THE SUBHALO–SATELLITE CONNECTION AND THE FATE OF DISRUPTED SATELLITE GALAXIES

XIAOHU YANG, H. J. MO, and FRANK C. VAN DEN BOSCH

1 Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, the Partner Group of MPA, Nandan Road 80, Shanghai 200030, China; xhyang@shao.ac.cn
2 Department of Astronomy, University of Massachusetts, Amherst, MA 01003-9305, USA
3 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Received 2008 August 18; accepted 2008 November 13; published 2009 March 3

ABSTRACT

In the standard paradigm, satellite galaxies are believed to be associated with the population of dark matter subhalos. The assumption usually made is that the relationship between satellite galaxies and subhalos is similar to that between central galaxies and host halos. In this paper, we use the conditional stellar mass functions of satellite galaxies obtained from a large galaxy group catalog together with models of the subhalo mass functions to explore the consequences of such assumption in connection to the stellar mass function of satellite galaxies and the fraction and fate of stripped stars from satellites in galaxy groups and clusters of different masses. The majority of the stripped stars in massive halos are predicted to end up as intracluster stars, and the predicted amounts of the intracluster component as a function of the velocity dispersion of galaxy system match well the observational results obtained by Gonzalez et al. (2007). The fraction of the mass in the stripped stars to that remain bound in the central and satellite galaxies is the highest (∼40% of the total stellar mass) in halos with masses $M_h \sim 10^{14} h^{-1} M_\odot$. If all these stars end up in the intracluster component (Max), the total amount of these stars is accreted into the central galaxy (Min), then the maximum fraction of the total stars in the whole universe that is in the diffused intracluster component is ∼19%, and the minimum is ∼5%. In the case of “Max,” the stellar mass of the intracluster component in massive halos with $M_h \sim 10^{13} h^{-1} M_\odot$ is roughly six times as large as that of the central galaxy. This factor decreases to ∼2, 1, and 0.1 in halos with $M_h \sim 10^{12}$, $10^{13}$, and $10^{12} h^{-1} M_\odot$, respectively. The total amount of stars stripped from satellite galaxies is insufficient to build up the central galaxies in halos with masses $\lesssim 10^{12.5} h^{-1} M_\odot$, and so the quenching of star formation must occur in halos with higher masses. In semianalytical models and simulations that do not resolve the diffused component, caution must be exercised when using the observed stellar mass/luminosity function of galaxies to constrain the star formation, feedback and merger processes in dark matter halos.

Key words: dark matter – galaxies: halos – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

Recent years have seen a dramatic impetus to link galaxies to their dark matter halos. In particular, the development of powerful statistical tools such as the halo model, the halo occupation distribution (HOD) and the conditional luminosity function (CLF), combined with the availability of large redshift surveys such as the two-Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000), have resulted in reliable descriptions of how galaxies with different properties are distributed over halos of different masses (e.g. Jing et al. 1998; Peacock & Smith 2000; Berlind & Weinberg 2002; Yang et al. 2003; van den Bosch et al. 2003, 2007; Zheng et al. 2005; Tinker et al. 2005; Cooray 2006; Brown et al. 2008; Cacciato et al. 2008).

An important aspect of this galaxy–dark matter connection is that there are two different kinds of galaxies: central galaxies, which reside at rest at the center of their dark matter halo, and satellite galaxies, which orbit the halo associated with a central galaxy. It is generally believed that satellite galaxies themselves reside in dark matter subhalos. Prior to being accreted into their current host halo, satellite galaxies were central galaxies, and their associated subhalos were host halos (throughout this paper we use the term “host halo” to refer to a dark matter halo that is not a subhalo). This implies a direct link between the occupation statistics of dark matter halos, and their merger/accretion histories.

While orbiting the host halo, subhalos and their associated satellite galaxies are subjected to dynamical friction which causes the substructure to lose its momentum and to sink toward the center of the host halo. In the mean time, the substructure is subjected to tidal forces which try to dissolve it. In particular, tidal heating and stripping cause the system to loose mass, and may even result in the complete disruption of a subhalo and its satellite galaxy. There are thus three possible fates for the stars in satellite galaxies: (i) they remain bound to a surviving satellite galaxy, (ii) they are accreted by the central galaxy, or (iii) they are stripped from the satellite galaxy, giving rise to a stellar halo, which are stars that orbit the host halo but that are not gravitationally bound to any particular galaxy. Throughout this paper we will refer to the stars that belong to (ii) and (iii) combined as the “nonsurviving population.” Obviously, the satellites that are disrupted contribute their entire stellar content to the central galaxy or stellar halo, while the survived satellite galaxies may also contribute significantly due to tidal stripping.

