MERGING HISTORY AS A FUNCTION OF HALO ENVIRONMENT

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ABSTRACT

According to the hierarchical scenario, galaxies form via merging and accretion of small objects. Using N-body simulations, we study the frequency of merging events in the history of the halos. We find that at \( z \lesssim 2 \) the merging rate of the overall halo population can be described by a simple power law \((1 + z)^3\). The main emphasis of the paper is on the effects of environment of halos at the present epoch \((z = 0)\). We find that the halos located inside clusters have formed earlier \((\Delta z \approx 1)\) than isolated halos of the same mass. At low redshifts \((z < 1)\), the merger rate of cluster halos is \(3\) times lower than that of isolated halos and \(2\) times lower than merger rate of halos that end up in groups by \(z = 0\). At higher redshifts \((z \sim 1 - 4)\), progenitors of cluster and group halos have \(3-5\) times higher merger rates than isolated halos. We briefly discuss implications of our results for galaxy evolution in different environments.

1. INTRODUCTION

A significant fraction of mass in the universe is believed to be in the form of dark matter (DM). According to the standard theoretical paradigm of structure formation, small-mass DM perturbations collapse first and the resulting objects then merge to form increasingly larger DM halos. Baryonic matter (gas) is assumed to follow the gravitationally dominant dark matter. Galaxies, thus, could have been formed within dense DM halos when the infalling gas reaches sufficiently high overdensities to cool, condense, and form stars. The most convincing observational evidence for substantial amounts of dark matter even in the very inner regions of galaxies comes from HI studies of dwarf and low surface brightness galaxies. The gravitational domination of DM on the scale of galaxy virial radius implies that collisionless simulations can be used to study the formation of the DM component of galaxies.

Interactions between halos, such as mergers, collisions, and tidal stripping, are thought to play a crucial role in the evolution of galaxies. In particular, there is a substantial evidence that elliptical galaxies may have formed by mergers of disk systems (e.g., Barnes 1999). Observations of faint distant systems indicate that interaction rate rapidly increases with redshift (e.g., Abraham 1999). Intuitively, one could expect that the merging rate of galaxies should depend on environment (in particular, on the local density and velocity dispersion). For example, Makino & Hut (1997) found under some simplifying assumptions that the merging rate in clusters is proportional to \( n^2 \sigma^{-3} \) where \( n \) is the number density of galaxies in the cluster and \( \sigma \) is their one dimensional velocity dispersion of galactic velocities. Since the environment changes with time one could also expect dramatic changes in the evolution of the merging rate.

In order to study the evolution of the merging rate and its dependence on environment one must follow the evolution of halos in a representative cosmological volume. Moreover, the simulation must have sufficiently high mass and force resolutions. Insufficient resolutions leads to structureless virialized halos instead of systems similar to observed groups and clusters of galaxies with wealth of substructure. This effect is well known as the overmerging problem (e.g., Moore et al. 1996, Frenk et al. 1996, Klypin et al. 1999).

Cosmological scenarios with cold dark matter (CDM) alone cannot explain the structure formation both on small and very large scales. Variants of the CDM model with a non-zero cosmological constant, \( \Lambda \), have proven to be very successful in describing most of the observational data at both low and high redshifts. Moreover, from a recent analysis of 42 high-redshift supernovae Perlmutter et al. (1999) found direct evidence for \( \Omega_{\Lambda} = 0.72 \), if a flat cosmology is assumed. Also, from the recent BOOMERANG data Melchiorri et al. (1999) found strong evidence against an open universe with \( \Lambda = 0 \). For our study we have chosen a spatially flat cosmological model with a cosmological constant \( \Omega_{\Lambda} = 0.7 \) and the present-day Hubble constant of \( H_0 = 70 \text{ km/s/Mpc} \).

The goal of this study is to determine the distribution with redshift of merging events for halos which exist at \( z = 0 \). We study this merging rate and its dependence on environment of halos at \( z = 0 \). The paper is organized as follows. In the next section we define the merging events studied in this paper. In § 3 we describe the cosmological model and the numerical simulation. We briefly describe our halo finding algorithm, the definition of environment and the detection of progenitors of halos. The technical details of these procedures are presented in the Appendix. We use the extended Press-Schechter formalism to test our
procedure. In § 4 we discuss the merging of halos found in the simulation and compare our results with observations. In § 5 we summarize our results and briefly discuss their implications.

2. MERGING OF HALOS

According to the hierarchical scenario, galaxies and the dark matter halos associated with them have been formed in a process of merging with other halos and accretion of small objects. Here merging denotes the coalescence of two objects with comparable masses whereas accretion means the infall of objects with masses much smaller than the mass of the accreting object. Obviously, there is no sharp distinction between the two processes.

