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Influence of baryonic physics on the merger timescale of galaxies in *N*-body/hydrodynamical simulations

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ABSTRACT

In previous work, we studied the merger timescale of galaxies in a high-resolution cosmological hydro/*N*-body simulation. We now investigate the potential influence of uncertainties in the numerical implementation of baryonic physics on the merger timescale. The simulation used in the previous work was affected by the overcooling problem, which caused the central galaxies of large halos to be too massive. This might be responsible for producing a shorter merger timescale than that in the real universe. We perform a similar simulation, but in which the stellar mass is reduced significantly to model another extreme case of low stellar mass. Our result indicates that in this case the merger timescale is systematically higher than that we measured before. However, the difference in these two cases is only about 10%, except for satellites in nearly radial orbits where the difference is larger, reaching 23 percent. Since the two simulations correspond to both the low and high stellar mass limiting cases, and nearly radial orbits account for only a small part of the satellites' orbits, our results indicate that the fitting formula that we presented previously is applicable to good accuracy.

Key words. galaxies: clusters: general – galaxies: kinematics and dynamics – methods: numerical

1. Introduction

It is believed that structures form hierarchically in the universe, larger objects being assembled by the merging of smaller building blocks. When a massive group is formed, its central galaxy acquires a special position such that it grows by accreting its surrounding gas and satellite galaxies. These satellite galaxies gradually lose their energy and angular momentum under the action of dynamical friction, and finally sink to the center of the host halo (primary halo), merging with the central galaxy. An accurate merger timescale is a crucial ingredient in understanding the role of mergers in galaxy growth. In theoretical computation of this timescale, the formula given by Lacey & Cole (1993) is generally used. It is derived from Chandrasekhar's formula for dynamical friction (Chandrasekhar 1943).

In our previous work (Jiang et al. 2008, hereafter J08), we used a high-resolution *N*-body/hydro simulation to show that, this widely used dynamical friction formula underestimates the timescale of minor mergers and overestimates that of major mergers. We then applied a new fitting formula for the merger timescale measured from the simulation (refer to Eq. (5) in J08),

$$T_{\rm fit} = \frac{f(\epsilon)}{2C}\frac{m_{\rm pri}}{m_{\rm sat}}\frac{1}{\ln\Lambda}\frac{r_{\rm vir}}{V_{\rm c}}, \tag{1}$$

where C is a constant, approximately equal to 0.43; ϵ is the circularity parameter of the satellite's orbit, which is defined to be the ratio of the angular momentum to that of a circular orbit of the same orbital energy; $f(\epsilon)$ is the function that denotes the circularity dependence, $f(\epsilon) = 0.94\epsilon^{0.60} + 0.60$, obtained by fitting a two parameter function $f(\epsilon) = a\epsilon^{b} + 0.60$; and $V_{\rm c}$ and $r_{\rm vir}$ are the circular velocity and the virial radius of the primary halo, respectively, assuming that it is an isothermal sphere. The Coulomb logarithm $\ln\Lambda$ is in the form of $\ln[1+(\frac{m_{\rm pri}}{m_{\rm sat}})]$. Therefore, the mass dependence is represented purely as the mass ratio of the primary halo to the satellite halo $\frac{m_{\rm pri}}{m_{\rm sat}}$. We showed that this fitting formula could account properly for the mass dependence and the circularity dependence. Lagos et al. (2008) investigated the impact of this formula in a semi-analytical model, finding that it caused a delay in the period of maximum merger activity towards $z \sim 1.5$ compared to $z \sim 2.5$ obtained for Lacey & Cole (1993), and provided a slightly closer agreement with the observed morphologies at the high-mass end compared to the formulae given by Lacey & Cole (1993) and Boylan-Kolchin et al. (2008), who gave a different result from ours. Kang (2009) showed that this improved galaxy merger timescale was successful in reproducing the V-band luminosity function of Milky-Way satellites. Petsch & Theis (2008) found that a mass-dependent Coulomb logarithm, similar to our description, could model the dynamical friction of satellites in host halos reasonably well.

