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Constraints on the Merging Timescale of Luminous Red Galaxies, Or, Where Do All the Halos Go?

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ABSTRACT

In the ΛCDM cosmology dark matter halos grow primarily through the accretion of smaller halos. Much of the mass in a halo of $10^{14}\,M_{\odot}$ comes in through accretion of $\sim 10^{13}\,M_{\odot}$ halos. If each such halo hosted one luminous red galaxy (LRG) then the accretion of so many halos is at odds with the observed number of LRGs in clusters unless these accreted LRGs merge or disrupt on relatively short timescales (~ 2 Gyr). These timescales are consistent with classical dynamical friction arguments, and imply that $2-3$ LRGs have merged or disrupted within each halo more massive than $10^{14}\,M_{\odot}$ by $z = 0$. The total amount of stellar mass brought into these massive halos by $z = 0$ is consistent with observations once the intracluster light (ICL) is included. If disrupted LRGs build up the ICL, then the hierarchical growth of massive halos implies that a substantial amount of ICL should also surround satellite LRGs, as suggested by recent observations of the Virgo cluster. Finally, we point out that these results are entirely consistent with a non-evolving clustering strength and halo occupation distribution, and note that observations of the latter in fact support the hypothesis that merging/disruption of massive galaxies does indeed take place at late times.

1 INTRODUCTION

The formation and evolution of massive red galaxies provide a critical testing ground for modern theories of galaxy formation based on hierarchical merging of dark matter halos. Ongoing growth of massive halos via mergers is a generic feature of hierarchical models, such as cold dark matter (CDM). However evidence for the ongoing assembly of massive galaxies is at best inconclusive. Evolution in the galaxy stellar mass and luminosity functions at the massive/luminous end appears quite modest since $z = 1$ (e.g. Drory et al. 2004; Bundy et al. 2005; Borch et al. 2006; Fontana et al. 2006; Faber et al. 2006; Willmer et al. 2006; Brown et al. 2007; Caputi et al. 2006; Wake et al. 2006) though estimates of the merger rate of massive galaxies present a less consistent picture (van Dokkum 2005; Bell et al. 2006; Masjedi et al. 2006; White et al. 2007). If, as theory predicts, massive halos are constantly accreting halos that are themselves hosts of massive galaxies, what is the fate of these accreted galaxies?

Two physical effects can cause satellite galaxies to 'disappear' from an observational sample. Tidal forces acting on a satellite as it orbits in the host halo potential can cause it to *disrupt*. At the same time, dynamical friction (DF) causes a satellite to lose energy to the background dark matter halo and eventually causes the satellite to sink toward the center and *merge* with the central galaxy of the host halo. While such notions, and their relevance to the evolution of galaxies within clusters, have been known for decades (e.g. Chandrasekhar 1943; Ostriker & Tremaine 1975; Ostriker & Hausman 1977; Merritt 1984), accurate merger times of satellite galaxies have been historically hard to calculate, and are poorly constrained observationally. Unfortunately, the problem cannot at present by circumvented by brute-force simulations due both to severe resolution requirements and the uncertain effects of baryon condensation on the survival of satellite halos (see e.g. Moore et al. 1999; Klypin et al. 1999; Diemand et al. 2004; Gao et al. 2004a,b; Reed et al. 2005). In addition, while DF is usually considered in a collisionless medium (such as dark matter), DF acting in a collisional medium (such as intracluster gas) is stronger (weaker) than in the collisionless case for satellites traveling at supersonic (subsonic) speeds (Ostriker 1999). Observational constraints on the merging timescale of satellites would hence provide valuable insight into this complex dynamical process.

This paper explores observational constraints on the average merging timescale of luminous red galaxies (LRGs). We assign LRGs to dark matter halos that have grown more massive than $M \sim 10^{13}\,M_{\odot}$ and use an N-body simulation to follow their accretion onto larger dark matter halos with $z = 0$ mass comparable to observed rich groups and clusters ($M > 10^{14}\,M_{\odot}$). Comparison with the observed multiplicity function of LRGs at $z \sim 0.3$ implies that accreted LRGs must merge on timescales comparable to those predicted by Chandrasekhar's formula (~ 2 Gyr). While this may not be surprising, the relative flood of massive halos onto more massive halos implies that a substantial number of LRGs have