During the formation of every halo there are events (let us name them major mergers), when mass of the halo increases substantially over a short period of time. Such events are very important because they can lead to dramatic changes in the structure of dark matter halos and galaxies they harbor. For example, the increase in mass leads to the change of potential and, likely, density structure of the dark matter halo. One may expect even more dramatic changes for the baryonic component. Infalling objects may, for example, damage or even destroy stellar disk. The inflow of material may also serve as a source of fresh gas and may therefore induce increase in star formation rate. At the same time, collisions between halos may result in shock heating of the gas, which would tend to delay or prevent star formation for some period of time.

Impact of a major merger on the structure of a halo or a galaxy likely depends on a particular configuration of the merging event: one massive infalling object or accretion of many small-mass objects, gas-rich or gas-poor mergers, etc. Nevertheless, it is reasonable to expect that accretion of many small halos is as damaging as merging with one massive satellite of the same total mass. Thus, it is logical to define major merger event as an accretion event in which mass of a halo increases substantially (say, by more than 20% - 30%) over a short period of time (e.g., one dynamical time of the halo), as opposed to a single merger with a massive halo.

There is another issue related to the major merger definition and statistics. One can consider mergers in a population of all halos present at a given redshift. In this case, one counts all merging events and divides the count by the total number of halos. This gives an estimate of the merging rate. The procedure should be used, for example, if one compares the frequency of close pairs with theoretical predictions. In this paper we consider a different statistics: we study merging history of present day halos. Namely, we ask the following question: what is the probability that the most massive progenitor of a halo identified at redshift $z$ had a major merger at this redshift? At relatively small redshifts ($z < 1$), the merging rate of galaxy-size halos is low and the differences between the merger rates defined in these two different ways are small. At higher redshifts the differences may become substantial.

We are also interested in the effect of the environment of halos on their merging rate. The environment of a given halo changes with time. An isolated halo may fall into a group or cluster and groups, in their turn, may then be accreted onto clusters. In this paper, we study the differences between merging histories of halos residing in different environments at $z = 0$.

The ultimate outcome of merging or accretion event depends on both the time interval and on the fractional mass increase within this time interval. Observationally, the time scale of merging is the time interval for which traces of the event can be observed. Physically, this time scale is of order of the dynamical time of accreting halo. A reasonable lower limit on the merging time scale is the crossing time of the halo defined as the ratio of the halo radius, $R$, to the typical accretion velocity, $V$:

$$t_{\text{cross}} \approx 1 \, \text{Gyr} \left( \frac{R}{200 \, \text{kpc}} \right) \left( \frac{V}{200 \, \text{km s}^{-1}} \right)^{-1}.$$  (1)

The crossing time is approximately equal to one gigayear for a wide range of halo masses. We conclude therefore that it is reasonable to consider time interval as large as 500 Myrs in analyzing the simulations. For our analysis we have used the simulation outputs at 25 time moments. Although the time intervals between two stored moments differ slightly, the mean interval is about 0.5 Gyr.

In § 3.1 we will use the extended Press-Schechter formalism to test the effects of the different choices for the time interval. We find that our results do not change significantly if we vary the time interval from 0.1 to 0.5 Gyr. We have chosen a minimum fractional mass increase of 25% to define a major merger. The resulting merging rate depends slightly on the choice of this value as discussed in § 4. To summarize, in the remainder of the paper the major mergers are defined as accretion events in which mass $M_1$ of the most massive progenitor of a present-day halo increases by more than 25%: $(M_2 - M_1)/M_2 > 0.25$, where $M_2$ is halo mass after merging.

In general, during the evolution of a halo in the simulation its mass increases due to accretion and merging. However, interacting halos may also exchange and lose mass. In particular, tidal stripping (and thus mass loss) becomes important in the dense environment of clusters (Klypin et al. 1999; Gottl"ober et al. 1999a). Depending on the environment of the halo at $z = 0$, we have divided our sample into three subsamples: isolated halos, halos in groups, and halos in clusters.

Merging rates estimated using the extended Press-Schechter (EPS; Bond et al. 1991; Lacey & Cole 1993) formalism are expected to be close to those in numerical simulations. We use the EPS formalism to test robustness of our assumptions and parameters used in the analysis (e.g., the time interval of the merging). It should be noted that halos are treated differently in simulations and in the EPS formalism. By definition, in the EPS formalism the halos are isolated and their mass can only increase with time. Substructure (subhalos inside a larger halo) is not considered by the EPS. Let us consider a merger of two isolated halos with substructure. From the point of view of the EPS formalism this is a single merging event: the mass of the resulting merger product is considerably higher than the mass of the individual merging systems. In the simulation we would detect the mass growth for the most massive progenitor of the merged halo, but not for the individual subhalos present as substructure. In fact, the subhalos may even lose some mass due to the tidal stripping. To summarize, an accretion event that should be classified as a merger on mass-scale of a group or cluster, may
the evolution of 256\(^3\) through a merger of two massive groups; at

The age of the universe in this model is \(\approx 13.5\) Gyrs.