However, complex baryonic physics relevant to the formation of galaxies is still poorly understood, and cannot be implemented unambiguously in hydro simulations. Our simulation is also affected by this kind of problems, among which the overcooling problem is the most probable one affecting our result. Gas overcooling in the central galaxies of massive halos exists in current hydrodynamical simulations with star formation and supernovae feedback (e.g., Borgani et al. 2004; Saro et al. 2006). This might be related to a lack of AGN feedback to a certain degree. A higher stellar mass for either the central or the satellite galaxy may result in a shorter merger timescale. If the central galaxy is more massive and thus more extended, the merger remnant would probably be identified earlier. For the satellite galaxy, its mass becomes crucial in determining the merger timescale when the dark matter has already severely stripped, and therefore a more massive satellite will lead to an earlier merger according to Eq. (1). Will the potential uncertainties in the implemented

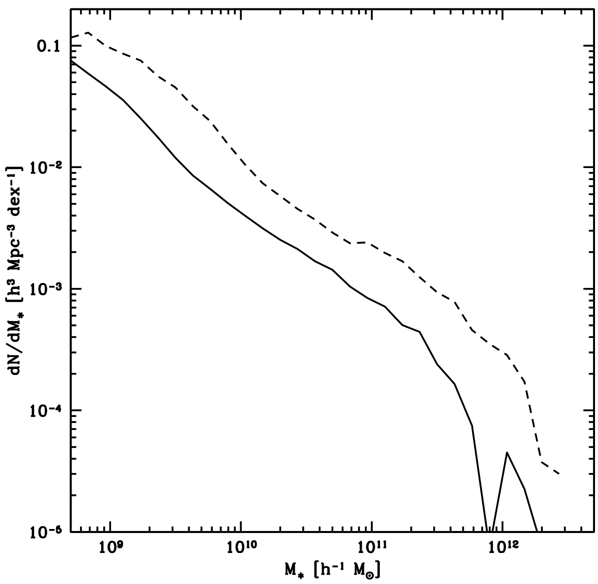

Fig. 1. Stellar mass function at $z = 0$ in this work (solid line) and in J08 (dashed line).

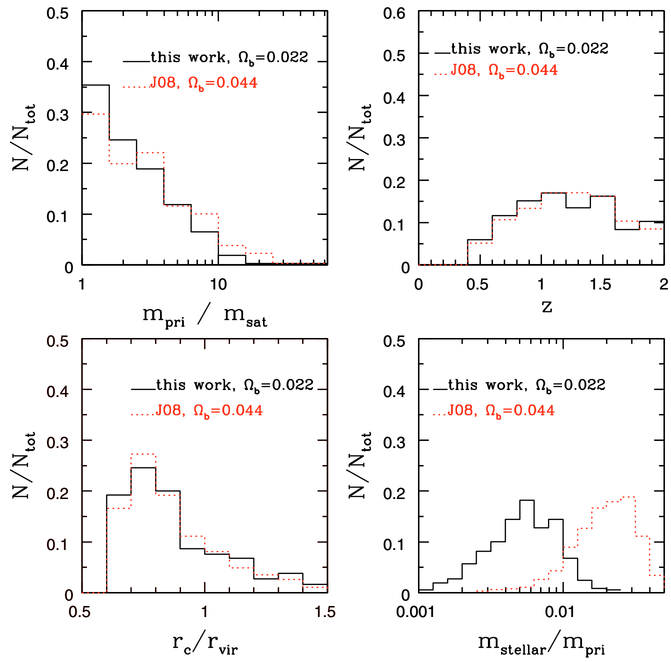

Fig. 2. Some statistical properties of all mergers in this work (solid histograms) and in J08 (dotted histograms). The panels from the top left to the bottom left clockwise display the distributions of the mass ratio of the primary halo to the satellite halo, redshifts at which halo mergers are identified, the mass ratio of the stellar mass of the central galaxy to the primary halo, and the ratio of r_c to the virial radius r_{vir}, respectively.

