of galaxies, and the structure of individual galaxies and that of a cluster, evolve.

2. Encounters of Two Halos

2.1. Numerical Simulations

An encounter of two halos is the elementary process of evolution cluster of galaxies. We carried out numerical experiments of hyperbolic encounters of two dark halos (spherical, pure N-body, collisionless) with unequal masses. This study the generalization of the study by Funato and Makino 1999, which is done for identical two halos.

Outcome We observed the changes in mass m and energy e of each halo after an encounter. The relative change of mass of each galaxy per one collision $|\Delta m/m|$ and that of energy is $|\Delta e/e|$ are expressed as functions of collision distance p, and velocity V and the mass ratio $m_{\rm cp}/m$. Here m_1 and m_2 corresponds to the mass of the observed halo and that of counterpart.

Models We adopted a Hernquist model as a halo model. In one hyperbolic encounter both two halos are modeled on Hernquist models. Both of them have similar density profiles but have different mass and radius.

The mass of the smallest halo is set to be 1. Here we uses a standard unit in which the gravitational constant G is 1, the binding energy and one dynamical time of the halo with mass 1 is 0.25 and 2 (Heggie and Matieu, 1984).

For the N-body realization of a Hernquist model we introduced a cut-off radius $r_{\rm cut}$. The cut-off radius $r_{\rm cut}$ is also scaled as the half-mass radius is scaled.

The number of particles is 4096 for the smallest halo. The number of particles in one halo is in proportion to the mass, *i.e.*, 8192 for the halo with mass $m = 2$, 16384 for the halo with mass $m = 4$, and so on.

Parameters of Encounter Orbit Orbits of hyperbolic encounters of two bodies are expressed by using two parameters. There are a few possibilities about choosing a pair of two parameters : the impact parameter and the velocity at infinity, or specific orbital energy and angular momentum or the orbital energy and angular momentum for the reduced mass, and so on. Anyway these pairs are equivalent with each other and conversion between them is straightforward.

We adopt relative distance and velocity at pericenter of two halos as orbit parameters. We set the initial position and velocity of each halo on the orbit having the the given distance and velocity at pericenter. Both of the ranges of distance p and relative velocity V are ten times larger of the size of smaller halo.

Initially the distance of two halos is which are more than twenty times of the smaller halo. It means that the distance is more than five times larger than the larger one and more than two times larger than the cut-off radius of both two halos.

The ranges of parameters are summarized as follows. Figure 1 is a sample of snapshots of an encounter. (1)impact parameter : p. $1 \leq \frac{p}{r_h} \leq 10$. (2) collision velocity : V. $2 \leq \frac{V}{\sigma} \leq 10$. (3) mass of counter part dark halos : m_{cp} $1 \leq \frac{m_{cp}}{m} \leq 8$. Since we are interested in stripping of masses of galaxies, our experiment covers non-merging region in the parameter space.

Strictly speaking, unlike encounters of two point masses, orbits of encounters of two N-body systems the problem cannot be expressed by only two parameters, since the encounter is inelastic. During encounters the orbital energy is no longer conserved. The orbital energy is transformed into the energy of inner energy of each halo. Therefore the orbit becomes different from that the point mass follows.

How the orbital energy will be transformed into the inner energy depends on the inner structure of each galaxy. It is, therefore, not clear what should be the most appropriate parameters in order to express the orbit of two halos.

When we investigate the merging criterion, we have to be careful about this point. During the encounter which will result in merging is, the energy exchange between orbital and inner energy are as high as the initial inner energies.

However energy change between inner and bulk energy is not so large in the case of a hyperbolic encounter.

Therefore, the conversion between distance and velocity at pericenter and that at infinity assuming that they are point-masses provides a good approximation.

2.2. Cluster simulations

Evolution of virialized cluster models are simulated.

Initial Condition and Models The initial conditions are summarized as follows (as for detail, see Sensui *et al.*2000). (i)There are 128 galaxies (dark halos) in 1 cluster. (ii)The mass of each galaxy m is set to be 1, and the total mass of the cluster M is 128: $M/m = 128$. (iii) The half-mass radius of each galaxy r_h is about 1, and that of the cluster is $20r$: $R/r = 20$. (iv) The velocity dispersions of each galaxy σ is $1/sqrt(2)$. Since both each galaxy and the cluster are in virial equilibrium, the ratio of velocity dispersion is $v/\sigma = 2.5$, for the case in which all mass is initially bound to galaxies. (v) We adopted a Plummer model