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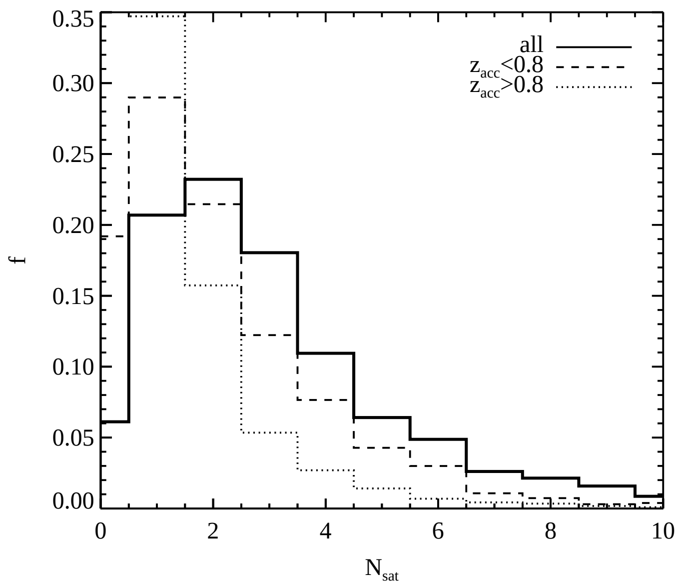

Figure 1. Fraction of halos at $z = 0$ with $M > 10^{14}\,M_\odot$, f, that have absorbed $N_{\rm sat}$ halos with mass $> 10^{13}\,M_\odot$. The thick solid line is for halos accreted at all epochs, while the dashed (dotted) line indicates only those halos accreted after (before) $z = 0.8$, i.e. when the Universe was half its present age for our assumed cosmology. No distinction is made here between halos that have dissolved and halos that remain as bound satellites. On average, 3.2 halos with mass $> 10^{13}\,M_\odot$ have accreted onto these more massive halos by $z = 0$.

disrupted over the history of the Universe. Though these numbers may at first glance appear large (on average $2-3$ disrupted LRGs per $z = 0$ halo with $M > 10^{14}\,M_\odot$) we show that the total stellar mass brought in by these accreted LRGs is consistent with the observed stellar mass in clusters so long as one counts both observed massive galaxies and the observed intracluster light.

The following sections describe in more detail the salient accretion properties of massive dark matter halos (§2), the inferred merging timescale of LRGs, if LRGs correspond to massive halos (§3), and the implied total stellar mass brought into massive $z \sim 0$ dark matter halos by these accreted LRGs (§4). We conclude in §5. Throughout we assume a flat ΛCDM cosmology with $(\Omega_m, \Omega_\Lambda, h, \sigma_8) = (0.25, 0.75, 0.72, 0.8)$, and use a virial mass definition, M_{200}, corresponding to the mass contained within a region that has mean density equal to 200× the critical density (see e.g. Evrard et al. 2007).

2 THE ACCRETION HISTORY OF MASSIVE DARK MATTER HALOS

A robust expectation of a Universe dominated by cold dark matter is the hierarchical growth of structure, and in particular the growth of dark matter halos via the accumulation of smaller halos. An illustrative example of the accretion history of dark matter halos is shown in Figure 1. There we plot the multiplicity function for halos more massive than $10^{14}M_\odot$, i.e. the distribution of the number of halos with $M > 10^{13}\,M_\odot$ that have accreted onto halos with $z = 0$ mass greater than $10^{14}M_\odot$ (see the appendix for details regarding the simulation used to compile this information). We refer to these more massive halos as "hosts" throughout. There are 2339 such hosts in our simulation at $z = 0$, corresponding to a number density of $\sim 2 \times 10^{-5}$ Mpc^{-3}. Note that these distributions are not symmetric. On average, halos more massive than $10^{14}\,M_\odot$ have been bombarded by 3.2 halos with mass $> 10^{13}\,M_\odot$ over a Hubble time. Here we do not distinguish between halos that were accreted directly onto the host halo and those that were accreted onto an intermediate halo that later accreted onto the host, although such a distinction will be utilized in the following sections. The accretion of such massive halos is roughly equally important both at low and high redshift: on average two such halos have been accreted at $z < 0.8$ (the Universe was about half its present age at $z = 0.8$ for the cosmology assumed herein).