The idea that satellite galaxies are stripped and/or disrupted is a standard prediction of hierarchical models of structure formation. Numerous studies have addressed how this phenomenon gives rise to stellar halos in systems ranging from spiral galaxies like our own Milky Way (e.g. Searle & Zinn 1978; Johnston et al. 1996; 2001; Robertson et al. 2005; Font et al. 2006) to
rich galaxy clusters (e.g. Gallagher & Ostriker 1972; Merritt 1983; Mihos 2005; Willman et al. 2004; Lin & Mohr 2004; Conroy et al. 2007; Purcell et al. 2007; 2008; Henriques et al. 2008). There is also ample observational support for the existence of stellar halos formed out of disrupted satellite galaxies. In particular, in recent years it has become clear that the stellar halo of the Milky Way reveals a large amount of substructure in the form of stellar streams (Helmi et al. 1999; Yanny et al. 2003; Bell et al. 2008). In some cases these streams can be unambiguously associated with their original stellar structure (Ibata et al. 1994; Odenkirchen et al. 2002). Similar streams have also been detected in our neighbor galaxy M31 (e.g. Ferguson et al. 2002). Unfortunately, due to their extremely low surface brightnesses, it is very difficult to detect stellar halos in more distant galaxies (but see Zibetti et al. 2004). Consequently, our knowledge of stellar halos around individual galaxies is fairly limited. However, groups and clusters of galaxies also contain a significant stellar halo component, which is usually referred to as “intracluster stars” (ICS)4. In fact, data indicates that the fraction of stars associated with such an ICS component increases with increasing halo mass (Gonzalez et al. 2007): in massive clusters the mass of the stellar halo can be as large as ten times the stellar mass of the central (brightest) cluster galaxy (Gonzalez et al. 2005; Seigar et al. 2007).

With the use of high-resolution numerical simulations, it has recently become possible to accurately determine the properties (mass function, spatial distribution, orbits, density profiles, spins) of the population of dark matter subhalos (e.g. Gao et al. 2004; De Lucia et al. 2004; Tormen et al. 2004; van den Bosch et al. 2005; Weller et al. 2005; Diemand et al. 2007; Giocoli et al. 2008). If subhalos are indeed associated with satellite galaxies, these properties should be related to the luminosity function, spatial distribution, orbits, and structural properties of satellite galaxies. Unfortunately, the exact link between satellite galaxies and dark matter subhalos is not trivial. Since the stellar component of a satellite is expected to be more tightly bound than its surrounding dark matter (due to dissipation during the formation process), the dark matter is more easily stripped, thus causing the ratio between stellar mass and total mass to increase with time. Consequently, it is to be expected that the occupation statistics of subhalos as a function of their (current) mass are different from those of host halos. However, since subhalos were host halos before being accreted, it seems likely that the occupation statistics of subhalos as a function of their mass at the time of accretion are identical to those of host halos at that time. Indeed, it has been shown that models based on this ansatz are extremely successful in explaining the correlation functions and luminosity functions of galaxies at different redshifts (e.g. Vale & Ostriker 2004, 2006; Conroy et al. 2006). However, since satellite galaxies only make up a small fraction (≤ 30%) of the total galaxy population (e.g. van den Bosch et al. 2007, 2008; Tinker et al. 2007; Yang et al. 2008a), this consistency cannot be considered a sensitive test of the subhalo–satellite connection. This is also apparent from the fact that models that link satellite properties to the current subhalo mass can also fit the data remarkably well (see e.g., Mandelbaum et al. 2006; Kim et al. 2008).

In this paper, we use the conditional stellar mass function of satellite galaxies and the relation between stellar mass and halo mass for central galaxies, together with the subhalo mass functions obtained from recent numerical simulations, to determine the relation between satellite galaxies and dark matter subhalos. In particular, we investigate what fraction of satellite galaxies survives, what fraction is accreted into the central galaxy, and what fraction is tidally disrupted. Our approach is empirical, because the stellar mass functions and the central stellar mass–halo mass relation are obtained from a large SDSS galaxy group catalog. The structure of this paper is organized as follows. Section 2 gives a brief description of the data and the model used in this paper. In Section 3 we present our predictions of the conditional stellar mass functions for satellite galaxies. In Section 4 we discuss the possible fates of the stars that are stripped from the satellite galaxies. Finally, we summarize our results in Section 5. Throughout this paper we adopt a ΛCDM cosmology with parameters that are consistent with the three-year data release of the WMAP mission (hereafter WMAP3 cosmology): $Ω_m = 0.238$, $Ω_L = 0.762$, $Ω_b = 0.042$, $n = 0.951$, $H_0/(100$ km s$^{-1}$ Mpc$^{-1}) = 0.73$ and $σ_8 = 0.75$ (Speagle et al. 2007).

### 2. DATA AND ANALYSIS

The data used in this paper is based on the SDSS galaxy group catalogs of Yang et al. (2007; hereafter Y07). These catalogs are constructed by applying the halo-based group finder developed by Yang et al. (2005) to the New York University Value-Added Galaxy Catalog (NYU-VAGC; see Blanton et al. 2005), which is based on SDSS Data Release 4 (Adelman-McCarthy et al. 2006). Detailed tests have shown that this group finder is very successful in associating galaxies according to their common dark matter halos, and that the halo masses that have been assigned to the groups are reliable.

