Environmental dependence of cold dark matter halo formation

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ABSTRACT

We use a high-resolution N-body simulation to study how the formation of cold dark matter haloes is affected by their environments, and how such environmental effects produce the age dependence of halo clustering observed in recent N-body simulations. We estimate, for each halo selected at redshift \( z = 0 \), an ‘initial’ mass \( M_i \) defined to be the mass enclosed by the largest sphere which contains the initial barycentre of the halo particles and within which the mean linear density is equal to the critical value for spherical collapse at \( z = 0 \). For haloes of a given final mass, \( M_f \), the ratio \( M_i/M_f \) has large scatter, and the scatter is larger for haloes of lower final masses. Haloes that form earlier on average have larger \( M_i/M_f \), and so correspond to higher peaks in the initial density field than their final masses imply. Old haloes are more strongly clustered than younger ones of the same mass because their initial masses are larger. The age dependence of clustering for low-mass haloes is entirely due to the difference in the initial/final mass ratio. Low-mass old haloes are almost always located in the vicinity of big structures, and their old ages are largely due to the fact that their mass accretions are suppressed by the hot environments produced by the tidal fields of the larger structure. The age dependence of clustering is weaker for more massive haloes because the heating by large-scale tidal fields is less important.

Key words: methods: statistical – galaxies: haloes – dark matter – large-scale structure of Universe.

1 INTRODUCTION

In the standard cold dark matter (CDM) paradigm of structure formation, virialized CDM haloes are both the building blocks of the large-scale structure of the Universe and the hosts within which galaxies are supposed to form. During the last decade, the properties of CDM haloes, such as their internal structure, formation histories and clustering properties, have been studied in great detail using both N-body numerical simulations and analytical models. These studies have shown that the halo bias depends strongly on halo mass, in the sense that more massive haloes are more strongly clustered than their initial densities imply. Old haloes are more strongly clustered than younger ones of the same mass because their initial masses are larger. The age dependence of clustering for low-mass haloes is entirely due to the difference in the initial/final mass ratio. Low-mass old haloes are almost always located in the vicinity of big structures, and their old ages are largely due to the fact that their mass accretions are suppressed by the hot environments produced by the tidal fields of the larger structure. The age dependence of clustering is weaker for more massive haloes because the heating by large-scale tidal fields is less important.

Recently Gao, Springel & White (2005), using a very large N-body simulation of a ΛCDM cosmology, re-examined the dependence of halo bias on the properties of dark matter haloes. They found that, for low-mass haloes at redshift \( z = 0 \) with \( M_h \ll M_\star \), the bias depends not only on the mass but also on the formation time of dark matter haloes. For a given mass, haloes that have earlier formation times are on average more strongly clustered in space. This age dependence of halo clustering has been confirmed by a number of independent studies (e.g. Harker et al. 2006; Zhu et al. 2006). Since halo formation time is known to be correlated with halo concentration (e.g. Navarro, Frenk & White 1997; Jing 2000; Wechsler et al. 2002; Zhao et al. 2003a,b; Lu et al. 2006), the age dependence of halo clustering also shows up as a halo-concentration dependence of halo clustering (Wechsler et al. 2006). For massive haloes with \( M_h \gg M_\star \), the age dependence may be reversed, as shown in Wechsler et al. (2006) and Wetzel et al. (2006).

Although the mass dependence of halo clustering is well understood in the excursion-set model based on spherical collapse in

\( \star \) is the characteristic mass scale at which the rms of the linear density field is equal to 1.686 at the present time. For the present simulation \( M_\star \approx 1.0 \times 10^{13} h^{-1} M_\odot \).
Gaussian initial density field (Mo & White 1996), the formation-time dependence (or age dependence) is not. In the simplest excursion-set model from which the Press–Schechter formula is derived (Bond et al. 1991), the formation history of a halo is entirely determined by the local density field, independent of the mass distribution on larger scales. Therefore, the large-scale clustering of haloes is independent of formation time in this model. An age dependence of halo clustering is expected in the excursion-set model based on ellipsoidal collapse (Sheth, Mo & Tormen 2001), because here the collapse of a halo depends not only on the local density field but also on the tidal field generated by its large-scale environment. Unfortunately, this aspect of the model was not explored in any detail in Sheth et al. (2001). Instead, these authors used a mean relation between halo mass and the shape parameter of the large-scale tidal field to derive an average critical collapse overdensity that depends only on halo mass.