Halos more massive than $\sim 10^{13}\,M_\odot$ are expected to contain at least one massive galaxy at their center (Zehavi et al. 2005b) even at moderate redshifts (e.g. Yan et al. 2003, 2004; Coil et al. 2006). From Figure 1 we are lead to the conclusion that, *in the absence of mergers,* observed clusters with $M > 10^{14}\,M_\odot$ should contain on average 3.2 massive galaxies (and certainly more if accreted halos of lower masses also contain massive galaxies), with a significant tail toward much larger numbers. However, reproducing the observed clustering of massive galaxies at $z \sim 0$ (Zehavi et al. 2005a) would require closer to 1.2 galaxies in such halos in our simulation, in agreement with other work (Masjedi et al. 2006; Kulkarni et al. 2007). While these statements are only qualitative, they will be confirmed in the more quantitative discussion that follows. In order to reconcile the accretion properties of halos with observations, we are thus lead to consider the fate of these massive halos and the galaxies within them.

3 THE MERGING TIMESCALE OF LRGS

LRGs are massive galaxies with very little ongoing star-formation; they thus constitute the tip of the red sequence. They have uniform spectral energy distributions marked by numerous features and hence their redshifts are relatively straightforward to estimate photometrically (Padmanabhan et al. 2005, redshift uncertainties are $\delta z \sim 0.03$). Modeling of their spectral energy distributions has lead to the conclusion that these galaxies formed the bulk of their stars at $z > 2$ (e.g. Trager et al. 2000; Jimenez et al. 2006; Thomas et al. 2005), and hence are expected to evolve largely dissipationlessly at $z < 1$. Their clustering strength is large, suggesting that they live in massive dark matter halos $M > 10^{13}\,M_\odot$ (Zehavi et al. 2005a).

Recently, Ho et al. (2007) has measured the multiplicity function of LRGs extracted from the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006) for 43 clusters over the redshift range $0.2 < z < 0.5$.[1] Cluster virial masses were derived from *ROSAT* *X*-ray data and range

[1] The primary spectral feature used to measure photometric redshifts of LRGs is the 4000Å break; at $z < 0.2$ this feature moves out of the SDSS bandpass filters. Hence our sample is restricted to $z > 0.2$. Although Ho et al.'s sample extends to $z \sim 0.6$, for

from $10^{14.1} < M_{200}/M_{\odot} < 10^{14.9}$. The average stellar mass of the LRGs in this sample is $M_{\rm star} = 10^{11.6} M_{\odot}$, as determined from a color-based stellar mass estimator (for a Chabrier IMF; Bell et al. 2003). These clusters contain on average 2.5 LRGs. The reader is referred to Ho et al. (2007) for further details regarding these observations.

In this sample there are approximately five clusters that contain no LRGs[2]. When plotting the observed multiplicity function below we include both the one reported in Ho et al. and one where clusters with $N < 1$ are artificially assigned $N = 1$. This is done to afford a more robust comparison to our simple model (see below) where we *assume* that each cluster halo contains at least one LRG at the center. As discussed below, our conclusions are insenstive to this distinction.

The dark matter halo accretion history of massive halos (e.g. Figure 1) is closely related to the LRG multiplicity function. The former can be converted into the latter if one knows both the minimum halo mass (measured at the epoch of accretion) associated with accreted LRGs, $M_{\rm min}$, and the average time it takes for LRGs to merge and/or disrupt[3] once accreted. Below we argue for reasonable values of $M_{\rm min}$ and then attempt to directly constrain the average LRG merging timescale. We parameterize the probability that an LRG will have merged by a time $t_{\rm acc}$ since accretion onto the host halo via:

$$P_{\rm merge} = 1 - e^{-t_{\rm acc}/\tau} \tag{1}$$

where τ is the merging timescale. The number of LRGs predicted by this simple model is then

$$N_{\rm LRG} = 1 + \sum_i e^{-t_{\rm acc,i}/\tau} \tag{2}$$

where the first term counts one LRG at the center of the host halo and the second term counts those satellites with accretion epoch mass $> M_{\rm min}$ that have not merged. For the purposes of generating a multiplicity function we round the second term to the nearest integer. Note that in generating a multiplicity function we do not have to make a distinction between accretion events that did or did not occur within the main host halo. This distinction will only become relevant when discussing the merger rates of LRGs.