In Yang et al. (2008a, 2008b) we have used these group catalogs to determine the conditional luminosity functions (CLF) and the conditional stellar mass functions (CSMF) separately for central and satellite galaxies. Central galaxies are defined as the most massive group members in terms of their stellar mass, and satellites are the group members that are not centrals. The CSMF of satellite galaxies, $Φ_s(M_s|M_h)$, gives the average number of satellites with stellar masses in the range $M_s + dM_s$ that reside in a host halo of mass $M_h$. The open circles in Figure 2 reflect the scatter among these four results, which in general are much larger than the statistical errors obtained using bootstrap samples.

In order to link the satellites to the subhalo population, we also need the subhalo mass function (SHMF). In fact, since it is expected that the properties of satellite galaxies are linked to the mass of their subhalos at their time of accretion (see discussion in Section 1), we need the so-called “unevolved” SHMF, $n_{\text{un}}(m_s|M_h)$, which gives the number of subhalos that have been accreted by the main progenitor of a halo of present day mass $M_h$, as a function of their mass $m_s$ at the time of accretion. This unevolved SHMF should not be confused with the “evolved” SHMF: $n_{\text{ev}}(m'_s|M_h)$, which gives the number of subhalos with present-day masses in the range $m'_s + dm'_s$ that reside, at present, in a host halo of mass $M_h$. The unevolved SHMF evolves into the evolved SHMF due to the combined effect of dynamical friction, tidal stripping and tidal heating, which causes some subhalos to dissolve, and others to loose mass (see van den Bosch et al. 2005 for details).
Using high-resolution numerical simulations, Giocoli et al. (2008) found that the unevolved SHMF is accurately described by

\[
n_{un,0}(m_s|M_h) = \frac{0.176}{M_h} \left( \frac{m_s}{M_h} \right)^{-1.8} \exp \left[ -12.27 \left( \frac{m_s}{M_h} \right)^{3/2} \right].
\]

(1)

Figure 1 shows the predictions for the unevolved subhalo, sub1-subhalo, and sub2-subhalos for the CSMFs for mass halo. There are two possible explanations for this discrepancy. Comparing the model predictions with the observational data, we found that the stellar mass–halo mass relation for subhalos is different from that for the main halo due to the accretion. As we can see, the contributions from sub1-subhalos and sub2-subhalos to the total CSMF can be larger than that from the subhalos at log(m_s/M_h) ≲ −3 and ≲ −6, respectively. They can thus contribute a significant fraction of (small) satellite galaxies.

The final ingredient for our modeling is the conditional probability distribution, \( P_c(M_s|M_h) \), that a halo of mass \( M_h \) hosts a central galaxy with stellar mass \( M_s \). Using our SDSS galaxy group catalogs, YMB08 found that \( P_c(M_s|M_h) \) is well described by a log-normal distribution whose median is

\[
\langle M_s \rangle(M_h) = M_0 \left( \frac{M_h/M_s}{1 + M_h/M_s} \right)^{\alpha + \beta}.
\]

(3)

Here \( M_1 \) is a characteristic halo mass so that \( M_s \propto M_1^{\alpha + \beta} \) for \( M_h \ll M_1 \) and \( M_s \propto M_1^{\alpha} \) for \( M_h \gg M_1 \). The parameters obtained from the SDSS groups are: log \( M_0 = 10.306 \), log \( M_1 = 11.040 \), and \( \alpha = 0.315 \), and \( \beta = 4.543 \), where \( M_0 \) is in units of \( h^{-2} M_\odot \) and \( M_1 \) in \( h^{-1} M_\odot \) (see YMB08 for details). The width of \( \mathcal{P}_c(M_s|M_h) \) is found to be roughly independent of halo mass (see also More et al. 2009), with a dispersion \( \sigma(\log M_s) = 0.173 \).

3. THE DISRUPTION OF SATELLITE GALAXIES

The prediction of the CSMF of satellite galaxies can be written as

\[
\Phi_s(M_s|M_h) = \int_0^{\mathcal{P}_c(M_s|M_h)} n_{un}(m_s|M_h) dm_s,
\]

(4)

where \( \mathcal{P}_c(M_s|M_h) \) is the probability that a subhalo of mass \( m_s \) at the time of accretion hosts a present-day satellite galaxy with stellar mass \( M_s \), and

\[
n_{un}(m_s|M_h) = \sum_{i=0}^{N_{\text{max}}(i)} n_{un,i}(m_s|M_h)
\]