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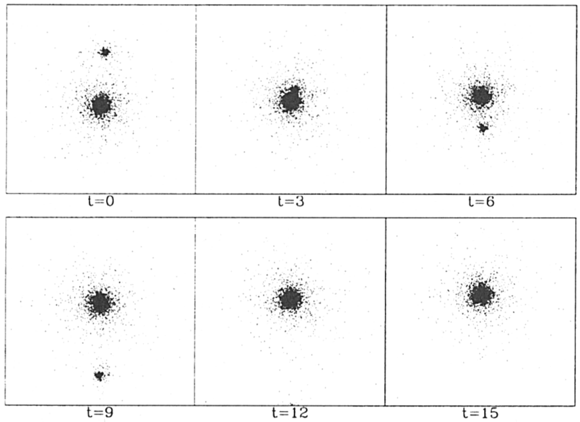

Figure 1. Snapshots of encounter of two halos

and several King models as cluster models. (vi) We adopted a Plummer model, a Hernquist model, and several King models as galaxy models.

Snapshots In Figure 2 a sample of snapshots of evolution is shown. In this figure, the figures in the left column show the distribution of particles bound to galaxies, while those in the right column show the particles which have escaped from galaxies to intracluster space. This figure shows that many particles escape from galaxy into a intracluster space to form a common halo.

3. Result

3.1. Mass Evolution through One Encounter of Two Halos

In order to see the result quickly, we show Figure 3, in which the relative mass change $|\Delta m/m|$ for various orbital parameters is plotted against mass ratio $m/m_{\rm cp}$. The line in each panel corresponds to $|\Delta m| \propto (\frac{m_{\rm cp}}{m})^1$.

In Figure 3, top panel shows the results in which the collision velocity V is fixed at $V/\sigma = 4$. Different curves correspond to the different collision distance p, which is changing for the range $p/r_{\rm g} = 2, 4, 6, 8$.

This figure shows that the dependence of relative mass change on the mass ratio is expressed as $\Delta m = \kappa(m_{\rm c}/m)^1$, where κ depends on the collision distance, however, the power index of $m_{\rm c}/m$ is 1 and it is independent of collision distance.

The middle and bottom panels of Figure 3 are the same as top one but for $V/\sigma = 8$ and for $V/\sigma = 10$, respectively.

These figures show that the relative mass change is expressed as $\Delta m = \kappa(m_{\rm c}/m)^1$, where κ depends on collision distances, while the power is independent of collision distance for these two collision velocities, too.

Comparison of these figures tells that κ depends on collision distances and velocities, while the power of the dependence on mass ratio is 1 independent of

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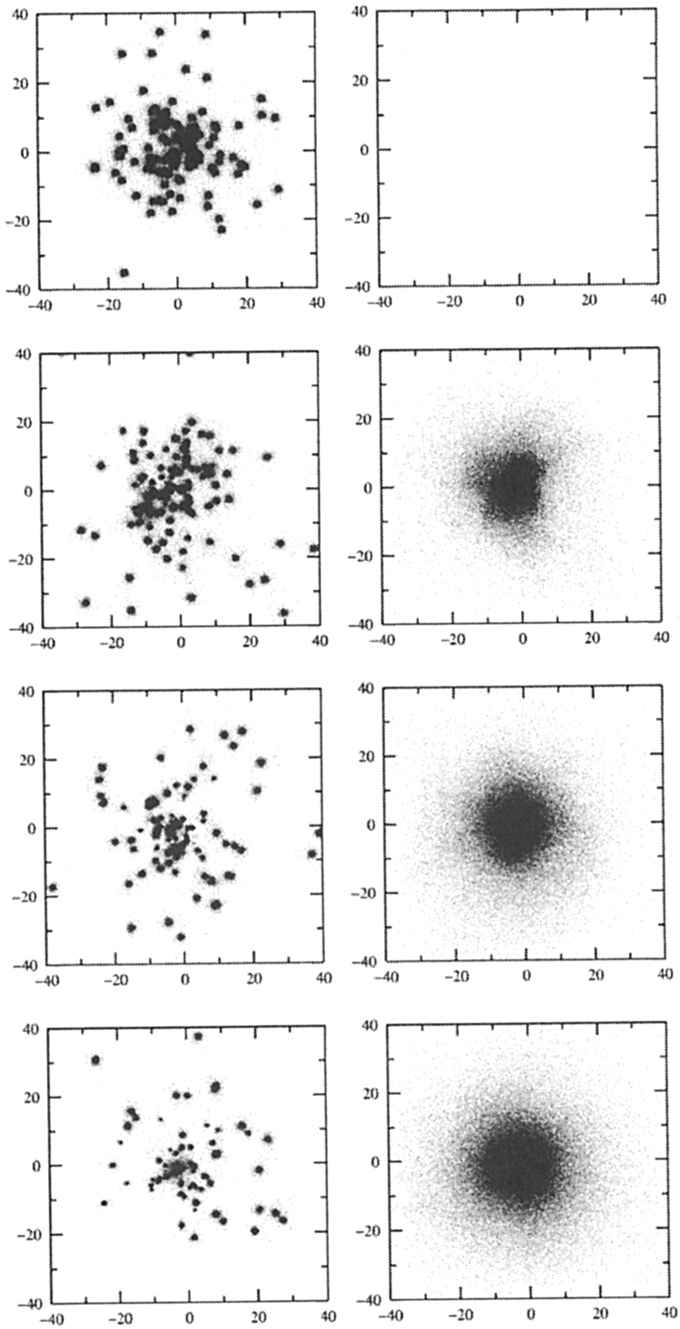