The minimum LRG stellar mass in the observed sample is $10^{11.3} M_{\odot}$. A minimum halo mass associated with LRGs can be estimated by assuming the universal baryon fraction $f_b = 0.17$ and an efficiency factor η of converting baryons into stars. While this factor is only poorly constrained even at low redshift, values of order ~ 0.1 are likely reasonable for these massive galaxies (Hoekstra et al. 2005; Mandelbaum et al. 2006) and imply a minimum LRG hosting halo mass of $M_{\rm min} \sim 10^{13} M_{\odot}$. Note that the minimum halo mass for hosting LRGs is here used to identify those accreted halos that are likely to host an LRG, with a significant fraction of the accretion occurring at $z \sim 1$ or higher. Thus this minimum mass will likely not directly correspond to the minimum halo mass hosting LRGs at $z \sim 0$, since the LRGs that have survived to the present epoch will have accreted much more dark matter, resulting in a larger value for $M_{\rm min}$ at the present epoch. In our simulations halos today are on average five times more massive than they were when they first crossed $M_{\rm min}$, making our estimate consistent with that inferred from $z \sim 0$ clustering (Zehavi et al. 2005a; Kulkarni et al. 2007). As we discuss in §4, $M_{\rm min}$ much larger than $10^{13} M_{\odot}$ would require unreasonably long dynamical friction times and $M_{\rm min}$ either much larger or much smaller would be in conflict with stellar mass estimates in clusters.

Figure 2 plots the resulting LRG multiplicity function both for LRGs in accreted halos more massive than $10^{13} M_{\odot}$ (solid lines) and observations (dashed lines). We also include predictions for LRGs associated with halos twice as massive as our fiducial minimum mass (dotted lines) in order

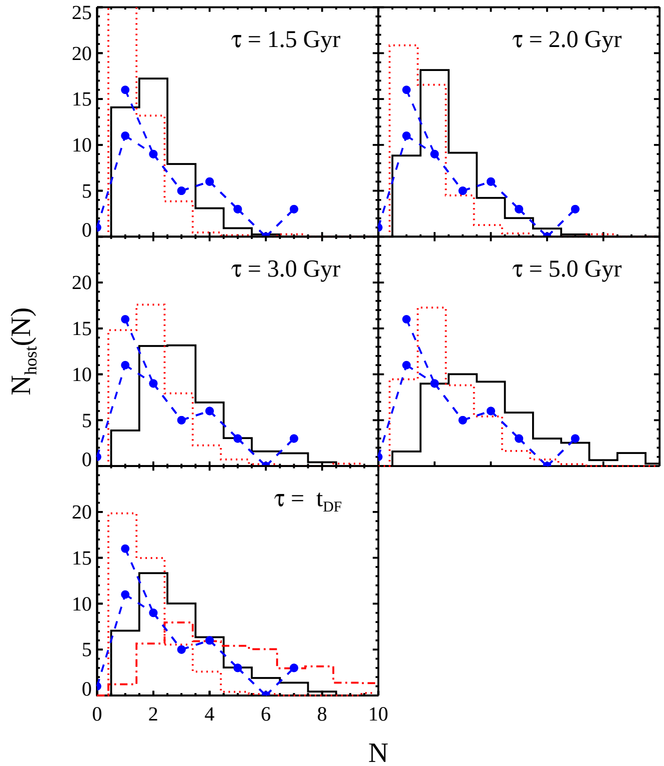

Figure 2. The multiplicity function of observed LRGs (*dashed line joining points*) and accreted dark matter halos for two accreted mass thresholds: $M > 10^{13} M_{\odot}$ (*solid line*) and $M > 2 \times 10^{13} M_{\odot}$ (*dotted line*). The observed curves diverge at $N < 1$ due to whether or not we artifically assign an LRG at the center of observed clusters with $N < 1$ (see text for details). *Top Four Panels:* Accreted halos are assumed to have disrupted after a time τ, shown in the upper right corner of each panel. It is apparent that if LRGs can be identified with halos of mass $> 10^{13} M_{\odot}$ then they must on average merge within ~ 2 Gyr. *Bottom Panel:* Accreted halos are assumed to have merged after a dynamical friction timescale (see Equation 3). This panel also includes halos more massive than $M > 5 \times 10^{12} M_{\odot}$ (*dot-dashed line*) for comparison.

our purposes we truncate it at $z = 0.5$ to limit the amount of possible evolution within the sample.