(5)

is the unevolved SHMF, including all sub\( i \)-subhalos up to level \( N_{\text{max}} \). We start by assuming that the stellar mass–halo mass relation does not evolve with redshift, so that \( \mathcal{P}_c(M_s|M_h) = \mathcal{P}_c(M_s|M_h = m_s) \). In this case, we denote the model prediction of \( \Phi_s \) by \( \Phi_{un} \), and so

\[
\Phi_{un}(M_s|M_h) = \int_0^{\mathcal{P}_c(M_s|M_h)} n_{un}(m_s|M_h) dm_s.
\]

(6)

The solid lines in each of the panels of Figure 2 show the CSMFs for mass halo. There are two different possible explanations for this discrepancy. First, halos of a given mass at high redshift may contain different satellite population contributed by the sub3-subhalos is roughly 1% in halos with \( \mathcal{P}_c(M_s|M_h) \) to refer to the \( h \)-th level of subhalos. In modeling the satellite population associated with the subhalos, neglecting the “sub-subhalo” populations may result in an underestimate of the number of satellite galaxies. This is especially true for massive systems, where the merging progenitors may already contain relatively massive satellite galaxies.

Fortunately, because of the similarities of the unevolved SHMF (Equation (1)), we can calculate the unevolved SHMF including the sub\( i \)-subhalo populations. Assuming that Equation (1) also applies to subhalos, the SHMF of sub\( i \)-subhalos can be written as

\[
n_{un,i}(m_s|M_h) = \int_0^{\mathcal{P}_c(M_s|M_h)} n_{un,0}(m_s,M_h) n_{un,i-1}(m_s|M_h) dm_s.
\]

(2)
from that of present day central galaxies. In order to explain the discrepancy, the stellar mass fractions of halos of a given mass then have to be lower at higher redshifts. Furthermore, since the extent of the discrepancy depends on halo mass, the amplitude of the redshift dependence has to be different for halos of different masses. This solution is not very likely, since it is rather contrived to assume that the star-formation efficiency in progenitor halos depends on the mass of the halo in which it will end up in the future. Nevertheless, we acknowledge that the average relation between halo mass and stellar mass may well evolve with redshift (see e.g., Conroy & Wechsler 2008 for empirical constraints in support of such evolution). However, given the typical accretion times for subhalos, we believe that this will not have a strong impact on our results. This is also supported by the work of Purcell et al. (2007), who have shown that the predictions for the stellar mass fractions are extremely robust to changes in the star-formation histories of the galaxies. The second, more likely, possibility is that the subhalos and their satellite galaxies experience mass loss and/or disruption due to the combined effect of dynamical friction and tidal forces.

In this paper we focus on the second possibility. In this case, a satellite galaxy can either be completely disrupted, hence does not contribute to the satellite population, or experience mass loss but survives as a satellite of lower mass. Both of these effects can change the predicted stellar mass function of satellite galaxies relative to \( \Phi_{\text{un}} \). As an illustration, let us consider a simple model in which a satellite is either completely disrupted or remains intact. This assumption is consistent with the simulation results that a satellite is quickly disrupted after it has lost a significant amount of mass (Moore et al. 1999). It is also valid if the disruption of a satellite is due to a merger into the central galaxy. As shown in van den Bosch (2005) and Giocoli et al. (2008), on average the instantaneous mass loss rate of a subhalo depends on the ratio between the instantaneous subhalo mass and the host halo mass at the time in question. Here we ignore such details. Instead we consider a simple model where the survivor fraction, \( f \), is a function of the ratio between the subhalo mass at accretion, \( m_s \), and the host halo mass at the present time, \( M_h \). Motivated by the roughly self-similar behavior of the subhalo population, we assume that \( f(m_s/M_h) \) is universal in halos of different masses. For a given \( f(m_s/M_h) \) the CSMF is given by Equation (4), but with \( n_{\text{un}}(m_s) \) replaced by \( f(m_s/M_h) n_{\text{un}}(m_s/M_h) \). We model \( f(x) \) using a polynomial form, \( f(x) = a + bx + cx^2 + dx^3 \), and determine the free parameters \( (a, b, c, d) \) by fitting the model to nine CSMFs that cover the mass range \( 12.0 \leq \log M_h \leq 14.7 \), each with a 0.3 dex bin width in halo mass. The CSMFs corresponding to the best-fit model are shown as the long-dashed lines in Figure 3. Note that this simple model fits the data surprisingly well, supporting the assumption that the survivor fraction depends only on \( m_s \) and \( M_h \) via their ratio. The best-fit \( f(m_s/M_h) \) is shown in Figure 4, which shows that the survivor fraction decreases monotonically with subhalo mass, from \( \sim 1 \) for subhalos with \( m_s \sim 10^{-3.5} M_h \) to \( \sim 0.1 \) for subhalos with \( m_s \sim 0.6 M_h \) (recall that \( m_s \) refers to the subhalo mass at the time of accretion). Thus, if the stellar mass–halo mass relation does not evolve with redshift, then more massive (relative to their host) subhalos and their associated satellite galaxies are predicted to have a smaller survival probability. This is consistent with a picture in which dynamical friction is responsible for transporting satellite galaxies to the inner regions of their host halos, where they are more likely to be disrupted by tidal forces or to merge with the central galaxy.
Figure 3. Same as Figure 2, but here we show the predicted total CSMFs using the unevolved (solid lines) SHMF and the best fit results (long-dashed lines) of the model described in the text, respectively. (A color version of this figure is available in the online journal.)

