The distribution of ejected subhaloes and its implication for halo assembly bias

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ABSTRACT
Using a high-resolution cosmological N-body simulation, we identify the ejected population of subhaloes, which are haloes at redshift z = 0 but were once contained in more massive ‘host’ haloes at high redshifts. The fraction of the ejected subhaloes in the total halo population of the same mass ranges from 9 to 4 per cent for halo masses from \( \sim 10^{11} \) to \( \sim 10^{12} \) M\(_{\odot}\).

Most of the ejected subhaloes are distributed within four times the virial radius of their hosts. These ejected subhaloes have distinct velocity distribution around their hosts in comparison to normal haloes. The number of subhaloes ejected from a host of given mass increases with the assembly redshift of the host. Ejected subhaloes in general reside in high-density regions, and have a much higher bias parameter than normal haloes of the same mass. They also have earlier assembly times, so that they contribute to the assembly bias of dark matter haloes seen in cosmological simulations. However, the assembly bias is not dominated by the ejected population, indicating that large-scale environmental effects on normal haloes are the main source for the assembly bias.

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, galaxies are supposed to form and evolve in dark matter haloes. The study of the clustering properties of dark matter haloes and their relation to galaxy clustering can thus help us to understand the connection between haloes and galaxies, and hence to understand how galaxies form and evolve in dark matter haloes. It is now well known that the correlation strength of dark matter haloes depends strongly on halo mass (e.g. Mo & White 1996; Mo, Jing & Borner 1997; Jing 1998; Sheth & Tormen 1999; Sheth, Mo & Tormen 2001; Seljak & Warren 2004), and this dependence, which is referred to as the halo bias, has been widely used to understand the clustering of galaxies via the halo occupation model (e.g. Jing, Mo & Börner 1998; Peacock & Smith 2000), and the conditional luminosity function model (e.g. Yang, Mo & van den Bosch 2003).

More recently, a number of independent investigations have shown that the halo bias depends not only on the mass but also assembly time of dark matter haloes, in the sense that haloes of a given mass, particularly low-mass ones, are more strongly correlated if they assembled half of their masses earlier (e.g. Gao, Springel & White 2005; Harker et al. 2006; Wechsler et al. 2006; Zhu et al. 2006; Bett et al. 2007; Gao & White 2007; Jing, Suto & Mo 2007; Wetzel et al. 2007; Li, Mo & Gao 2008). The origin of this assembly time dependence of the halo bias, referred to in the literature as the halo assembly bias, is important to understand, because if it is due to a process that can also affect galaxy formation and evolution in a halo, then it would affect our interpretation of galaxy clustering in terms of halo clustering. There have been theoretical investigations about the origin of the halo assembly bias (e.g. Desjacques 2008; Keselman & Nusser 2007; Sandvik et al. 2007; Wang, Mo & Jing 2007; Dalal et al. 2008; Hahn et al. 2008). Wang et al. (2007) find that old, small haloes tend to live near massive haloes, and suggest that the tidal truncation of accretion may be responsible for the assembly bias. This is consistent with the result of Maulbetsch et al. (2007), who find that most of the small haloes in high-density regions have ceased accretion. Along this line, Desjacques (2008) develops an ellipsoidal collapse model which takes into account the large-scale tidal field, while Keselman & Nusser (2007) perform simulations using the Zel’dovich (PZ) approximation to take into account the large-scale tidal effects. Both investigations find significant dependence of halo bias on halo assembly history, indicating that large-scale tidal effects may play an important role in producing the assembly bias. More recently, Ludlow et al. (2009, hereafter L09) study in detail five simulations of dark matter haloes and find that a significant fraction of small haloes are physically associated with nearby massive haloes. These small haloes have been once

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inside their host haloes but were ejected due to interactions with other subhaloes (see also Lin, Jing & Lin 2003; Gill, Knebe & Gibson 2005; Wang et al. 2005). L09 suggest that these ejected subhaloes may be responsible for the enhanced clustering of old small haloes. However, because of the small volume of their simulations, they were not able to quantify whether the ejected population alone can account for the assembly bias seen in cosmological simulations.

In this paper, we use a high-resolution N-body simulation in a cosmological box to study the distribution of ejected subhaloes in space and to quantify the contribution of this population of haloes to the assembly bias. The outline of the paper is as follows. In Section 2, we describe briefly the simulation used and how ejected subhaloes are identified. In Section 3, we study the distribution of the ejected subhaloes in phase space, and how the distribution depends on the properties of their hosts. In Section 4, we examine the contribution of the ejected subhaloes to the assembly bias obtained in our simulation. Finally, in Section 5, we discuss and summarize our results.