baryonic physics affect our results? In J08, we argued that these physical processes cannot alter our results significantly from a theoretical point of view. On the one hand, dynamical friction is very efficient only when satellites migrate to the central part of the primary halo, and therefore during the merging process satellites spend most of their time in the outer part of the primary halo except for some radial orbits. Consequently, the merger timescale is controlled by the conditions in the outer part of the primary halo, and the central galaxy of the primary halo cannot influence the results significantly. Furthermore, tidal stripping is not efficient enough to strip a significant fraction of a satellite's dark matter in the outer part of the primary halo. Therefore, the stellar mass of satellites does not play a decisive role either. On the other hand, semi-analytical results based on N-body simulations (Springel et al. 2001; Kang et al. 2005) are in qualitative agreement with ours, which indicates that our results are not affected by the baryonic physics. In this paper, we return to the accuracy of our fitting formula, quantifying the influence of improperly implemented baryonic physics on the merger timescale using a new hydro/N-body simulation.

2. Method

We performed a cosmological hydro/N-body simulation and measured the typical merger timescale of its constituent galaxies. The simulation and the way of obtaining the merger timescale are described in J08, and the reader is referred to that paper for more details. Here we provide only a brief description. The simulation uses the SPH code Gadget-2 (Springel 2005) and implements physical processes such as radiative cooling, star formation in a subresolution multiphase medium, and galactic winds (Springel & Hernquist 2003). The same cosmological parameters are adopted as those in J08, except that we decreased the baryonic density, i.e., adopted $\Omega_b = 0.022$, instead of the value of $\Omega_b = 0.044$ used in J08. Since the sum of the dark matter density and baryonic density remains unchanged, the large scale structure and the halo mass function are not affected. Only the masses of galaxies are reduced. Figure 1 compares the stellar mass function of galaxies in this work (solid line) with that of J08 (dashed line) at $z = 0$. The stellar mass is generally reduced to 1/3 when Ω_b is halved. The nonlinearity of the star formation efficiency with Ω_b is probably caused by the lower gas density at the halo center.

After identifying dark matter halos using the friends-of-friends (FoF) method, halo merger trees are built by tracing the halos at $z = 0$ back to $z = 2$. Since dynamical friction acts on satellite galaxies that orbit around their central galaxies, only the main branches of the merger trees are considered here. To reduce effects caused by the finite numerical resolution, J08 only retained satellite halos whose central galaxies were more massive than $2.0 \times 10^{10}\ h^{-1}\ M_\odot$. Here we reduce this mass limit to $1.0 \times 10^{10}\ h^{-1}\ M_\odot$, accounting for the decrease in the baryonic mass density by 50%.

Galaxies are also identified with the friends-of-friends method, using a linking length of 4.88 h^{-1} kpc. The merger timescale of galaxies is defined as the time that has elapsed between the moments when the satellite galaxy first crosses the virial radius of the primary halo and finally coalescences with the central galaxy. A merger is identified when the satellite galaxy and the central galaxy have the same descendant at one snapshot and continue to have the same descendant in the subsequent four snapshots ($\geq$0.5 of the dynamical time of a halo). We use this criterion to ensure that it is a true merger, not just a close flyby. In total, 370 mergers are identified before $z = 0$. Figure 2 compares the statistical properties of all mergers in this work (solid histograms) and in J08 (dotted histograms). The panels from the top left to the bottom left clockwise display the distributions of the mass ratio of the primary halo to the satellite halo, redshifts at which halo mergers are identified, the mass ratio of the stellar mass of the central galaxy to the primary halo, and the ratio of r_c to the virial radius r_{vir}, respectively. We see that the mass ratio of the central stellar mass to the primary halo is reduced by a factor of three in the simulation where the baryon density is half of its value in J08, consistent with the result shown in Fig. 1. Apart