Figure 4. Best-fit (survival) fraction of subhalos that can host satellite galaxies in the same way as halos can host central galaxies at present time \( z = 0 \). Here we assume that the subhalos in host halos of different masses have the same survival fraction as a function of \( m_s/M_h \). As shown in Figure 2 the best-fit predictions of this model are remarkably good.

4. MERGING, TIDAL DISRUPTION AND QUENCHING

We can use the stellar mass–halo mass relation to predict the following stellar mass components for halos of a given mass: the total stellar mass that the satellite galaxies bring into the host halo, which is given by

\[
M_{\ast,\text{un}}(M_h) = \int_0^\infty dM_\ast M_\ast \Phi_{\ast,\text{un}}(M_\ast|M_h),
\]

and the total stellar mass in surviving satellite galaxies,

\[
M_{\ast,s}(M_h) = \int_0^\infty dM_\ast M_\ast \Phi_{\ast,s}(M_\ast|M_h).
\]

Note that both \( M_{\ast,\text{un}}(M_h) \) and \( M_{\ast,s}(M_h) \) can be obtained without assuming whether a satellite is completely disrupted or only partly stripped. The difference between these two stellar masses, \( M_{\ast,\text{ns}}(M_h) = M_{\ast,\text{un}}(M_h) - M_{\ast,s}(M_h) \), is the total stellar mass of the nonsurvivors, which consists of the stars in satellite galaxies that are completely disrupted and those that are stripped from the satellite galaxies. In other words, \( M_{\ast,\text{ns}} \) is the sum of the stellar mass of the stellar halo (i.e., the ICS) plus the stellar mass of the central galaxy that has been accreted from satellite galaxies.

The left-hand panel of Figure 5 shows the predictions for \( M_{\ast,\text{un}} \) (long-dashed line), \( M_{\ast,s} \) (short-dashed line), and \( M_{\ast,\text{ns}} \) (dot–dashed line), all as functions of halo mass. For comparison, the solid line shows the stellar mass of central galaxies as a function of halo mass (i.e., the stellar mass–halo mass relation given by Equation (3)). Note that, in massive halos with \( M_h \gtrsim 10^{13} \, h^{-1} \, M_\odot \), the stellar mass in the nonsurviving component is larger than the stellar mass of the central galaxy.

The dashed line in the right-hand panel of Figure 5 shows \( M_{\ast,\text{ns}}/(M_{\ast,c} + M_{\ast,s}) \), the ratio between the stellar mass of the nonsurviving component and the combined stellar mass of the central galaxy and the surviving satellites. In terms of \( M_{\ast,\text{ns}}/(M_{\ast,c} + M_{\ast,s}) \), halos with \( M_h \sim 10^{13} \, h^{-1} \, M_\odot \) have the highest ratio, \( \sim 0.6 \), i.e., \( \sim 40\% \) of the total stellar mass is in the nonsurviving component. In less massive halos, the ratio drops rapidly due to the fact that the stellar mass–halo mass relation is extremely steep at the low mass end, so that low-mass subhalos contain very few stars even at their time of accretion. At the massive end the ratio also decreases due to two effects. First of all, for \( M_h \gtrsim 10^{12} \, h^{-1} \, M_\odot \) the stellar mass fractions decline with increasing halo mass (i.e., the slope of the stellar mass–halo mass relation is less than unity), so that more massive subhalos contribute fewer stars per unit dark matter mass. Second, many of the fainter satellite galaxies, which reside in less massive
subhalos, can survive since dynamical friction is not effective for subhalos with small \(m_s/M_h\).

The ratio of stars that are in the nonsurviving component in the entire universe to those that are locked up in either central or satellite galaxies can be estimated using

\[
R_{\text{ns}} = \frac{\int_0^\infty M_{s,\text{ns}}(M_h)n(M_h)dM_h}{\int_0^\infty [M_{s,c}(M_h) + M_{s,s}(M_h)]n(M_h)dM_h},
\]

where \(n(M_h)\) is the halo mass function (e.g., Sheth et al. 2001; Warren et al. 2006). We find that \(R_{\text{ns}} \sim 23\%\). If we assume that all of the stars in the nonsurviving component are turned into ICS, then \(\sim 19\%\), which is the upper limit, of the stellar mass in the universe is in ICS. On the other hand, if we assume that maximum of these stars are accreted by the central galaxies, then \(\sim 5\%\), which is the lower limit, of the stellar mass in the universe is in ICS.