[2] We say approximately because Ho et al. statistically remove interlopers based on photometric redshift uncertainties and hence clusters contain a non-integer number of LRGs.

[3] Throughout we use the words "merge" and "disrupt" interchangeably since our analysis does not distinguish between these two possibilities.

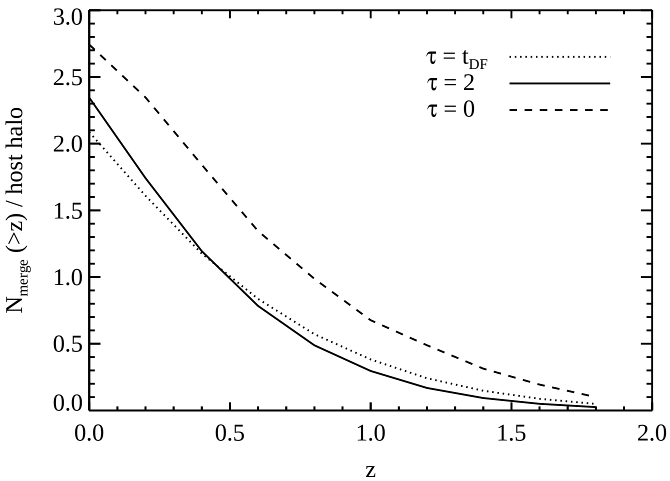

Figure 3. Number of accreted halos with $M > 10^{13}\,M_{\odot}$ that have merged with the host halo by redshift z, per $z = 0$ host halo with $M > 10^{14}\,M_{\odot}$. The merging time is computed in two different ways: a constant timescale of either 0 or 2 Gyr (*dashed* and *solid lines*) and a timescale determined by the Chandrasekhar dynamical friction formula (*dotted line*).

to illustrate the sensitivity to our assumed LRG halo mass threshold. Each panel in Figure 2 is the multiplicity function for a different merger timescale. The top four panels assume that the merger timescale, τ, is constant. It is apparent from these panels that if $M_{\rm min} \sim 10^{13}\,M_{\odot}$ then LRGs must merge on a characteristic timescale of ~ 2 Gyr. This timescale implies an average number of LRGs per cluster of 2.5, satisfyingly close to the observed value of 2.6.

Note that in order to compare to the observations we have weighted host halos at $z = 0.3$ (of which there are 460 in our simulation within the observed mass range) in such a way as to reproduce the mass distribution of the observed clusters. It is the combination of these two effects (higher redshift and different mass distribution) that does not allow a direct comparison between Figures 1 and 2.

If LRGs never merged, there would be on average 5.8 LRGs per $z = 0.3$ host halo (averaged over the observed distribution of halo masses). Comparing this number to the observed 2.5 LRGs per cluster highlights the importance and prevalence of LRG mergers.

The bottom panel in Figure 2 assumes that the merger timescale is equal to the dynamical friction timescale (Binney & Tremaine 1987):

$$t_{\rm DF} = 0.1\, t_H\, \frac{M_h/M_s}{\ln(1 + M_h/M_s)} \qquad (3)$$

where M_h and M_s are the host and satellite masses, z is the redshift, t_H is the Hubble time and all quantities are measured at the epoch of accretion. The average mass ratio at accretion is ~ 6 for our sample. The pre-factor, $0.1\,t_H$, is the characteristic time for a halo with mean density $\mathcal{O}(10^2)$ times the critical density. It is important to note that $t_{\rm DF}$ gets shorter both at higher redshift and for merger mass ratios closer to unity. In this lower panel we have additionally included results for halos of mass $M > 5 \times 10^{12} M_{\odot}$ (dot-dashed line) for comparison.