Since the properties of galaxies that form in a halo are expected to depend on the formation history of the halo, understanding the origin of the age dependence of halo clustering is crucial for a better understanding about how galaxies are related to their large-scale environments. In this paper we use a high-resolution N-body simulation to study how the formation of dark matter haloes is affected by their environments, and how such environmental effects can be used to understand the age dependence of halo clustering. The outline of the paper is as follows. In Section 2 we describe briefly the simulation. In Section 3 we study the age dependence of halo clustering in terms of halo properties in the initial density field. In Section 4 we examine the environments of dark haloes and how they may affect the formation histories of dark matter haloes. We discuss and summarize our results in Section 5.

2 SIMULATION AND DARK MATTER HALOES

The simulation used in this paper was obtained using the P3M code described in Jing & Suto (2002). This simulation assumes a spatially flat ΛCDM model, with density parameters Ωm = 0.3 and ΩΛ = 0.7, and the CDM power spectrum given by Bardeen et al. (1986), with a shape parameter Γ = Ωm h = 0.2 and an amplitude specified by σ8 = 0.9. The CDM density field was represented by 5123 particles, each having a mass of \( M_p \approx 6.2 \times 10^8 M_\odot \), in a cubic box of \( 100 h^{-1} \) Mpc. The softening length is 10 \( h^{-1} \) kpc. Outputs are made at 60 different redshifts between \( z = 15 \) and 0, with an interval given by \( \Delta \ln (1+z) = 0.047 \).

Haloes are identified with the friends-of-friends algorithm (e.g. Davis et al. 1985) with a linking length 0.2 times the mean particle separation. In order to ensure that only physically bound systems are selected, we discard all particles selected into a halo but are not bound on the basis of their binding energies. However, this step does not have any significant impact on our results. Haloes at \( z = 0 \) are related to their progenitors at higher \( z \) through halo merging trees. A halo in an earlier output is considered to be a progenitor of the halo in question if more than half of its particles are found in the final halo. The formation time of a halo is defined as the time when its most massive progenitor has exactly half of the final mass. Interpolations between adjacent outputs were adopted when estimating the formation times. In Fig. 1 we show the distribution of formation redshift for haloes in two mass ranges. These results are similar to those obtained in Li, Mo & van den Bosch (2005).

![Figure 1. The distribution of formation redshift for haloes in two mass ranges.](https://academic.oup.com/mnras/article-abstract/375/2/633/1444038/1444038)

In order to understand the origin of the age dependence of halo clustering, we examine the properties of dark matter haloes in the...
and denote the mass within it by $M_i$, we show the ratio between the initial mass, $M_i$, and the final halo mass, $M_\odot$, versus halo formation time for haloes in two mass ranges. These plots show that, for many low-mass haloes, the initial mass assigned according to the spherical collapse model is much larger than the final halo mass. Note that the initial/final mass ratio can be as large as 1000 for some low-mass haloes. This discrepancy between the Press–Schechter theory and cosmological simulations has been discussed in considerable detail in Sheth et al. (2001), and is the primary reason why Press–Schechter formula overpredicts the abundance of low-mass haloes. For high-mass haloes, the ratios are much closer to 1, suggesting that Press–Schechter formalism works better for high-mass haloes.

Fig. 3 also shows a clear trend that the initial/final mass ratio on average increases with the formation redshift, and the trend is stronger for haloes of lower masses. According to the halo bias model of Mo & White (1996), which is based on identifying haloes in the initial density field according to spherical collapse model, haloes of larger masses should be more strongly correlated. It is therefore interesting to check whether the age dependence of halo clustering observed in the simulation can be explained by the correlation between initial mass and formation time obtained here. To do this, we select low-mass haloes with final masses $1.2 \times 10^{11} > M_\odot > 6.2 \times 10^{10} h^{-1} \mathrm{M}_\odot$ and massive haloes with final masses $M_\odot > 10^{13} h^{-1} \mathrm{M}_\odot$. We bin haloes in each of the two mass ranges according to their initial masses $M_i$, and compute the bias factor as a function of $M_i$. The results are shown in Fig. 4. As expected, the bias factor increases strongly with mass. The prediction of the Mo & White (1996) bias model is shown as the solid curve. The model matches the simulation result for $M_i \sim M_\odot$, suggesting that large spherical patches are strongly clustered regardless of whether or not a small halo will eventually form in them. However, for $M_i \lesssim M_\odot$, the model overpredicts the bias factor. This is not surprising, because small patches in which a low-mass halo forms at the present time are biased towards low-density regions.