4.1. The Fate of Stripped and Dispersed Stars

We now investigate the fate of the stars that are stripped from satellite galaxies. In particular, we examine what fraction is actually disrupted by tidal forces, thus giving rise to a stellar halo (i.e., the ICS), and what fraction is accreted by the central galaxy. For this purpose, we show as the solid line in the right-hand panel of Figure 5, the ratio between the stellar mass of the nonsurviving component, \(M_{s,\text{ns}}\), and that of the central galaxy \(M_{s,c}\). As one can see, in small mass halos with \(M_h \lesssim 10^{13} \text{ h}^{-1} \text{ M}_\odot\), the mass of the stripped stars is much smaller than that of the central galaxy, indicating that the latter cannot have grown substantially due to the accretion of satellites. Rather, central galaxies in low-mass halos must have grown predominantly via star formation. It also means that if all the mass of the stripped stars ends up as a stellar halo, the mass of that stellar halo can only be a small fraction of the mass of the central galaxy. In halos with \(M_h \gtrsim 10^{13} \text{ h}^{-1} \text{ M}_\odot\), on the other hand, \(M_{s,\text{ns}} \gg M_{s,c}\), and a very significant fraction of the stellar mass of the central galaxy may consist of accreted stars stripped from satellites (but does not have to). It is also clear that we can exclude the possibility that all stripped stars are accreted into the central galaxy, as this would imply stellar masses for the brightest cluster galaxies that are about 8 times higher than observed. Rather, the stripped stars must have given rise to a substantial stellar halo.

The solid dots with errorbars in Figure 6 show the observed fractions of the total stellar mass present in groups and clusters that is contained in the central galaxy and the ICS as a function of the line-of-sight velocity dispersion. Data with errorbars are obtained from Gonzalez et al. (2007), measured within \(r_{500}\) for the 23 groups and clusters in their sample. The solid and dashed lines are our model predictions for the two extreme cases. See the text for details.

(A color version of this figure is available in the online journal.)
all stars of the nonsurviving component are added to the stellar halo (i.e., no stars stripped from satellite galaxies are accreted by the central galaxy). Clearly, this corresponds to the maximum amount of ICS possible. The dashed lines, labeled “Min,” correspond to the minimum amount of ICS, i.e., the stellar mass in the ICS is assumed to be \( \max(M_{*,ns} - M_{*,c}, 0) \). Note that the data of Gonzalez et al. (2007) are obtained within \( r_{500} \), the radius within which the cluster mass density exceeds the critical value by a factor of 500. In our model prediction, the total mass of satellite galaxies within \( r_{500} \) is estimated by assuming that the distribution of satellite galaxies follow the NFW (Navarro et al. 1997) profile with concentration appropriate for the halo mass in question. For the distribution of ICS, we consider two cases. Case I assumes that the ICS has the same distribution as the satellite galaxies, and the corresponding results are shown in Figure 6 as the two thin lines. Case II assumes that all ICS are distributed within \( r_{500} \), and the corresponding results are shown in Figure 6 by the two thick lines. It is reassuring that, for a given assumption of the ICS distribution, the two extreme models, “Max” and “Min,” give quite similar results. The prediction of Case I is in good agreement with the data over the entire range of masses probed, while Case II overpredicts the ratio moderately. It is unclear whether this moderate discrepancy necessarily implies that the distribution of the ICS extends beyond \( r_{500} \), because there are other factors that can cause such discrepancy. For example, stars in the central galaxy and in the ICS component may, on average, have a higher stellar mass-to-light ratio than those in the surviving satellites, so that the ratio \( (M_{*,c} + M_{*,ICS})/M_{*,total} \) is underestimated in the data due to the assumption of the same stellar mass-to-light ratio for all components. In addition, there are also uncertainties in the estimates of the velocity dispersions, \( \sigma \), particularly for poor systems. Given these uncertainties, we consider the overall agreement between the data and the model prediction remarkable. Clearly, better observational data are required in order to distinguish the different models considered here.

The idea that a significant fraction of the stars stripped from satellite galaxies end up as ICS is not only consistent (in fact, required) by the data, but has also been found in hydrodynamical simulations of galaxy clusters (e.g., Napolitano et al. 2003; Murante et al. 2004, 2007; Willman et al. 2004; Sommer-Larsen et al. 2005; Rudnick et al. 2006). In addition, as shown by Monaco et al. (2006) and Conroy et al. (2007), the creation of a significant ICS component is also required in order to reconcile the low rate at which massive galaxies have grown since \( z = 1 \), with the relatively high rate at which their host halos (i.e., the clusters) have grown in mass (see also Brown et al. 2008). Finally, Kang & van den Bosch (2008) argue in favor of the creation of stellar halos in order to prevent central galaxies from accreting too many blue and/or gas rich satellites, which would cause central galaxies to be too blue.