This comparison with simple dynamical friction estimates provides a satisfying cross check to the results in the upper panels. In particular, for our fiducial minimum LRG halo mass of $10^{13}\,M_{\odot}$, the dynamical friction timescale averaged over all the accreted halos is 2.4 Gyr (median time is 1.8 Gyr — the distribution is highly asymmetric), which is quite similar to the constant merger timescale that best matches the observed multiplicity function (~ 2 Gyr). From Figure 2 it is apparent that the simple DF timescale would not have reproduced the observed LRG multiplicity function if the minimum halos mass capable of hosting LRGs were substantially more or less massive than $10^{13}\,M_{\odot}$. The implication here is clear: if $M_{\rm min}$ is in fact considerably larger or smaller than $10^{13}\,M_{\odot}$ then simple DF arguments do not apply to the LRG population.

In fact, it is not at all clear that Equation 3 should apply here or in general to the dynamical evolution of satellite galaxies, as it is strictly valid for a point mass moving in an infinite, uniform background density field. Indeed, much work has gone into both testing the validity of Equation 3 with simulations (e.g. White 1983; van den Bosch et al. 1999; Velazquez & White 1999; Read et al. 2006) and developing extensions to it (e.g. Tremaine & Weinberg 1984; Colpi et al. 1999), including numerically following the evolution of the satellite orbit, including the mass loss due to tidal forces (Benson et al. 2002; Taffoni et al. 2003; Taylor & Babul 2004; Zentner et al. 2005). This body of work has shown that Equation 3 is at best a crude approximation to the realistic, time-dependent problem. For these and other reasons it is quite surprising, if not entirely coincidental, that the classical Chandrasekhar DF timescale adequately captures the merging timescale of LRGs.

As can be seen from the upper four panels in Figure 2, there is a degeneracy between the merger timescale and the minimum halo mass associated with LRGs in the sense that a larger $M_{\rm min}$ coupled to a larger timescale can produce roughly the same multiplicity function. Thus, if one thought that LRGs lived in more massive halos than what we have assumed here, then one would infer a longer merging timescale for LRGs. However, this is exactly opposite to what one would infer from dynamical friction arguments since $t_{\rm DF} \propto M_s^{-1}$. Furthermore, increasing $M_{\rm min}$ to $5 \times 10^{13}\,M_{\odot}$ would result in far too few LRGs in massive halos compared to observations, even if $\tau = \infty$; in this case the average number of LRGs per halo would be 1.6. As we describe in §4, $M_{\rm min}$ is further constrained by observations of the stellar light in massive halos.

These merger timescales can easily be cast into a discussion of LRG merger rates. For this discussion we consider the full host halo population at $z = 0$, rather than the population at $z = 0.3$ meant to coincide with the data from Ho et al., in order to draw more general conclusions about LRG mergers. Figure 3 plots the cumulative distribution of *merged* LRGs as a function of redshift, per host halo. The figure includes constant merger timescales of 0 and 2 Gyr and a timescale set by dynamical friction. The 0 Gyr case can equivalently be thought of as the distribution of *accreted* LRGs, since in this case the accretion and merging epochs are coincident. In this figure we only count LRGs that merge within the main progenitor of the $z = 0$ host halo. This figure is thus not directly comparable to Figure 1. In other words, if a halo merges within a halo that itself later mergers with the host halo then it is not counted here.

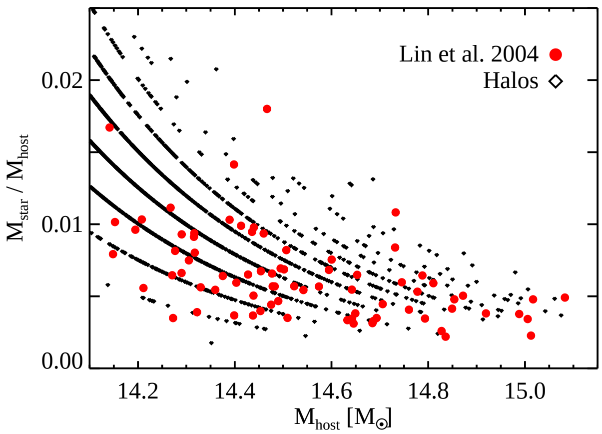

Figure 4. The total stellar-to-virial mass ratio as a function of $z = 0$ halo virial mass. Only galaxies more massive than $M_{\rm star} = 10^{11.3} M_\odot$ and the ICL are included in the stellar mass budget. Observations from Lin et al. (2004, *solid circles*) have been converted to total stellar masses, and are compared to total stellar masses estimated by assuming that every accreted halo with mass $> 10^{13}\, M_\odot$ hosts an LRG with $M_{\rm star} = 10^{11.6} M_\odot$ (*diamonds*).