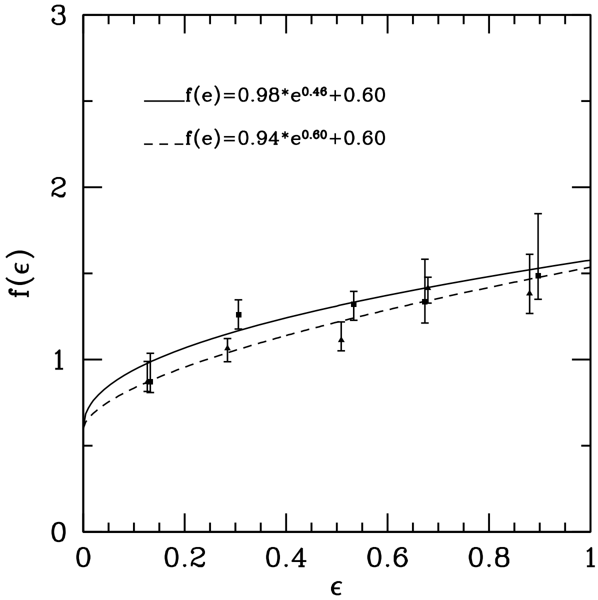

Fig. 3. Circularity function $f(\epsilon)$. Square points and the solid line show the results of the simulation in this work. The dashed line represents the fitting curve in J08. Errorbars represent the 68.3% interval of the $f(\epsilon)$ distribution.

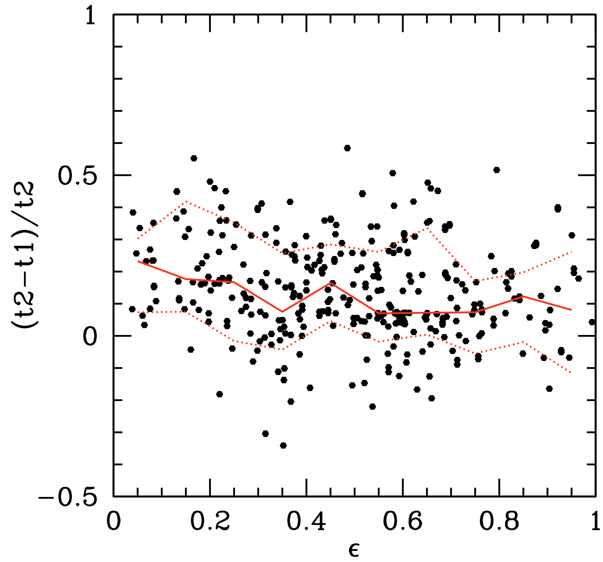

Fig. 4. The difference between the merger timescales in this work ($t2$) and in J08 ($t1$), plotted as a function of ϵ. The solid line represents the median value, and the two dashed lines enclose 68.3% of the merger points.

from this, all other statistics exhibit similar distributions in these two simulations, although there are slightly fewer minor mergers in this work than in J08 as displayed in the top left panel. This is a result of the lower number of low mass halos with their central galaxy mass above the mass threshold.

3. Result

As in J08, we find that the Coulomb logarithm $\ln(\Lambda)$ is represented more accurately by $\ln(1 + m_{\rm pri}/m_{\rm sat})$ than by the other two forms $\ln(m_{\rm pri}/m_{\rm sat})$ and $1/2\ln[1 + (m_{\rm pri}/m_{\rm sat})^2]$. Seen from Eq. (1), the influence of the lower stellar mass on the merger timescale can be represented by the circularity function $f(\epsilon)$, which is obtained from the measured merger timescale in the simulation. If all mergers were used in computing $f(\epsilon)$, there would be a selection bias against those long-time mergers. This is because the simulation stops at $z = 0$, and satellites with longer merger timescales for the same ϵ do not have enough time to merge into their central galaxies before $z = 0$. Therefore, the median value of $f(\epsilon)$ derived in this way would be systematically too low. This problem is particularly severe for larger ϵ, since it takes a longer time to merge on more circular orbits. To avoid this selection bias, we need to construct a *complete* sample in which all central-satellite pairs merge before $z = 0$ (the time at which our simulation stops). That is to say, galaxy pairs are more likely to be found at higher redshift, but a compromise is required to ensure enough statistics. As in J08, we constructed a *complete* sample of primary halos and satellites during the first 14 snapshots (redshift 1.55−2.0) with mass ratio greater than 0.1 (89 pairs). The completeness was 95.7%, slightly lower than that in J08.