The main goal of this study is the evolution of both isolated halos and halos located inside virial radii of larger group- and cluster-size systems. This requires high force and mass resolution of the simulation. The force and mass resolution required for a simulated halo to survive in the high-density environments typical of groups and clusters is \(\approx 1 - 3\) kpc and \(\approx 10^5 M_\odot\), respectively (Klypin et al. 1999). We use the Adaptive Refinement Tree (ART) N-body code (Kravtsov, Klypin & Khokhlov 1997) to follow the evolution of \(256^3\) dark matter particles with the range in spatial resolution of 32,000. With the required resolution we can simulate the formation of halos in a box of \(60 h^{-1}\)Mpc. With \(256^3\) dark matter particles the particle mass is \(1.1 \times 10^9 h^{-1} M_\odot\). We reach the force resolution of \(2h^{-1}\)kpc. In the box of this size there are sufficiently large number of halos in different environments. This allows us to study the merging rate of halos in different environments.

The evolution of an isolated halo (galaxy-, group-, or cluster-size), whose mass grows due to accretion and merging, is relatively simple. This mass growth is well described by the extended Press-Schechter model. However, in this analysis we are interested not only in the evolution of isolated halos but also in the evolution of subhalos located within groups or clusters, i.e. in the evolution of substructures of bigger isolated objects. In fact, isolated halos and subhalos in groups or clusters evolve differently (cf. Gottlöber et al. 1999a). For example, the latter may loose mass due to tidal interaction when falling into the group or cluster or merge with the host halo if their orbit decays due to dynamical friction.

The bottom panel of Fig. 1 shows a typical medium-size cluster of mass \(1.5 \times 10^{14} h^{-1} M_\odot\) and diameter of about \(3h^{-1}\)Mpc (extent of the shown particle distribution) at \(z = 0\). The figure shows that the final halo contains many subhalos. The figure shows all DM particles of the cluster which are linked using the friends-of-friends (FOF) algorithm with the linking length of 0.2 times the mean interparticle separation. (This linking length approximately corresponds to the virial overdensity). The particles are colored on a gray scale according to the logarithm of the local density at particle position smoothed over a sphere of the comoving radius of \(10 h^{-1}\)kpc. This cluster has formed through a merger of two massive groups; at \(z = 1\) (top of figure), the merger is still in progress. The two largest halos apparent at \(z = 1\) merged into one central object by \(z = 0\). The galaxy size halos that can be seen within this cluster were formed well before the cluster formation in a region of high density. At \(z < 1\), the cluster grows further through relatively mild accretion of dark matter and DM halos: mass increased by a factor 1.6 from \(z = 1\) to \(z = 0\). With the high resolution of the simulation we can follow the evolution of each halo (with mass above a certain threshold determined by the mass resolution of the simulation) from the moment of its formation until \(z = 0\).

Fig. 2 shows the extreme case when a large halo does not have substantial substructure within virial radius. In the bottom panel of Fig. 2 we show an isolated halo of mass \(1.5 \times 10^{13} h^{-1} M_\odot\). The extended dark matter halo has a diameter of about \(1h^{-1}\)Mpc. At redshift \(z = 1\) the progenitor of this halo is a group of small-mass halos with the total mass of \(9.4 \times 10^{12} h^{-1} M_\odot\) and a size of about \(1.3h^{-1}\)Mpc. This is an interesting but a rare case: in the simulation we found 20 halos (\(>10^{12} h^{-1} M_\odot\) ) that were classified as isolated at \(z = 0\) (no subhalos of \(v_{\text{circ}} > 100\) km/s), but whose \(z = 1\) progenitors were groups of four to seven members with \(v_{\text{circ}} > 100\) km/s. Observed counterparts of such merged halos could be the massive isolated ellipticals with group-like X-ray halos (see Mulchaey & Zabludoff 1999; Vikhlinin et al. 1999).

3.1. Finding halos at different redshifts

Identification of halos in dense environments and reconstruction of their evolution is a challenge. The most widely used halo-finding algorithms, the friends-of-friends (FOF) and the spherical overdensity, both discard “halos inside halos”, i.e., satellite halos located within the virial radius of larger halos. In order to cure this, we have developed and used two algorithms to find halos: the hierarchical friends-of-friends (HFOF) and the bound density maxima (BDM) algorithms (Klypin et al. 1999). The HFOF algorithm uses a set of different linking lengths in order to identify the substructures of large DM halos as “halos inside halos”. The BDM algorithm does the same by identification of all local density maxima and following the density profiles starting at these points.