We can assign to each halo a bias factor, $b$, according to its initial mass $M_i$ using the bias–mass relation given by the simulation. We can then average the values of $b$ for haloes in bins of formation redshift to predict the age dependence of halo clustering. The dashed curves in Fig. 5 show the bias-formation redshift relations obtained in this way for haloes in two mass ranges. The predictions match well the simulation results, suggesting that the observed age dependence of clustering for haloes of a given final mass can be entirely explained by the difference in the initial mass. Old, low-mass haloes are more

![Figure 2](https://academic.oup.com/mnras/article-abstract/375/2/633/1444038) The ratio between initial mass, $M_i$, and the final mass $M_\odot$ as a function of halo formation redshift. Results are shown for haloes in different mass ranges, as indicated in the panel.

![Figure 3](https://academic.oup.com/mnras/article-abstract/375/2/633/1444038) The ratio between initial mass, $M_i$, and the final mass $M_\odot$ as a function of halo formation redshift. Left-hand panel is for low-mass haloes with $1.2 \times 10^{11} > M_\odot > 6.2 \times 10^{10} h^{-1} \mathrm{M}_\odot$, while the right-hand panel is for haloes with $M_\odot > 1.0 \times 10^{13} h^{-1} \mathrm{M}_\odot$. The three curves in each panel represent the median, 20 and 80 percentiles.
strongly clustered than their younger counterparts simply because they are associated with perturbations of higher mass (i.e. patches corresponding to higher peaks) in the initial density field. The age dependence is weaker for more massive haloes, because their $M_i$ represent their final masses more faithfully.

4 THE ENVIRONMENTAL EFFECTS OF HALO FORMATION

The question is, of course, why some low-mass haloes can survive in a patch which itself should collapse to form a virialized halo according to spherical collapse model, and what prevents such haloes from accreting mass in later times. To have some ideas about what is going on during the formation of a low-mass old halo, we show in Fig. 6 the spatial distribution of dark matter particles in the neighbourhood of such a halo for a number of representative snapshots, with the particles that eventually end up in the final halo marked in colour. As one can see, the main part of the small halo collapses quickly to form a halo, which then grows only slowly while orbiting around a bigger halo that forms later. The early collapse is driven largely by the relatively high initial density of the material associated with the halo, as is demonstrated in Fig. 7 which shows the initial overdensity around a halo centre as a function of halo formation redshift. In Fig. 7 the overdensity is defined as the mean within a sphere that is centred at the initial position of the halo and has a radius such that the total mass it contains is equal to the mass of the halo. For low-mass haloes, there is a strong, positive correlation between the mean overdensity and the formation time. Haloes with earlier formation times have initial overdensity much higher than the critical density for spherical collapse (indicated as the horizontal line in the figure). With such overdensities, these perturbations can collapse in early times to form virialized halos.

The situation is very different for massive haloes, where the mean overdensity is close to the critical value for spherical collapse (see Fig. 7b).

There are two possibilities why low-mass old haloes stop accreting mass at relatively early times. The first is that these haloes reside in locally low-density regions, and so there is no material for them to accrete. To test this, we estimate the total mass between $r_{60}$ and $3r_{60}$ (with $r_{60}$ the virial radius) for each halo and plot the mean mass density (in units of mean density of the Universe) within these two radii versus halo formation redshift in Fig. 8(a). This figure shows that there is in fact a slightly larger amount of mass around older haloes, and so the truncation of the growth of old, low-mass haloes cannot be explained by the lack of material around them. However, the availability of material is a necessary, not a sufficient condition for halo accretion. In order for the material around a halo to be accreted by the halo, the velocity of the material to be accreted relative to the halo must be sufficiently low. To see if this condition is fulfilled, we estimate the velocity difference $|v_p - v_h|$ for all particles with halo-centric distances between $r_{60}$ and $3r_{60}$, where $v_p$ is the velocity of the host halo, and $v_i$ is the velocity of a CDM particle. Fig. 8(b) shows the velocity difference (in units of halo virial velocity) versus halo formation redshift. There is a clear trend that particles in the neighbourhood of an older halo have systematically larger velocity differences with the host halo. For the oldest haloes, the velocity differences for most particles are significantly larger than the virial velocities of the haloes. These particles cannot be accreted by the halo, because they are too energetic. Thus, the reason why late accretions by old, low-mass haloes are truncated is that they are embedded in ‘hot’ regions where particles are moving too fast for them to capture. The situation is very different for...
massive haloes (Figs 8c and d). First of all, the mean densities in their neighbourhoods are quite independent of halo formation redshift (Fig. 8c). More importantly, the velocity differences between a halo and particles around it are smaller than the virial velocity and so most of these particles can be accreted by the halo in subsequent evolution.