Recently Purcell et al. (2007) used the analytic model for subhalo infall and evolution of Zentner et al. (2005), combined with empirical constraints on the stellar mass fractions of accreted subhalos, to predict the diffuse stellar mass fractions of dark matter halos. They predict that the average stellar mass fraction in diffuse, intrahalo light increases strongly from \( \sim 0.005 \) for small galaxy halos \( (\sim 10^{11} h^{-1} M_\odot) \) to \( \sim 0.2 \) for poor groups \( (\sim 10^{13} h^{-1} M_\odot) \), after which the trend with mass flattens considerably. A comparison with the right-hand panel of Figure 5 shows that this is in remarkable agreement with our predictions that have been deduced using a completely different approach. In addition to this, Purcell et al. (2007) also compared their model predictions to the observational data of Gonzalez et al. (2007), similar to our comparison in Figure 6, and reached a similar conclusion as ours, namely that the vast majority of subhalo stars must be deposited into a diffuse halo component. Similar results have also been obtained by Henriques et al. (2008) using a semianalytical model for galaxy formation that includes a simple treatment for the disruption of satellite galaxies. It is reassuring that different approaches yield results that are in such good agreement.

### 4.2. A Lower Limit on the Halo Mass for Quenching Star Formation

In hierarchical models of structure formation, massive halos are built up by the mergers of smaller ones. Over the years, it has become clear that a successful model for galaxy formation in such a hierarchical framework requires a mechanism that can quench star formation in massive galaxies. Currently, the most favored quenching mechanism is feedback from an active galactic nucleus (AGN), which is often assumed to operate above a given halo mass, \( M_q \) (e.g. Croton et al. 2006; Cattaneo et al. 2006, and references therein). We can use the results presented above to put a lower limit on this quenching mass \( M_q \), as follows.

In general, the stars in a central galaxy may come from two different channels: (i) in situ formation, and (ii) accretion from satellite galaxies (those that are part of the nonsurviving component). Consider a model in which star formation is abruptly quenched in halos with \( M_h > M_{q} \). In such quenched halos, the total amount of stars from channel (i) is at most equal to \( M_{*,0} \), the stellar mass contained in the central galaxy of a halo with mass \( M_h \). It may be smaller than \( M_{*,0} \), because part of this mass may be due to accretion rather than in situ formation. The total amount of stars from channel (ii) is at most \( M_{*,ns} \), because part of the disrupted mass may end up in the ICS. In Figure 7, we show the ratio \( (M_{*,ns} + M_{*,0})/M_{*,c} \), as a function of halo mass. Different lines show the results for different values of \( M_q \) [\( \sim 0 \) (solid line), \( 10^{11.8}, 10^{12.0}, 10^{12.2}, 10^{12.4} h^{-1} M_\odot \)]. As one can see, if \( M_q \leq 10^{12.4} h^{-1} M_\odot \), the total stellar mass from the two channels, \( M_{*,ns} + M_{*,0} \), is insufficient to account for the stellar masses of the central galaxies in halos with \( M_h \sim 10^{12.2} h^{-1} M_\odot \). However, for \( M_q \geq 10^{12.4} h^{-1} M_\odot \), both the ratio \( (M_{*,ns} + M_{*,0})/M_{*,c} \) \( > 1 \) for all halo masses. This
implies that if a quenching mass $M_q$ exists, it must be larger than or equal to $10^{12.4} h^{-1} M_\odot$.

5. DISCUSSION AND SUMMARY

Using the conditional stellar mass functions for satellite galaxies obtained by Yang et al. (2008b) and the subhalo mass functions given by Giocoli et al. (2008), we study the connection between subhalos and satellite galaxies. Assuming that at the time of accretion satellite galaxies are associated with subhalos according to the same stellar mass–halo mass relation as present day central galaxies with halos, we predict the stellar mass function of satellite galaxies and compare our model predictions with observations. Our main results can be summarized as follows:

1. Assuming that the stellar masses of satellite galaxies do not evolve after they are accreted into the host halos, we find that the model overpredicts the population of satellite galaxies, especially in low-mass halos. One solution, albeit unlikely, is that the stellar mass fractions of halos at higher redshifts are lower than at the present. The other, which is considered in the present paper, is that a significant fraction of satellite galaxies have been stripped of their stars or even totally disrupted.

2. Assuming that the amount of disruption of satellite galaxies is a function of the ratio between the mass of the subhalo and that of the host halo, we find that the surviving fraction can be described by $f(x = \log(m_s/M_h)) = -0.041 - 0.820x - 0.422x^2 - 0.078x^3$. The decrease in $f$ with increasing $m_s/M_h$ is consistent with the idea that dynamical friction brings subhalos and satellite galaxies to the inner part of the host halo where stripping and disruption are more efficient.

3. The majority of the stars stripped from satellites in massive halos are predicted to end up as ICS, and the predicted amounts of the intracluster component as a function of the velocity dispersion of galaxy system match well the observational results obtained by Gonzalez et al. (2007).