The HFOF and BDM algorithms are complementary. Both of them find essentially the same halos above a reasonable mass threshold (\(>30\) particles). Therefore, we believe that each of them is a stable algorithm which finds in a given dark matter distribution the DM halos. The advantage of the HFOF algorithm is that it can handle halos of arbitrary, not only spherically symmetric, shape. The advantage of the BDM algorithm is that it describes better the physical properties of the halos because it separates background unbound particles from the particles gravitationally bound to the halo and constructs density and velocity profiles for each halo.

It is difficult and usually ambiguous to find mass of a halo located within a larger halo. The formal virial radius of such a halo is equal to the bound system’s virial radius. If necessary, we define halo mass as mass within its tidal or truncation radius defined as a radius where the halo density profile starts to flatten. We try to avoid the problem of mass determination by assigning not only the mass to a halo, but finding also its maximum circular velocity \(v_{\text{circ}} = \sqrt{GM(<R)/R_{\text{max}}}}\). Numerically, \(v_{\text{circ}}\)
can be measured more easily and more accurately than the mass. Beside of being more stable numerically, the circular velocity is also more meaningful observationally.

For our analysis we need a halo sample which is as complete as possible but does not contain any fake halos. Recently, we have shown that the halo samples constructed from the simulation used here do not depend on the numerical parameters of the halo finder for halos with $v_{\text{circ}} \geq 100$ km/s (Gottl"ober et al. 1999a). At $z = 0$, we decided to be even more restrictive and limit analyses to halos with a circular velocity of $v_{\text{circ}} > 120$ km/s which contain more than 100 bound particles within a radius of $100h^{-1}\text{kpc}$. To avoid misidentifications we have required that each halo of our sample has a unique progenitor at the last five time steps (see Appendix for details). At $z = 0$ our halo sample consists of 4193 halos. The halo number density, $0.019h^{3}\text{Mpc}^{-3}$, roughly corresponds to the number density of galaxies with $M \lesssim -18.5$ in the Las Campanas redshift survey (Lin et al. 1996).
Fig. 2.— An example of (rare) merging of a group of halos to an isolated galaxy-size halo. Top: a group of halos of total mass $9.4 \times 10^{14} h^{-1} \, M_\odot$ at $z = 1$. Bottom: at $z = 0$ this group has merged to form an isolated halo of $1.5 \times 10^{14} h^{-1} \, M_\odot$. No subhalos with maximum circular velocities $> 100$ km/s has survived. The bar between the panels corresponds to a length of $100 h^{-1}$kpc (comoving).

3.2. Definition of environment

As mentioned above, the goal of this paper is to study the merging history of the halos as a function of their environment at present ($z = 0$). To characterize the environment we have run friend-of-friend analysis of the simulation outputs with a linking length of 0.2 times the mean interparticle distance. The FOF algorithms, thus, identifies clusters of DM particles with average overdensity of about 200. The virial overdensity in the ΛCDM model under consideration is about 330 which corresponds to a linking length of about 0.17. Therefore, the objects which we find have a slightly larger extent than the objects at virial overdensity. We have increased the linking length to account (at least partially) for the halos gravitationally bound to the cluster halo but located just outside at the epoch of identification.

For each of the identified halos, we find a host halo if such host exists (see Appendix). We call the halo isolated, if it does not belong to any higher-mass host. We call the halo a cluster if it belongs to a particle cluster with a total mass larger than $10^{14} h^{-1} M_\odot$. Finally, we identify group
halos as halos consisting of 3 or more subhalos and having masses of $\lesssim 10^{14} h^{-1} M_{\odot}$. Two halos located within a common cluster of overdensity 200, are considered to be pairs. In the subsequent analysis, we have omitted all pairs due to the following reasons. A massive halo with a single subhalo of much smaller mass should probably be considered isolated. Subhalos of even smaller mass could have been unresolved or missed due to the limited mass resolution so that such pair, depending on mass, should have been a small group rather than an isolated halo. To avoid this kinds of confusing identifications of the environment, we have omitted all pairs. The analyzed halos, therefore, are classified as isolated, cluster, or group halos.

The procedure described above results in identification at $z = 0$ in our $60 h^{-1}$ Mpc box of 401 cluster halos (10 %) in 18 clusters, 743 halos in groups (18 %) and 2545 isolated halos (60 %). The remaining 504 halos are found in pairs (12 %). The first cluster has formed between $z = 2.5$ and $z = 2$. The fraction of galaxies in clusters increases with time, whereas the fraction of isolated galaxies in the considered mass range decreases, and the fraction of pairs remains approximately constant (Gottlöber et al. 1999c).

3.3. Progenitors of halos

For each of the halos in our $z = 0$ sample we have constructed a complete evolution tree over 25 epochs ($z = 0$, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.5, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0, 6.1, 7.2, 10.0). Procedure of progenitor identification is based on the comparison of lists of particles belonging to the halos at different redshifts both back and forward in time (for details see the Appendix). Our algorithm of tracing halo histories identifies the correct “ancestor-descendant” relationships rather accurately, with estimated ancestor-descendant misidentifications $\lesssim 2\%$ of the cases (Gottlöber et al. 1999a). These misidentifications happen usually with small-mass halos consisting of only a few tens of particles (below the mass limit of halos in our sample), i.e. the halos in the mass range of our sample are not significantly affected.