Figure 2. Snapshots of evolution of a cluster of galaxies

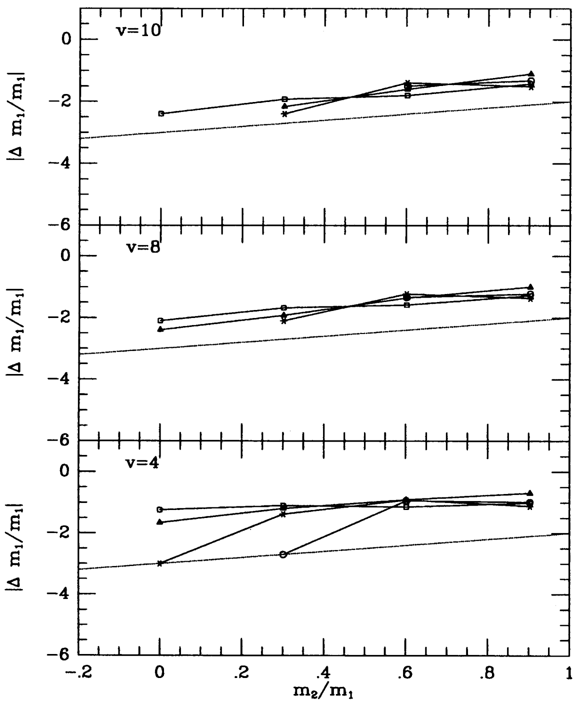

Figure 3. Relative mass change through on encounter. Horizontal axis corresponds to mass ratio of the counterpart halo.

collision distance for these two collision velocities. Therefore the relative mass change is expressed as

$$\Delta m \quad = \quad k\left(\frac{m_{\rm cp}}{m}\right)^{a}\left(\frac{p}{r_{\rm g}}\right)^{b}\left(\frac{V}{\sigma_{\rm g}}\right)^{c}, \qquad (1)$$

where κ is a coefficient, m , $r_{\rm g}$ and $\sigma_{\rm g}$ are the mass, radius and velocity dispersion of the halo, and $m_{\rm cp}$ is the mass of the counter part halo, respectively.

Using result of our numerical experiments (present and FM99), we determined (a, b, c) as $(a, b, c) = (1, -2, -3)$.

4. Evolution of Galaxies in Cluster Environment

Theoretical Estimate of Mass Evolution This estimate is the generalization of the theory shown in Funato (2001, hereafter F01), in which only encounters of equal mass halos are considered.

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As a result of numerical experiments of encounters of two dark halos, we obtain the following relation for the change of mass per one collision:

$$\frac{\Delta m}{m} = k\left(\frac{m_{\rm cp}}{m}\right)^{1}\left(\frac{p}{r_{\rm g}}\right)^{-2}\left(\frac{V}{\sigma_{\rm g}}\right)^{-3} \tag{2}$$

Using equation (1), we can estimate mass loss from galaxies per unit time of the cluster $T_{\rm cr}$ as follows.

$$\frac{dm_{\rm g}}{dt} = \kappa m_{\rm g}\int_{m_{\rm min}}^{m_{\rm max}} m_{\rm cp}\phi(m_{\rm cp})\int V^2 dV\int pdp\cdot Vf(V)\cdot\Delta m_{\rm g}. \tag{3}$$

Here $\phi(m)$ is the mass function of halos and κ is the normalization factor of the halo counts. The cross section is estimated by using $f(V)$, which is assumed to be an isotropic Maxwellian distribution with mean velocity $V_{\rm c}$.