Figure 3 shows the median value of $f(\epsilon)$ (square points) and its best fit curve (solid line). The original result in J08 is also indicated by triangles and a dashed line. We see that the solid line lies above the dashed line, which is indicative of a longer merger time than the original result. The discrepancy is larger for low circularity bins than high circularity bins. As we discussed in the introduction, lowering the baryonic content leads to a prolonged merger timescale. However, galaxies on relatively radial orbits are more likely to be affected, causing the fitting curve to be flatter (the exponent of the fitting function decreases from 0.60 to 0.46). Satellites on relatively radial orbits spend more time in the inner region of the halo where the tidal stripping is efficient, and therefore central galaxies of these satellite halos play a more important role in determining the merger times, less massive galaxies taking a longer time to merge. However, the difference shown by the two fitting curves is only about 10% at most. We caution that the statistics used here is small, and therefore a case-by-case comparison of the two simulations might provide a clearer view. We find the corresponding merger pairs in the simulation in J08 for mergers identified in this work, and compare the merger timescales. Figure 4 plots the difference as a function of the circularity parameter. We use $t1$ to represent the timescale in J08, and $t2$ for that in this work. The solid line represents the median value of the difference between the two timescales, and the two dashed lines enclose 68.3% of the merger points. Most mergers have a longer $t2$ than $t1$ as we expect. The median value is generally at a level of 10%, with an increasing trend from $\epsilon = 0.3$ to lower values of ϵ. The highest value of 23% is reached for $\epsilon \leq 0.1$. This is consistent with our previous discussion that low circularity orbits are more likely to take a longer time to merge.

We have only considered mergers on the main branches of the merger trees built for halos at $z = 0$. However, mergers can also occur among halos that are not on the main branches of the $z = 0$ halos, especially at high redshift. These non-main branch halos may enter the main branches at a later time. In Figure 5 we show the redshift distribution of mergers that are not on the main branches (dotted line), compared with those on the main branches (solid line). Here the same mass limit ($1.0 \times 10^{10}\ h^{-1}\ M_{\odot}$) is imposed on the central galaxies. Mergers on the non-main branches have a total number of about 1/3 of that on the main branches, their contribution to the entire merger population being larger at $z > 1$ than at lower redshift. In Fig. 6 we examine whether our result would be affected when these mergers are taken into consideration. The median value of the merger timescale in this simulation ($T_{\rm merg}$) normalized by that obtained using Eq. (1) ($T_{\rm fit}$) is plotted as a function of ϵ.

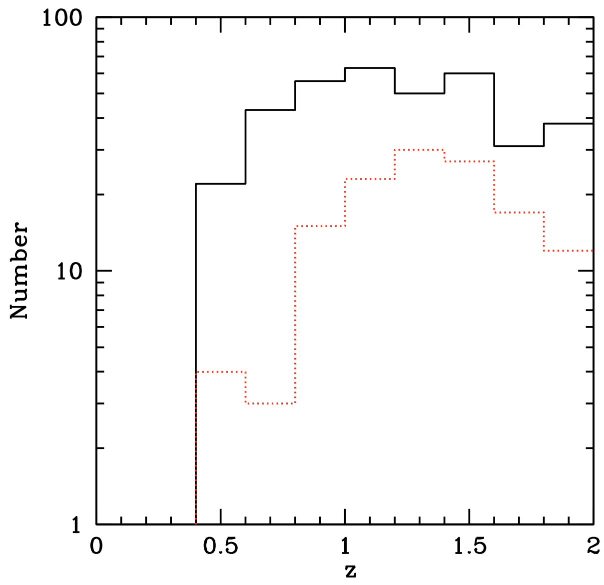

Fig. 5. Redshift distributions for main branch mergers (solid line) and mergers not on the main branches (dotted line).