2 SIMULATION AND DARK MATTER HALOES

2.1 Numerical simulation and halo identification

The simulation used in this paper is obtained with the P3M code described in Jing & Suto (2002). It assumes a spatially-flat ΛCDM model, with density parameters Ωm = 0.3 and ΩΛ = 0.7. The CDM power spectrum is assumed to be that 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 is traced with 5123 particles, each having a mass \( M_p \sim 6.2 \times 10^8 h^{-1} M_\odot \), in a cubic box of 100 \( h^{-1} \) Mpc. The softenning length is \( \sim 10 h^{-1} \) kpc (S2 type).

The simulation, started at redshift 72, is evolved with 5000 time steps to the present day (\( z = 0 \)) and has 60 outputs from \( z = 15 \), equally spaced in \( \log (1 + z) \). Dark matter haloes were identified with a friends-of-friends (FOF) algorithm with a link length that is 0.2 times the mean particle separation.

2.2 Ejected subhaloes

Our analysis focuses on the ejected subhaloes which are identified as FOF haloes at redshift \( z = 0 \). In order to determine whether a halo is an ejected subhalo or a normal halo, a detailed merging tree for each FOF halo is required so that we can trace a FOF halo back in time to see whether it has ever been within another FOF halo. We consider a halo at any given redshift \( z > 0 \) to be a progenitor of a descendant halo in the next output, if more than half of its particles are found in the descendant. A given halo in general can have one or more progenitors but only one descendant. We can therefore use the uniqueness of the descendant to build up the merging tree for each halo. Each FOF halo at the present time has one and only one merging tree to describe its assembly history. There is a small fraction of haloes at \( z > 0 \) that have dispersed and have no descendant at \( z = 0 \). These haloes are excluded in our analysis. The merging tree of a halo can be used to verify whether an isolated FOF halo (called halo ‘A’) at \( z = 0 \) was accreted into a massive halo earlier. To do this, we search in the next snapshot (in reverse order of time) a ‘host’ halo that contains at least half of the particles in halo ‘A’, but does not belong to the merging tree of halo ‘A’. If no such a ‘host’ halo is found in this snapshot, we take the most massive progenitor of halo ‘A’ in this snapshot and repeat the same procedure for this progenitor as we have carried out for halo ‘A’. This procedure is continued until a ‘host’ halo is found or the tree ends. If such a ‘host’ halo is found, halo ‘A’ is then identified as an ejected subhalo, which is said to be ejected at the time, \( t_e \), when the ‘host’ halo is found. Note that the ejection time, \( t_e \), is defined to be the time of the snapshot at which the ‘host’ and ‘ejected’ haloes were just separated from the same FOF group.

We also define an accretion time, \( t_c \), as the time when half of the particles in the most massive progenitor of halo ‘A’ at ejection time is first contained in the most massive progenitor of its ‘host’. If no ‘host’ halo is found before the merging tree ends, halo ‘A’ is said to be a normal halo. Applying this method to all haloes at \( z = 0 \), we construct a catalogue of ejected subhaloes, and the total number of ejected subhaloes is listed in Table 1 in three mass ranges. We denote the masses of an ejected subhalo and of the corresponding ‘host’ halo at any time \( t \) as \( M_e(t) \) and \( M_{\text{host}}(t) \), respectively, and we use \( M_0 \) to denote the mass of a normal halo at redshift \( z = 0 \). Thus, \( M_{\text{host}}(t_e) \) is the mass of the ‘host’ halo at the time of ejection, and \( M_{\text{host}}(t_0) \) is the mass of the descendant of the ‘host’ at the present time, \( t_0 \).

In Fig. 1, we show \( M_e(t_e)/M_{\text{host}}(t_e) \) versus \( M_e(t_0)/M_{\text{host}}(t_0) \) for haloes with \( 6.2 \times 10^{10} < M_e(t_0) < 1.2 \times 10^{11} h^{-1} M_\odot \). The corresponding histograms for \( M_e(t_e)/M_{\text{host}}(t_0) \) and \( M_e(t_0)/M_{\text{host}}(t_0) \) are also shown in the figure. The results for other mass ranges are similar and are not shown. As one can see, the majority of the ejected subhaloes were ejected by ‘host’ haloes that are much more massive than the ejected subhaloes themselves. Only small fraction of haloes are ejected by host haloes with comparable masses: about 11 per cent (34 per cent) of ejected subhaloes have a mass larger than 0.5 (0.1) times of their host halo mass. Furthermore, most of the ejected haloes have masses that are similar to those at the time of ejection, indicating that mass loss or accretion after ejection is not severe. However, the distribution has two extended tails, and the 10th and 90th percentile values are 0.73 and 1.48, respectively.