Now we define the halo detection epoch as the epoch at which the halo has reached a threshold when it can be expected to host a galaxy. The threshold is taken to be $v_{\text{circ}} > 50$ km/s for the first time. Our halo-finder assumes a minimum circular velocity, $v_{\text{circ}} > 50$ km/s, and a minimum number of bound particles of 40, for the progenitors of our halos at $z > 0$. In Fig. 3 we show how many cluster and isolated halos were detected per redshift interval as a function of redshift. In this figure we show only cluster halos; halos in groups show similar behavior. Due to the construction procedure of our sample (§ 3.1), all present-day halos exist already at $z = 0$. Fig. 3 shows that in general cluster halos form earlier than isolated halos. The maximum formation rate is reached at $z \approx 3$ whereas the maximum of the formation rate of isolated halos is reached later ($z < 2.5$). Cluster halos form in regions of higher overdensity and therefore reach the detection threshold earlier.

The integral over the curves of Fig. 3 gives us the completeness of the progenitor samples as a function of redshift. It reaches 90% (50%) at $z = 2$ ($z = 4$) for halos in
clusters and at $z = 1.5$ ($z = 3$) for isolated halos.

Let us consider a subsample of halos with $150 > v_{\text{circ}} > 200$ km/s (Fig. 4, thick lines). Cluster halos of this sample form earlier ($z \sim 4$) than isolated halos. We see the same tendency for the subsample of the most massive halos with $v_{\text{circ}} > 300$ km/s (thin lines), however due to poor statistics we do not see the maximum of formation rate of these massive cluster halos. The progenitor of the central halo of the most massive cluster (which corresponds to a massive central cD galaxy) can be identified at $z = 15$ as an object of $3 \times 10^{10} h^{-1} M_\odot$.

3.4. Extended Press-Schechter formalism

To test how sensitive the merger rate estimates are to our assumptions, we use the synthetic merger histories generated using the extended Press-Schechter formalism (hereafter EPS, Bond et al. 1991; Bower 1991; Lacey & Cole 1993). Specifically, we use the “N-branch trees with accretion” method of Somerville & Kolatt (1999) to construct merger histories for the host.

In this method the progenitors of a halo of mass $M_h$ at a given epoch and in mass range $[M_p^{\text{min}}, M_h]$ are determined through a series of Monte-Carlo picks using probability for a halo to have accreted mass $\Delta M$ during time $\Delta t$ (see eq. 2.29; of Lacey & Cole 1993). $M_p^{\text{min}}$ is the minimum progenitor mass that is kept track of, specific to particular intended use of the merger histories. The method was slightly modified; at each step we require the number of progenitors in the mass range of interest to be close to the expected average. This modification significantly improves agreement of the progenitor mass function generated by the method with the analytical prediction (Kravtsov et al. 2000). We refer reader to Somerville & Kolatt (1999) for further details of the method.

Using the EPS method we have generated a sample of 1350 merging histories of halos of mass $10^{12} M_\odot$ at $z = 0$. This is a typical mass for halos in our numerical catalogs. We followed merger histories back in time until the mass of the most massive progenitor falls below $4 \times 10^{10} M_\odot$, the same minimum mass that was used in analysis of the simulation. With a mean $\Delta z$ of about 0.003 the shortest history (425 steps) starts at $z = 1.4$, whereas the longest (3802) starts at $z = 11$. Our goal is to use the high temporal resolution of the EPS merging histories to test the effect of the coarse temporal resolution of the merger his-
As discussed in § 2, we define a major merger as an event in which the mass of a halo increases by more than a certain threshold in a given time interval. In Fig. 5 we show five of the original EPS merger histories (solid lines) and the major merger events detected (solid triangles) using the original time steps of the history and a threshold of 0.35. The dashed lines show the evolution of the same halos tracked only at 25 time moments used in the simulation (see § 3.3) where the open triangles denote the major merger events detected for this history using the same definition of the major merger as before. One can see that at $z \lesssim 2$ each solid triangle is accompanied by an open one. At higher $z$ there are exceptions. In one of the histories two subsequent merger events detected in the original merger history are detected as only one event in the coarse-time history. In another history (rightmost curve) two successive minor mergers in the original history (at $z \approx 5$), that are not classified as “major” add up to a major merger when the time resolution is degraded. The fact that two (or more) successive minor mergers occurring within less than $0.5$ Gyrs are treated as one major merger is not necessarily wrong. The physical effect of large mass accretion within a short time interval may be the same regardless of whether this accretion was through a single major or several minor mergers. However, the fact that coarse temporal resolution may masquerade several major mergers as one, may lead to an underestimate of the merger rate at $z \gtrsim 2$.