When the dependence of mass change Δm on the mass ratio is $\propto m_{\rm cp}/m$, it is easily found that the result of integration respect to $m_{\rm cp}$ in equation (3) does not depend on mass function $\phi(m)$. For any mass function, integration respect to the mass of counter part $m_{\rm cp}$ gives

$$\frac{dm_{\rm g}}{dt} = nm_{\rm g}\int V^2 dV\int pdp\cdot n\cdot Vf(V)\cdot\Delta m_{\rm g}, \tag{4}$$

where n is the number density of halos, $m_{\rm g}$ is the total mass in the cluster bound to galaxies. Equation (4) is the same as that in F00, which is derived under a condition that all halos have same masses.

After integrating respect to the impact parameters and velocities as in F00 and integrating respect to time, we obtain the average mass decrease of galaxy is as follows.

$$m_{\rm g}(t) = m_{\rm g0}\left[1+m_{\rm g0}^{\frac{7}{4}}At\right]^{\frac{4}{7}}, \tag{5}$$

$$M_{\rm ch}(t) = Nm_{\rm g0}\left(1-\left[1+m_{\rm g0}^{\frac{7}{4}}At\right]^{\frac{4}{7}}\right), \tag{6}$$

where A is a constant coefficient.

Comparison with result of N-body simulations Equation (5) shows the decrease of average mass of galactic halos. The horizontal and vertical axes correspond to time and average mass of one galactic halo, respectively. The solid curve corresponds to theoretical estimates and the dashed and dotted curves do to results of N-body simulations. The dashed curve shows the evolution of mass averaged over all halos initially existing, including disrupted halos (*i.e.* including halos with $m_{\rm g} = 0$). The dotted curve shows that averaged over surviving halos (*i.e.*, averaged excluding disrupted halos with $m_{\rm g} = 0$). Equation (6) shows the increase of mass of common halo. In Figure 4(b) the total mass of common halo is plotted against time t. Solid and dashed curves correspond to the theoretical estimates according to equation (6) and result of N-body simulation, respectively. Here the coefficient A is determined in order to match

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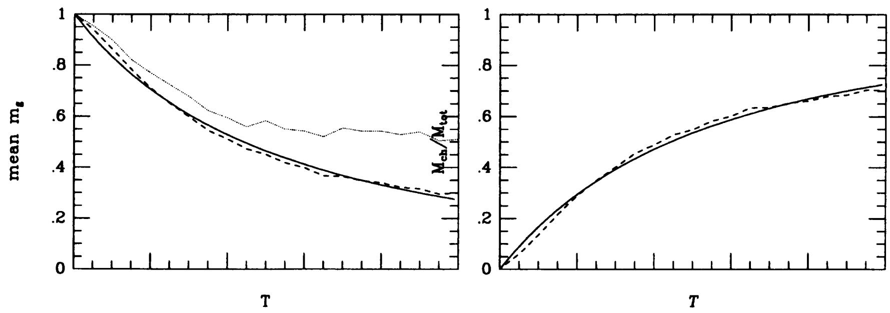

(a) (b)

Figure 4. Mass evolution of individual halos (a) and common halo (b).

the former to the latter. Figure 4(b) shows that the increase of the mass of common halo of N-body simulation agrees excellently with that of theoretical estimates.

Figure 4(a) shows that the decrease of the average mass of surviving galactic halos of N-body simulation agrees well with that of theoretical estimates, too, except for the latest phase.

In relatively the latest phase, there is a little difference between decrease of mass of surviving halos in numerical simulation and that of theoretical estimates. The difference is caused by the complete disruption of galactic halos. In other words, the number evolution of halos (*i.e.*, $N(t)$). Since the difference is as small as the fluctuation due to the number of $N(t)$, the prediction of present status according to equation (6) is appropriate. As cluster evolves, the difference may become larger. As a result the trend might be different and the interpretation and prediction for future behavior may require more careful estimates/study.

Comparison with result of Fokker-Planck simulations A numerical study using Fokker-Planck simulation of evolution of an isolated cluster of galaxies is done by Takahashi, *et al.*(2001a, 2001b). In their study, Takahashi developed a Fokker-Planck method including the effect of inelastic collision between two halos. Their result is in good agreement of those of our N-body simulations. This agreement also implies that the evolution of our model cluster is driven by interaction between two halos.

5. Structure of Individual Halos and Galaxies

5.1. Velocity Dispersion versus Mass of Halo

Relation between mass and velocity dispersion of galaxies after $4.5T_{\rm cr}$ in our N-body simulation is shown in Fig 5.