In our analysis, we remove all systems with \( M_e(t_0)/M_{\text{host}}(t_0) < 0.5 \), i.e. the haloes that have accreted more than their initial masses after ejection. Note that the removed haloes is a very small fraction, about 5 per cent, of the total sample (Table 1). Including them does not have any significant impact on the results to be presented below. After the removal, the final numbers of the ejected subhaloes in different halo mass ranges are also given in Table 1. For comparison, we also list the corresponding numbers for all (ejected plus normal) haloes in these mass ranges. About 4–9 per cent of all the haloes in the mass ranges considered are ejected subhaloes, and the fraction decreases with increasing \( M_e(t_0) \). It is possible that an ejected subhalo after ejection can exchange mass with nearby haloes or with the background density field, so that some of the particles contained in the ejected subhalo at the

| \( M_e(h^{-1} M_\odot) \) | \([6.2 \times 10^{10}, 1.2 \times 10^{11}]\) | \([1.2 \times 10^{11}, 3.7 \times 10^{11}]\) | \([3.7 \times 10^{11}, 10^{12}]\) |
|---|---|---|---|
| Ejected (total) | 2115 | 1076 | 231 |
| Ejected (final) | 2009 | 1056 | 220 |
| Ejected+Normal | 22697 | 16490 | 5850 |

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The present time may not be contained in its ‘host’ halo. In order to quantify this, we consider an ejected mass, \(M_e\), which is defined as the mass of particles which are contained both in the ejected subhalo at \(z = 0\) and in its ‘host’ halo at the ejection redshift. The ratio between \(M_e\) and \(M_s(t_0)\) can then be used as a measure of the fraction of retained mass of an ejected subhalo. In Fig. 2, we show the probability distribution of \(M_e/M_s(t_0)\). As one can see, most of the ejected subhaloes at \(z = 0\) can retain more than 70 per cent of their original masses at ejection. This also shows that our method for identifying ejected subhaloes is valid, in the sense that most of their masses were indeed once contained in their hosts.

2.3 Halo assembly times

We define the assembly redshift, \(z_f\), of a halo at redshift \(z = 0\) as the redshift when its most massive progenitor first reaches half of the final mass of the halo. If necessary, interpolation between two adjacent outputs is used. Here, we do not use the merging tree described above to search for the progenitor. Instead, we use the method described in Wang et al. (2007) (see also Hahn et al. 2008). Very briefly, a halo in any given output at \(z > 0\) is considered to be a progenitor of the halo at \(z = 0\) if more than half of its particles are found in the final halo. In most cases, the merging trees constructed with this method are very similar to that constructed with the method described above. The advantage of the method adopted here is that it can trace an ejected subhalo backwards to the time even before it is accreted by its host halo. Since ejected haloes may be strongly stripped by their host haloes and lose part of their masses, the assembly redshifts of the ejected subhaloes are generally higher than their ejection redshifts and can be identified with this method.

3 THE RELATIONSHIP BETWEEN EJECTED SUBHALOES AND THEIR HOSTS

In Fig. 3, we show the histograms of the scaled time period an ejected subhalo stayed in its host: \((t_e - t_d)/t_{dy}\). Here, \(t_d\) is the dynamical time at \(r_{200}\) of each host halo at the ejection time, with \(r_{200}\) the virial radius within which the mean overdensity of the halo
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Figure 3. The histograms for \((t_e - t_a)/t_{200}\) of ejected subhaloes. The white histograms show the result for ejected subhaloes with masses \(M_s(t_e) > 6.2 \times 10^{10} \, h^{-1} M_\odot\). And red and green histograms show the results for two subsamples indicated in the panel.