In the following we want to test whether the estimates of the merging rate are influenced by the relatively coarse time intervals used in simulation analysis. To this end, we tracked the original EPS merger histories in equally spaced time intervals of 500 Myr, 250 Myr, and 100 Myr. We have then counted the major mergers as events in which mass increases by more than 25% in a given time interval. Finally, we have calculated the merging rate of the EPS halos in the same way as for the halos of the simulation: the number of major merger events per halo per Gigayear. The result is shown in the three panels of Fig. 6. The solid line is a power law fit ($\propto (1 + z)^a$) for $z < 2$ epochs, with $a = 2.40$ for $\Delta t = 500$ Myr, $a = 2.38$ for $\Delta t = 250$ Myr, and $a = 2.27$ for $\Delta t = 100$ Myr.

There is a good agreement of the merging rates for different time intervals. The somewhat lower merging rate in case of $\Delta t = 100$ Myr is a result of the poor statistics at low $z$. Obviously, the merging rate increases with redshift, but it cannot increase to infinity due to the adopted major merger definition. Clearly, if one assumes that all halos underwent a major merger in the given time interval $\Delta t$ (the algorithm by design cannot detect multiple major merger events in a particular time interval, see above), the merging rate reaches its maximum value $1/\Delta t$, i.e., 2, 5, or 10 in the three panels of Fig. 6. One can see that the curves in this figure indeed flatten before reaching this value, but at different epochs. This flattening is due to the limited mass resolution of the simulation. At a given time moment and with a given resolution, some of the halos fall below the detection threshold at the earlier time moment, i.e., for these halos major merging events cannot be detected. With larger $\Delta t$ this probability increases and reduces therefore the rate and epoch at which this effect sets in. However, Fig. 6 shows that for the interval of $\Delta t = 0.5$ Gyr (the interval used in our simulation analysis), the results are robust for $z \lesssim 2$.

In Fig. 7 we compare two different detection schemes of major merger events. Open circles denote all major merger events detected by the condition $(M_2 - M_1)/M_2 > 0.25$. These events include events due to the merger of two massive halos and multiple mergers and/or rapid accretion. The filled circles denote the subsample of binary mergers of two massive progenitors. Note that in the upper panel almost all open circles coincide with filled circles at $M > 2 \times 10^{12} h^{-1} M_\odot$, i.e., the major merger events detected through the mass growth are in fact due to binary mergers. With decreasing mass and increasing redshift the number of major mergers with only one massive progenitor rapidly increases. This is simple due to the fact that with decreasing mass of the halo the probability that its second massive progenitor is already below the detection
threshold increases. Although in the EPS formalism one could easily extend the tree to lower masses, in simulations one is limited by the mass resolution. In the lower panel of Fig. 7 we plot the merging rates detected for all major mergers (open circles, the same as the top panel of Fig. 6) and for binary major mergers (filled circles). There is no differences at $z < 2$. We conclude that there is no difference between the two definitions at redshifts $z < 2$. It is more reasonable to analyze the simulation using the mass growth, $(M_2 - M_1)/M_2$, as a major merger definition, because this procedure provides informations to somewhat larger redshifts (see Fig. 7, lower panel). More investigations are necessary to understand whether the bend at higher $z$ is real.

4. RESULTS AND DISCUSSION

As was noted above, to identify major mergers we calculate the relative mass growth $(M_2 - M_1)/M_2$ during the time interval $t_2 - t_1$. Due to the selection of simulation output redshift, the time intervals (see Sect. 3.3) have somewhat variable length. As a reminder, we assume a major merger to have occurred if the relative mass growth is larger than 0.25. As discussed in the previous section, we calculate the total change of mass, not only the contribution of merging with another massive halo. In the previous section we have shown that variable time intervals do not change the result if this merger rate is normalized by time interval. Therefore, we calculate the merger rate as the number of major-merging events of the progenitors of our halo sample per gigayear normalized to the number of progenitors at a given moment. In Fig. 8 we show the evolution of the merger rate in this definition. The estimated merger rate is obtained by averaging over three subsequent time intervals in order to reduce the scatter. The error bars are $\sqrt{N}$ errors for the number of events detected.

For redshifts $z \lesssim 2$ our sample is 90 % complete. For these redshifts the merger rate can be fitted by a simple power law $(1 + z)^{3.0}$. There is an indication of flattening of the merging rate at higher redshifts. As shown in Fig. 3 at $z \gtrsim 2$ we are rapidly loosing the halo progenitors due to mass resolution. Moreover, Fig. 6 also shows that this effect is likely to be due to the limited mass resolution. However, as we have argued above, prediction for the evolution at $z \lesssim 2$ is reliable.