It is easy to understand why old, low-mass haloes are embedded in hot environments. As shown in Fig. 6, these haloes are formed in the vicinity of big structures that are dominated by one or more massive haloes. To see this more clearly, we plot in Fig. 9 the mass of the most massive neighbouring halo within a distance of $2 \, h^{-1} \text{Mpc}$ from a low-mass halo as a function of the formation redshift of the low-mass halo. An old low-mass halo almost always has a massive halo in its neighbourhood. These old low-mass haloes are similar to the subhalo population seen in high-resolution $N$-body simulations (e.g. Klypin et al. 1999; Moore et al. 1999), except that they have not yet merged into the virialized part of a massive halo. Although the formation of the more massive neighbouring haloes occurred at later times, the tidal field of the large structure can accelerate the particles around low-mass haloes, thereby increasing their velocities.

Figure 6. CDM particle distributions around a low-mass old halo (with final mass $M_h = 1.2 \times 10^{11} \, h^{-1} M_\odot$ and formation redshift 3.86) at a number of different redshifts (as indicated in the panels). Particles that eventually end up in the final halo are plotted in red.
Figure 7. The correlation between the initial overdensity, defined on the halo mass scale, and halo formation redshift. Results are shown for low-mass haloes with $1.2 \times 10^{11} > M_h > 6.2 \times 10^{10} \, h^{-1} M_\odot$ (left-hand panel) and for massive haloes with $M_h > 1.0 \times 10^{13} \, h^{-1} M_\odot$ (right-hand panel). The three curves in each panel show the median, 20 and 80 percentiles. The horizontal lines indicate the critical overdensity for collapse (at the initial redshift $z = 72$) based on spherical collapse model.

Figure 8. Left-hand panels: the mean density (in units of the mean density of the Universe) between $r_{\text{vir}}$ and $3r_{\text{vir}}$ as a function of halo formation redshift. Each point represents a halo. Right-hand panels: the velocity difference for particles located between $r_{\text{vir}}$ and $3r_{\text{vir}}$ as a function of halo formation redshift. Here each point represents a dark matter particle. Upper panels are for low-mass haloes with $1.2 \times 10^{11} > M_h > 6.2 \times 10^{10} \, h^{-1} M_\odot$, and lower panels and for massive haloes with $M_h > 1.0 \times 10^{13} \, h^{-1} M_\odot$. The three curves in each panel are the median, 20 and 80 percentiles.

relative to the low-mass haloes. Furthermore, massive pancakes and filaments can form in high-density patches prior to the formation of massive haloes, and heat up the particles in them in a way similar to the preheating mechanism discussed in Mo et al. (2005). Note that these two processes are related, because the formation of pancakes and filaments is related to the local tidal field. As discussed in Mo et al. (2005), the tidal effect and preheating are expected to have more significant impact on smaller haloes, which may explain why...
the age dependence of halo clustering is weaker for more massive haloes.

5 DISCUSSION AND SUMMARY

In this paper, we have used a high-resolution N-body simulation to study how the formation of CDM haloes may be affected by their environments, and how such environmental effects may produce the age dependence of halo clustering seen in recent large N-body simulations. We have shown that old low-mass haloes are almost always associated with initial perturbations that correspond to higher peaks than their present masses imply. Consequently, these haloes are strongly clustered in space despite their low masses at the present time. Because of their associations with large density perturbations, old low-mass haloes are almost always found in the vicinity of big structures that are dominated by one or more massive haloes at the present time. Mass accretions into these low-mass haloes are limited at late times by the tidal field of the larger neighbouring structures. Such environmental effects are weaker for more massive haloes, which explains why the age dependence of halo clustering is weaker for more massive haloes.

Our results demonstrate clearly that environmental effects play an important role during the formation of dark matter haloes, especially of low-mass haloes. Since the properties of galaxies that form in a halo are expected to depend on the formation history of the halo, such environmental effects may have important implications for galaxy formation in different environments. Galaxies that form in old, low-mass haloes are presumably old and faint, and our results suggest that many such galaxies may be located in the vicinity of relatively massive galaxy systems. These galaxies likely represent an extension of the satellite galaxies observed in galaxy systems such as the local group and other groups/clusters of galaxies. Observationally, it is known that satellite galaxies in galaxy groups are dynamically old systems (dwarf ellipticals and dwarf spheroids) that contain mainly old stellar populations. It is interesting to see whether the stellar populations and kinematics of low-mass galaxies in the neighbourhoods of nearby galaxy groups have properties similar to those of the satellite population.

Theoretically, it is very interesting to see if the ellipsoidal collapse model that incorporates large-scale tidal field into the dynamics can indeed explain the environmental effects discussed here and the age dependence of halo clustering observed in N-body simulations. We will come back to this problem in a future work.

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