is 200 times the critical density. The dynamical time is defined as

\[
t_{200} = \frac{v_{200}(t_a)}{\rho_{200}(t_a)} = \frac{1}{10H(t_a)},
\]

where \(v_{200}\) is the circular velocity at \(r_{200}\) and \(H(t_a)\) is the Hubble constant, at the ejection time. As one can see, the time period an ejected subhalo stays within its host ranges from \(<0.5\) to \(>4\) times the dynamical time. To examine this time period in more detail, we split the ejected subhaloes sample into two subsamples according to the \(M_s(t_e)/M_{\text{host}}(t_e)\) ratio. The red (dark) and green (light) histograms in Fig. 3 represent the results with \(M_s(t_e)/M_{\text{host}}(t_e) < 0.1\) and \(>0.1\), respectively. Evidently, the distribution for the case with \(M_s(t_e)/M_{\text{host}}(t_e) < 0.1\) is peaked around 2, and only 24 per cent of haloes have \((t_e - t_a)/t_{200} < 1\). Under this condition, haloes with large \(M_s(t_e)/M_{\text{host}}(t_e)\) ratio show quite a different distribution. It peaks at \(<0.6\), and the fraction of haloes with \((t_e - t_a)/t_{200} < 1\) is more than 55 per cent. This indicates that many of the ejected subhaloes with a large \(M_s(t_e)/M_{\text{host}}(t_e)\) may be fly-bys which happen to be close to another halo and be linked to it by the FOF group finder. They may, therefore, represent a population that is different from the population with a small \(M_s(t_e)/M_{\text{host}}(t_e)\), which most likely have run through their hosts. In what follows, we will treat these two populations separately.

We show the probability distribution of ejected subhaloes in their distances to the host haloes at \(z = 0\) in Fig. 4. Here, the distance is scaled by \(r_{200}\) of each host halo at redshift \(z = 0\). We use the scaled distance \(r/r_{200}\) instead of \(r\), because \(r_{200}\) is the only important length scale related to the dynamics of a virialized halo. As one can see, the distribution peaks at \(r/r_{200} \sim 1.6\). This is different from what is shown in L09, because their result includes also subhaloes within host haloes. Most of the ejected subhaloes are distributed within \(4r_{200}\), in good agreement with the finding of L09, but the distribution has a long tail at large distance. Our detailed examination shows that the long tail is dominated by ejected subhaloes that have masses much not smaller than those of their ‘hosts’ at ejection. If we exclude the ejected subhaloes with \(M_s(t_e)/M_{\text{host}}(t_e) > \mu\), then the extended tail disappears as long as \(\mu\) is chosen to be smaller than 0.1. The distribution obtained for \(\mu = 0.1, 0.05\) and 0.01 as indicated in the panel. The distance is scaled by \(r_{200}\) of each host.

Ejected subhaloes in general are distributed around massive haloes, but there are also normal haloes which are distributed near massive haloes but have never been inside a massive halo. In Fig. 5, we show the average fraction of ejected subhaloes around their host haloes. This is the ratio between the number of ejected subhaloes and that of the total population (ejected plus normal) as a function of the scaled distance to the host haloes. The left-hand panel shows the average fractions of ejected subhaloes with \(6.2 \times 10^{10} < M_s(t_e) < 1.2 \times 10^{11} h^{-1} M_\odot\) around host haloes in three mass ranges. In the right-hand panel, we show the results for ejected subhaloes with \(1.2 \times 10^{11} < M_s(t_e) < 10^{12} h^{-1} M_\odot\). In the mass ranges probed here, the ejected fraction as a function of the scaled distance is insensitive to the masses of both the ejected subhaloes and the host haloes. The fraction is between 30 and 75 per cent in the range \(r_{200} < r < 2r_{200}\) and between 10 and 40 per cent in the range \(2r_{200} < r < 3r_{200}\). These results are in agreement with those of L09, who found fractions of about 65 and 33 per cent in the similar distance ranges (see also Gill et al. 2005; Wang et al. 2005), although the mass ranges for both the host halo and the ejected subhaloes considered by them are quite different from what we are considering here. Note that, at large-scaled distances, the fraction of ejected subhaloes around host haloes with the lowest mass is larger than that around massive host haloes. This is again due to the
population in which the ejected subhaloes have masses comparable to their hosts at the time of ejection.