The fraction of the mass in the stripped stars to that in the surviving central and satellite galaxies is predicted to be the highest ($\sim 40\%$) of the total in halos with masses $\sim 10^{14} h^{-1} M_\odot$. If all these stripped stars end up in the intracluster component (Max), or maximum of them are accreted into the central galaxy (Min), then we can predict that a maximum $\sim 19\%$ and a minimum $\sim 5\%$ of the total stars in the whole universe are in terms of the diffused intracluster component.

4. Stars stripped from satellite galaxies are not sufficient to build up the central galaxies in halos with masses $\lesssim 10^{13.5} h^{-1} M_\odot$, and so star formation should not be quenched in halos with masses up to at least $10^{12.9} h^{-1} M_\odot$.

It should be pointed out once again that our results are based on the assumption that subhalos have the same stellar mass–halo mass relation as the host halos at redshift $z = 0$. If the total amount of stars that can form in a halo at higher redshift is larger than that in a halo of the same mass at lower redshift (e.g., Cooray 2005), the predicted disrupted fraction of satellite galaxies would be larger, and so would be the predicted mass of ICS. On the other hand, if the total amount of stars that can form in high-$z$ halos is lower than that in its $z = 0$ counterparts, the predicted ICS fraction would be lower. It is interesting that the observed ICS fraction is matched well with the assumption that the total amount of stars that can form in a halo of a given mass is independent of redshift. This assumption is also consistent with the results obtained by Wang et al. (2006) based on a semianalytical model of structure formation. However, current semianalytical models of galaxy formation ignore the existence of the ICS component, so that the stars that formed in subhalos are assumed either to remain in satellite galaxies or to merge into central galaxies. Consequently, such models either predict too high a mass for the central galaxies in massive halos or overpredict the number of satellite galaxies in group-sized halos.

As described above, the mass fraction of stars in the diffuse ICS component is much larger than that in the central galaxies for halos with masses $\gtrsim 10^{14} h^{-1} M_\odot$, and even in the whole universe, this stellar mass component is a significant fraction of $\sim 19\%$ (upper limit) or $\sim 5\%$ (lower limit). The implication of the existence of such a stellar component for galaxy formation has yet to be explored. Indeed, if the total amount of stars in groups, clusters and in the universe is larger than that implied by the observed stellar mass function of galaxies, and if semianalytical models and numerical simulations do not resolve the ICS component, then it would be incorrect to use the observed stellar mass/luminosity function of galaxies to constrain star-formation efficiency and feedback. Furthermore, the fraction of the ICS component in halos of different masses may also convey important information about the evolution of galaxies in different environments. Clearly, more theoretical work is required in order to make full use of the information provided by the ICS component.

We are grateful to the anonymous referee for useful and insightful comments that helped to improve the presentation. This work is supported by the One Hundred Talents project, Shanghai Pujiang Program (No. 07pj14102), 973 Program (No. 2007CB815402), the CAS Knowledge Innovation Program (Grant No. KJCX2-YW-T05) and grants from NSFC (Nos. 10533030, 10673023, 10821302). H.J.M. would like to acknowledge the support of NSF AST-0607535, NASA AISR-126270 and NSF IIS-0611948.

REFERENCES

Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Bell, E. F., et al. 2008, ApJ, 680, 295
Berlind, A. A., & Weinberg, D. H. 2002, ApJ, 575, 587
Blanton, M. R., et al. 2005, AJ, 129, 2562
Brown, M. J. I., et al. 2008, ApJ, 682, 937
Cacciato, M., van den Bosch, F. C., More, S., Li, R., Mo, H. J., & Yang, X. 2008, MNRAS, submitted (arXiv:0807.4932)
Cattaneo, A., Dekel, A., Devriendt, J., Guiderdoni, B., & Blaizot, J. 2006, MNRAS, 370, 1651
Colless, M. et al. 2001, MNRAS, 328, 1039
Cooray, A., & Wechsler, R. H. 2008, arXiv:0805.3346
Cooray, A., Wechsler, R. H., & Kravtsov, A. V. 2006, ApJ, 647, 201
Cooray, A., Wechsler, R. H., & Kravtsov, A. V. 2007, ApJ, 668, 826
Cooray, A. 2005, MNRAS, 364, 303
Cooray, A. 2006, MNRAS, 365, 842
Croton, D. J., et al. 2006, MNRAS, 365, 11
De Lucia, G., et al. 2004, MNRAS, 348, 333
Diemand, J., Kuhlen, M., & Madau, P. 2007, ApJ, 667, 859
Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452
Font, A. S., Johnston, K. V., Bullock, J. S., & Robertson, B. E. 2006, ApJ, 638, 585
Gallagher, J. S., III, & Ostriker, J. P. 1972, AJ, 77, 288
Gao, L., White, S. D. M., Jenkins, A., Stoehr, F., & Springel, V. 2004, MNRAS, 355, 819
Giocoli, C., Tormen, G., & van den Bosch, F. C. 2008, MNRAS, 386, 2135