In figure 5(a), the velocity dispersions of galaxies at $t = 4.5\,T_{\rm cr}$ are plotted against their masses for three different runs. In these runs all of initial galactic halo models are Plummer models but the initial cluster models are a Plummer (run-name is denoted as "PP"), King 7 ("PK7") and Hernquist models ("PH"),

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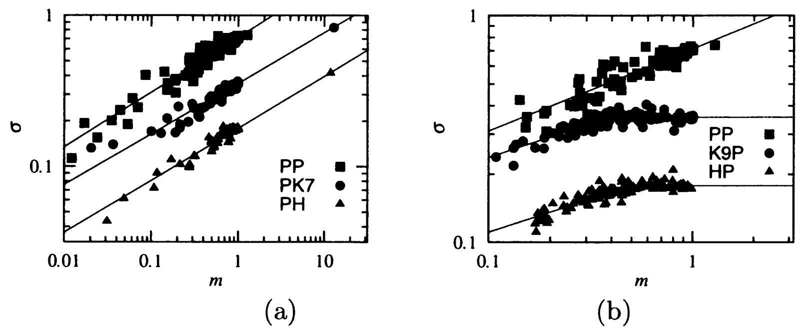

Figure 5. mass - σ relation of galactic halos after several crossing times

respectively. The velocity dispersions for galaxies are shifted downwards by a factor of two for the run PK7 and by a factor of four for the run PH to make it easy to distinguish them from those of the run PP. Figure 5(a) shows that the m–σ relation does not depend on the initial cluster model and that the galaxies in a cluster evolve along a line $\sigma \propto m^{1/3\sim 1/4}$.

Figure 5(b) is same as figure 5(a) but for other three runs. In this Figure, symbols correspond to 3 different initial galactic halo models. Squares correspond to run PP. Circles do to the runs in which the initial galactic halo model is King 9 model and the parent cluster is Plummer model (denoted as "K9P"). Triangles do to those in which the initial galactic halo is a Hernquist model and the parent cluster is Plummer model (denoted as "HP").

It is remarkable that for runs K9P and HP, the velocity dispersions were almost constant for the galaxies with $m \leq 0.4$ (K9P) or $m \leq 0.5$ (HP), and for those smaller than those conditions, they are distributed along the lines $\sigma \propto m^{1/3\sim 1/4}$.

This sharp contrast among different runs is to be understood when we take account of the difference in central concentration of initial halo models.

A King 9 model, which is more centrally concentrated than a Plummer model, has an extended halo, in which binding energy of many particles is near zero. Such high energy particles easily escape without heating process of inner particles: After around 50% of its mass is removed, even a King 9 model galaxy no longer has an extended halo. Thus, further removal of its mass is associated with the net heating, resulting in the decrease in the velocity dispersion.

According to the above argument, the Hernquist model should behave similarly to the King 9 model, since it also has an extended halo. In fact, as we can see from figure 5(b), their evolution tracks are very similar.

To summarize, no matter what is the initial profile of the galaxies, their dynamical evolution driven by the encounters with other galaxies follows the direction $\sigma \propto m^{1/3\sim 1/4}$, at least after a significant fraction of the initial mass has been removed from them.

Note that this evolutionary track is consistent with the observed Faber–Jackson relation (Faber & Jackson, 1976, hereafter FJ relation) between the luminosity L and velocity dispersion σ of cluster ellipticals. The FJ relation is

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expressed as $L \propto \sigma^4$. We need to assume that M/L is constant to relate our numerical result on the relation between the mass and the velocity dispersion.

This might sound unreasonable, since the outskirts of the galaxy must be dominated by the dark matter. However, as we have seen in figure 5, while the mass in the outskirts is removed, the velocity dispersion remain almost constant. Therefore, we can conclude that the dynamical evolution of galaxies through encounters is qualitatively consistent with the observed FJ relation. More quantitative discussion is given in Sensui et al. (2000).

6. Summary

The decrease of the average mass of halos is approximated as

$$m_g(t) = m_{g0}\left[1 + m_{g0}^{\frac{7}{4}} A t\right]^{\frac{4}{7}},$$

where A is a constant coefficient. This result indicates that more than half ($\sim 80\%$) of the mass of the cluster is in the intracluster space.

Between mass of galactic dark halos and velocities the relation $m \propto \sigma^4$ will be developed after more than half of mass is stripped from individual halos. Our result suggest that galaxies, each of which is enbeded in a halo, will distribute around the relation $L \propto \sigma^4$.

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