Recently, Le Fèvre et al. (1999) published the first direct observational measurement of the merger fraction at redshifts $z > 0.5$. They have used visual merger identifications as well as statistics of close pairs of galaxies. To transform the observed merger fraction into a merger rate requires knowledge of the lifetime of a merger, i.e. the time for which the traces of the merging event can be observed. An upper limit of 0.4 to 1 Gyr, as assumed by Le Fèvre et al. (1999), approximately corresponds to the time step which we have used to derive the merging rate. Le Fèvre et al. (1999) have derived a merger rate varying with redshift as $(1 + z)^{5.2 \pm 0.6}$. This result is in good agreement with our theoretical prediction.

In principle, the evolution of the merger rate is a very important observable for testing cosmological models. In practice, both the theoretical and observational estimates of merging rates depend on a number of assumptions. In our model estimates, the result depends mainly on the definition (mass threshold) of major merger events. Increasing the threshold 0.25 to 0.4, corresponds to a faster evolution described by $(1 + z)^{5.7}$. Lowering the threshold to 0.20, results in a slightly slower evolution of the merger rate. Observationally, merger rate evolution is determined by empirical and theoretical predictions. It is important to note that the evolution of pair numbers or by morphological studies (e.g., Abraham 1999). In the first two cases the merging rate is not directly measured and the conversion of the measured quantities to the merging rate is not straightforward. The third approach, i.e. observing mergers in progress, is the most direct one (cf. Le Fèvre et al. 1999).

From an excess of power in the observed two-point angular correlation function at angular scales $2'' \leq \theta \leq 6''$ Infante et al. (1996) determined a merging rate of galaxies $(1 + z)^{2.2 \pm 0.5}$. According to Burley et al. (1994) the pair fraction in deep HST images grows with redshift as $(1 + z)^{3.5 \pm 0.5}$ from which they deduce a merger rate $(1 + z)^{2.5 \pm 0.5}$ On the contrary, Carlberg et al. (1994) conclude from the evolution of the close pair $(\theta \leq 6''$) fraction that the merger rate–redshift relation is $(1 + z)^{4.1 \pm 1.0}$. Finally, Yee & Ellingson (1995) found for the close pair (projected distance less than $20h^{-1}\text{kpc}$) evolution rate a somewhat deeper redshift dependence $(1 + z)^{4.0 \pm 1.5}$. Different authors used different relationships between the evolution of pair fraction and the evolution of the merger rate. Nevertheless, the derived merger rates are in general agreement and also in agreement with our theoretical predictions.

It is very interesting to see whether the merger rate evolution depends on the halo environment. In Fig. 9 we show the merger rate of cluster, group and isolated halos normalized to the merger rate of all halos shown in Fig. 8. The higher rate of major mergers at early epochs for cluster and group halos is due to the higher density in regions, where cluster and groups have been forming. Note that the clusters have not yet existed at $z \gtrsim 2 - 3$. As clusters with large internal velocities form, merging rate quickly decreases (Makino and Hut 1997; Kravtsov & Klypin 1999; Mamon 2000). There are almost no major merger events of cluster halos in the recent past. Those 8 events at
z = 0.1, 0.25, and 0.5 have probably happened just outside the clusters before the halos were accreted by cluster or, alternatively, they might have occurred within the surviving low internal velocity substructure within cluster. Note also that the massive central halo of the cluster (which should correspond to the observed brightest cluster galaxies) may accrete other halos after the cluster has been formed (Dubinski 1998; Mamon 1999). If the accreted halo is massive enough a major merging event would be detected. The low merger rate in simulated clusters has been noted also by Ghigna et al. (1998), although mergers within accreted substructure have been observed (Springel et al. 2000).

APPENDIX

Appendix: Technical details
A: Halo identification: Our halo identification algorithm (see Klypin et al. 1999 for more details) starts with the search of local density maxima assuming a smoothing radius of the order of ~ 10h^{-1}kpc. This radius defines the scale of the smallest objects we are looking for. Once the centers of potential halos are found, we start the procedure of removing unbound particles and finding the size of halos. We determine the mass of the dark matter particles in concentric spherical shells around the halo center, the mean shell velocity, and the velocity dispersion relative to the mean. We assume that particles with velocities larger than the escape velocity at the position of the particle are not bound to the halo and do not take them into account when calculating halo properties. Using the density profile of the halo we estimate the maximum rotational velocity and the radius at which the maximum is reached. We will call this radius, radius of the halo.

Removal of unbound particles is important in the case when a halo with a small internal velocity dispersion moves inside a larger halo. In many cases, the small-mass subhalos can be unambiguously identified only after removing the unbound background particles of the larger halo. To avoid misidentifications of group or cluster halos as galaxy halos we have introduced a maximum possible halo radius of 100h^{-1}kpc. We assume this radius to be the halo radius if the circular velocity profile is still increasing at this distance.