In Fig. 6, we show the scaled radial velocity, $v_r/v_{200}$, versus scaled distance for both ejected and normal haloes within $5 \times r_{200}$ of the host haloes of ejected haloes. Here, $v_{200}$ is the circular velocity of each host halo, and $v_r$ is the relative peculiar velocity along the separation between a host and an ejected or a normal halo. We also split the ejected subhaloes and normal haloes into four subsamples according to the scaled distance and calculate the average velocity and average distance for each subsample. The results are shown as the big symbols in the figure. We consider two mass ranges of host haloes, $M_{\text{host}} > 10^{13} h^{-1} M_\odot$ and $10^{13} > M_{\text{host}} > 10^{12} h^{-1} M_\odot$. Note that some normal haloes may be counted more than once since they may be within $5 \times r_{200}$ of more than one host halo. Clearly, the ejected subhaloes and normal haloes show different distribution in the phase space. The radial velocity distribution of ejected subhaloes associated with massive hosts is quite symmetric and quite independent of the distance to the hosts, suggesting that on average there is about equal chance for an ejected subhalo to be moving away from or falling back towards the host. It is also consistent with the results of L09, although the velocities shown in their paper are the peculiar velocities plus the Hubble flow. The average radial velocity of ejected haloes associated with low-mass hosts increases with the distance to the hosts. This is because of the contamination of the fly-bys mentioned above. The behaviour of normal haloes is quite different. Most of the normal haloes are preferentially moving towards the host haloes, as indicated by the systematically negative values of $v_r$. The average value of $v_r/v_{200}$ is about $-0.5$, independent on the distance and the mass of the hosts. The difference here suggests that the ejected subhaloes are a distinctive population among the total halo population. A careful search shows that the scaled velocity dispersion of normal haloes around small host haloes is larger than that around massive host haloes. This may be due to the fact that environmental effects play a more important role around smaller hosts.

Gao et al. (2004) find that the abundance of subhaloes within host haloes decreases with the formation redshift of the hosts, indicating that subhaloes in early-formed host haloes are more likely to be disrupted. However, as pointed out by L09, the subhaloes within a host halo represent a rather incomplete census of the substructure physically related to the host. It is thus important to check whether the abundance of the ejected subhaloes is also related to the assembly time of their hosts. In Fig. 7, we show the number of ejected subhaloes as a function of the assembly redshift of the host halo. The left-hand panel is the result for host haloes with $M_{\text{host}}(t_0) > 10^{14} h^{-1} M_\odot$ and $M_{\text{host}}(t_0) > 0.00031$. As one can see, there is a clear trend that older host haloes tend to eject more subhaloes, although the scatter is quite large. To compare with Gao et al. (2004), we also show the results with $M_{\text{host}}(t_0)/M_{\text{host}}(t_0) > 0.001$ in the right-hand panel of Fig. 7. The trend is weaker, likely
due to the statistical variation caused by small numbers. This trend suggests that the old host haloes tend not only to destroy their subhaloes, but also to eject them. The decrease of subhalo abundance with formation redshift observed by Gao et al. (2004) is therefore a result of both subhalo ejection and destruction. For each host, the number of destroyed subhaloes, \( N_d \), reads

\[ N_d = N_s - (N_e + N_c), \]

where \( N_s \) is the number of total accreted subhaloes, and \( N_e \) and \( N_c \) are the numbers of surviving subhaloes within the host and of ejected subhaloes, respectively. Thus, in order to quantify the importance of ejection and destruction, one needs detailed merging trees to trace the evolution of subhaloes within their hosts.

4 THE ORIGIN OF ASSEMBLY BIAS

Due to the strong interaction with their hosts before ejection, ejected subhaloes may lose part of their mass. Since it is difficult for them to accrete more mass after ejection, the ejected subhaloes should have acquired most of their mass before the ejection. Thus, on average these haloes should have assembly times (defined in Section 2.3) that are earlier than their normal counterparts. In order to show this, we first split the halo sample in a certain mass range into 10 equal-sized subsamples according to assembly redshift. We then calculate the fraction of ejected haloes and the average assembly redshift for each of these subsamples and show the fraction versus the redshift in Fig. 8. Among the 10 per cent haloes with the highest assembly redshifts, about 12–27 per cent are ejected subhaloes depending on the subhalo mass in question. The fraction decreases rapidly down to about 2–5 per cent for haloes with the lowest assembly redshifts. Since the ejected subhaloes are expected to be located in high-density regions due to their associations with massive haloes, they are expected to be strongly clustered. The presence of this population of ejected subhaloes may therefore contribute to the assembly bias seen in cosmological N-body simulations (e.g. Gao et al. 2005; Jing et al. 2007).