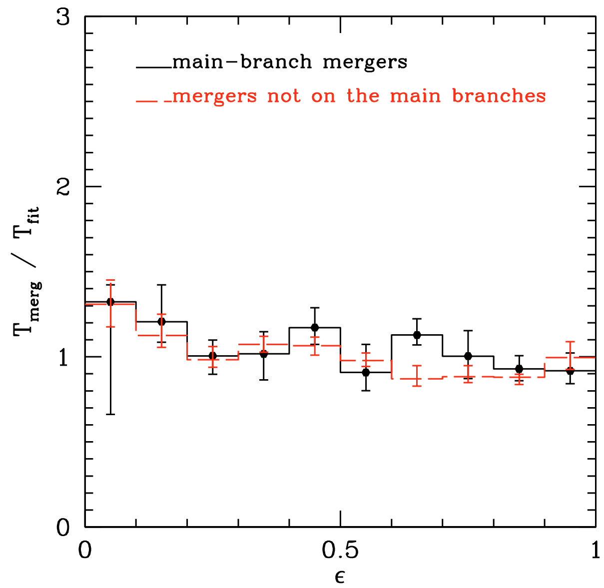

Fig. 6. The median value of the merger timescale ($T_{\rm merg}$) normalized by the value obtained with Eq. (1) ($T_{\rm fit}$). The solid line denotes main branch mergers, while the dashed line represents those not on the main branches.

Main-branch mergers are indicated by the solid line, while those on the non-main branches are represented by the dashed line. The two lines show consistent values, which means that non-main branch mergers have similar merger timescales to main branch mergers. This would be a natural conclusion if all the merging events on non-main branches occur in isolated halos. However, we find that about one third of these mergers happen when the primary halo has already become a subhalo of a more massive halo. This indicates that the merger between the sub-subhalo and its central galaxy in a subhalo is a similar process to that in an isolated halo. We note that mergers in subhalos that we identify here only involve sub-subhalos that are not stripped off their subhalo systems. Sub-subhalos that are stripped from sub-halos may merge with the central galaxies of main halos. This kind of merger probably has a different timescale because of its complexity, and needs to be investigated in future work.

We note that our artificial cut in the baryon budget causes galaxies to reduce their masses to 1/3 of their original value. In J08, the relevant mass range of galaxies lies mostly around the characteristic mass of galaxies, where the mass function conforms to the observed one the most. Therefore, the galaxy masses are lowered too much by adopting a value of $\Omega_{\rm b}$ that is half its value in J08. That is to say, the timescale difference in these two simulations is probably overestimated for the whole merger sample. Consequently, our fitting formula shown in Eq. (1) should be applicable to good accuracy.

4. Conclusion

In Jiang et al. (2008), we studied galaxy mergers in a cosmological hydro/N-body simulation, and presented a fitting formula for the merger timescale of galaxies. However, because of uncertainties in the implemented baryonic physics, the simulation used in that paper had some shortcomings. Our results were most probably affected by the overcooling problem, which caused the stellar mass of central galaxies in massive halos to be too high. This might produce a shorter merger timescale than in the real universe. In this short paper, we have investigated the influence of uncertainties in baryonic physics on the fitting formula. We have modeled an extreme case of low stellar mass by artificially reducing the baryon budget to half its value in a cosmological hydro/N-body simulation, detecting subsequently a systematic increase in the merger timescale. However, the difference between these two cases is only about 10%, except for satellites in relatively radial orbits where the difference is larger, reaching 23 percent. We note that the stellar mass decreases to one third of its original value in our new simulation. While this simulation represents an extreme case, the difference in the stellar mass by three times produces only a marginal difference in the result. This indicates the robustness of our fitting formula to different reasonable implementations of baryonic physics. Furthermore, since low circularity orbits for which the discrepancy is the largest, account only for a small part of the satellites' orbits, the fitting formula in Jiang et al. (2008) is valid to good accuracy.

We also find that, mergers between sub-subhalos and their central galaxies in subhalos have similar merger timescales with those for isolated halos. But for sub-subhalos that are stripped off subhalos and deposited into the potential of the main halos, further work is needed to quantify their merger timescales.

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