We have analyzed a high-resolution collisionless simulation of the evolution of structure in an LCDM model. We have followed the formation and evolution of DM halos in different cosmological environments and estimated the evolution of the major merger rate of dark matter halos.

We have found that regardless of their present-day mass, halos that end in clusters form earlier than isolated halos of the same mass (Figs. 3 and 4). We find that at redshifts z < 2 major merger rate evolves as (1 + z)^{-3.0}, in good agreement with observations. Finally, we have calculated the merging rate evolution as a function of halo environment at z = 0 (Fig. 9). The merger rate of halos located in clusters or groups at present increases faster back in time than that of isolated halos. The cluster and group halos are therefore predicted to have a higher rate of major merger events in the past. At z < 1, the merger rate of cluster and group halos drops very quickly, while numerous major merger events for isolated halos have been detected down to z = 0. This implies possible systematic differences between cluster and field ellipticals. Evidence for such differences was found by de Carvalho & Djorgovski (1992), while Bernardi et al. 1998 detected close similarity between cluster and field early type galaxies.

The agreement between theoretical predictions and observations are encouraging and supports the validity of the hierarchical structure formation scenario. Future, higher resolution simulations should extend the predictions presented here to higher redshift and, in case of gasdynamics simulations, provide a more straightforward connection to observations. On the observational side, the ever increasing size of the high-redshift galaxy samples should also allow estimates of the merger rate at high redshifts in the near future.

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The halo identification scheme is crucial for the algorithm which finds the most massive progenitor of a halo. Due to
our halo definition, DM particles can belong to more than one halo (e.g., a particle may be gravitationally bound to both
the subhalo and to its host halo). At a given time moment, some of the particles gravitationally bound to a halo might be
outside of the formally defined halo radius. Both situations must be taken into account if one constructs the evolution
history of halos using lists of particles belonging to a given halo.

We use the constructed density profile and estimated radius to assign each halo a mass and circular velocity. To
construct halo catalogs, we select all halos with maximum circular velocities above a certain minimum value. In addition,
we have rejected all halos with the number of bound particles below a minimum threshold.

There are also some special cases in halo identification. For example, after a recent merger two local density maxima
could be found within a common halo. The halo finder tends to identify such a configuration as two halos at a distance
of the order or smaller than the radius of the halos. Also, at a given moment small clumps in a dense environment could,
by chance, appear as bound clumps which, however, disappear by the next time moment. These misidentifications could
masquerade as recent merging events. To avoid these kinds of misidentifications, we have required that each halo of the
sample at \( z = 0 \) has a unique progenitor at the last five time steps (see § 3.3). If a progenitor has been already identified
as progenitor of another halo, the smaller mass halo is discarded. This procedure, which removes about 6% of the halos,
reduces the number of fake merger detections and makes the results more reliable.

B: Definition of environment: We define the environment of a halo using the mass of the virialized host (if any) to
which the halo belongs. We find virialized systems using a friends-of-friends algorithm with a linking length of 0.2 times
the mean density. For each halo, we determine the particle with the shortest distance to the center of mass of the halo.
Then we search for the virialized object to which the particle belongs. Since these objects have overdensities of the order
200, we are confident that our halo of higher internal overdensity belongs to a virialized host if the most central particle
belongs to it.

C: Progenitor identification: We begin by identification of all particles bound to a halo at a given redshift \( z_i \). Then
we find all objects (identified halos, small groups of particles below the detection limit of halos, isolated particles) at
the previous redshift \( z_{i+1} \) which contain any of the particles of the halo in question. The time interval between the two
redshifts is typically of the order of 0.5 Gyr. We repeat this procedure for all halos at a given redshift. We thus obtain
complete information on the origin of the particles found in halos at redshift \( z_i \). However, due to the halo identification
procedure described above this information is not equivalent to the mass of the progenitor objects. Indeed, we have
determined the mass at the radius of the maximum rotational velocity. To get the mass growth due to merging and
accretion we must compare the masses of the halo and its progenitor which are defined in the same way.

It is relatively straightforward to identify the most massive progenitor for isolated halos: it is simply the halo which
contains the largest fraction of particles of the descendant. In a dense environment, on the other hand, the identification
is more complicated. For example, the particles of a subhalo belong both to the satellite halo and the hosting halo at an
earlier moment, so that both would be identified as progenitors. To avoid this (and similar) misidentifications we identify
not only the ancestors of all halos found at \( z_i \) but also the descendants of all halos found at \( z_{i+1} \) and check whether a
given halo is really the descendant of its ancestor by searching for the maximum subsamples of particles belonging to the
corresponding halos. With such somewhat extensive procedure we reduce the misidentifications of progenitors to \( < 2\% \)
of all considered cases. Note, that these misidentifications lead to scatter in the mass evolution history.

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