In order to examine whether or not the ejected subhaloes are fully responsible for the assembly bias, we estimate the halo bias as a function of assembly redshift separately for all haloes, normal haloes and ejected (sub)haloes. We first estimate the mean overdensity of dark matter within a sphere of radius \( R \) around each dark matter halo, \( \delta(R) \), and then measure the bias parameter of a given set of haloes using

\[ b = \frac{\langle \delta_h(R) \rangle}{\langle \delta_m(R) \rangle}, \]

where \( \langle \delta_h(R) \rangle \) is the average overdensity around the set of haloes in question, and \( \langle \delta_m(R) \rangle \) is the average overdensity within all spheres of radius \( R \) centred on dark matter particles. This method has been demonstrated to reproduce the bias obtained using autocorrelation function of haloes (Wang et al. 2007). The results are shown in Fig. 9. As expected, the ejected subhaloes in general have a much higher bias parameter than other haloes of similar masses. The bias parameter for ejected subhaloes with \( M(h_e) / M_{\text{host}}(t_0) > 0.1 \) is lower (blue dash dot lines), presumably because they are associated with hosts of lower masses, as mentioned above. However, even if all ejected subhaloes are excluded, the assembly bias is still significant (see the red dash lines in Fig. 9). For haloes with masses larger than \( 10^{12} h^{-1} M_\odot \), the assembly bias is almost entirely due to normal haloes instead of ejected subhaloes. Even for haloes of lower masses (e.g. \( \sim 10^{11} h^{-1} M_\odot \)), including ejected only increases the bias parameter by 50 per cent. The reason is that the fraction of ejected subhaloes is small among the total halo population of the same mass. Thus, ejected subhaloes cannot explain the full range of mass dependence of the assembly bias.
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5 SUMMARY AND DISCUSSION

In this paper, we use a high-resolution cosmological simulation to study the distribution of the ejected subhaloes, their connection to the host haloes and their contribution to the halo assembly bias seen in cosmological simulations. Our main results are summarized as follows.

(i) The fraction of the ejected subhaloes in the total halo population of the same mass ranges from 9 to 4 per cent for halo masses from $\sim 10^{11}$ to $\sim 10^{12} h^{-1} M_\odot$.

(ii) The time period an ejected subhalo stays in its host has wide distribution, ranging from less than 0.5 to more than four times the dynamical time of the host. The distribution peaks at 2 and 0.6 for ejected subhaloes with $M_\text{h}(t_e)/M_\text{host}(t_e) < 0.1$ and $>0.1$, respectively, indicating the existence of two distinctive populations of ejected haloes.

(iii) Most of the ejected subhaloes are found to be distributed within about four times the virial radius of their hosts. The fraction of ejected subhaloes is about 30–75 per cent within the distance range between $r_{200}$ and $2r_{200}$ to the hosts and about 10–40 per cent in the distance range $2r_{200} < r < 3r_{200}$.

(iv) The radial velocity distribution of ejected subhaloes is quite symmetric, while normal haloes of the same mass generally tend to fall on to nearby massive haloes.

(v) The number of subhaloes ejected from a host of given mass increases with the assembly redshift of the host. Thus, subhaloes tend to be less abundant in haloes that formed earlier, not only because subhaloes in such hosts are more likely to be destroyed but also because they are more likely to be ejected.

(vi) Ejected subhaloes in general reside in high-density regions, and have a much higher bias parameter than normal haloes of the same mass. They also have earlier assembly times, so that they contribute to the assembly bias of dark matter haloes seen in cosmological simulations.

(vii) The assembly bias is not dominated by the ejected population. This indicates that large-scale environmental effects may also be important in the formation of normal halo population, and in producing the assembly bias.

The results obtained here may have important implications to the understanding of galaxy distribution in the cosmic density field. As a subhalo pass through a massive host, tidal and/or ram-pressure stripping by the host halo may get rid of the gas reservoir in the ejected halo, thereby quenching star formation in it. The situation may be similar to what happens to satellite galaxies, although the ejected galaxies are not observed as satellites in massive haloes. If the quenching processes are effective, we would expect a population of faint red galaxies that are not contained in any massive haloes but are distributed around them. It is therefore interesting to see if such a population of galaxies does exist. In a recent investigation, Wang et al. (2008) found that the reddest 15–20 per cent among all faintest galaxies are physically associated with massive haloes. About half of this population resides within massive haloes.
as satellites. The other half resides outside massive haloes and are distributed within about three times the virial radii of their nearest massive haloes. Very likely, this population of galaxies are hosted by the ejected subhaloes we are studying here. Clearly, it is interesting to study further the connection between ejected subhaloes and this population of galaxies, so as to understand how environmental effects operate on satellite galaxies in their host haloes.

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