This plot is thus meant to capture the number of mergers actually occurring *within the main progenitor* of the host halo.

The dynamical friction timescale is shorter than 2 Gyr at high redshift and longer than 2 Gyr at low redshift; this results in a more gradual increase in the merger rate per unit redshift compared to a constant merger time of 2 Gyr. Since the constant and dynamical friction timescales are different at redshifts both greater and less than 0.3, comparisons to the multiplicity function at different epochs can in principle rule out either (or both) of these timescales. Both the constant 2 Gyr timescale and that determined by dynamical friction imply that $2 - 2.5$ LRGs have merged with the host halo by $z = 0$. Moreover, the figure indicates that a substantial number of LRGs are merging/disrupting at $z < 1$. In the next section we set this in the context of recent observational results of the stellar mass budget in groups and clusters.

4 THE TOTAL CLUSTER STELLAR MASS

The merger rate of LRGs found in the previous section indicates that a significant number of LRGs must have disrupted over the history of massive halos. In particular, a merger timescale of $\tau = 2$ Gyr implies that on average $2 - 3$ LRGs have disrupted within each host halo more massive than $10^{14}\, M_\odot$ by $z = 0$ (and approximately 2.1 since $z = 1$). In this section we discuss how reasonable such a disruption rate is in light of the total stellar mass observed in clusters at $z \sim 0$.

The amount of stellar mass brought into massive halos by LRGs can be estimated in the following way. We consider halos that have a mass at $z = 0$ greater than $10^{14}\, M_\odot$ and assign a stellar mass of $10^{11.6} M_\odot$, the mean stellar mass of the observed LRG sample, to the center of each. Then, each halo that was accreted onto these $z = 0$ halos is assigned the same amount of stellar mass if the halo mass at accretion is $> 10^{13}\, M_\odot$. This exercise is thus meant to count the total amount of stellar mass that was at some point associated with LRGs. We make no distinction between disrupted and non-disrupted LRGs except in one case: if, according to our best-guess LRG merger timescale (2 Gyr), an LRG halo would have disrupted not in the main progenitor of the $z = 0$ halo but rather in some smaller halo that would itself later accrete onto the main progenitor but does not merge, then we do not count this LRG in the final stellar mass budget. In this case the disrupted LRG contributes to the satellite's ICL (i.e. ICL that surrounds the satellite and is distinct from the central ICL). As it turns out, only 20% of all accreted halos more massive than $10^{13}\, M_\odot$ fall into this category and including these halos in the stellar mass budget does not appreciably change our conclusions.

We compare to data presented in Lin et al. (2004) who have compiled information on 93 clusters at $z < 0.1$, including X-ray observations used to derive cluster virial masses and luminosities of cluster members derived from 2MASS photometry. From these data Lin et al. have estimated the luminosity function (LF) of each cluster, assuming that the faint-end slope is fixed at $\alpha = -1.1$. Using their LFs we are able to estimate the total luminosity in galaxies brighter than $L_K = 2.8 \times 10^{11} L_\odot$ which corresponds to the minimum luminosity of the Ho et al. LRG sample. This total luminosity is converted into stellar mass by assuming a mass-to-light ratio of $M_{\rm star}/L_K = 0.72$ which is appropriate for red galaxies with a Chabrier IMF (Bell et al. 2003). The LFs reported in Lin et al. (2004) do not include the brightest cluster galaxy (BCG); we thus add these in separately. Finally, we have assumed that each cluster contains intracluster light (ICL) with a stellar mass equal to the mass of the BCG identified by Lin et al. (i.e. $L_{\rm ICL} = L_{\rm BCG}$). This amount of light associated with the ICL is consistent with recent observations (Zibetti et al. 2005; Gonzalez et al. 2005). In this "total" cluster luminosity we do not include any possible ICL associated with satellites; it is for this reason that we did not include LRGs that disrupted in halos which themselves later merged with the host.

Figure 4 presents a comparison between the data from Lin et al. (2004) and the stellar mass associated with accreted halos. The agreement is encouraging. Note that varying any one of our assumptions can change the results from both the data and our model; the important point to take away from this comparison is that the influx of massive galaxies embedded within accreted halos appears to roughly agree with the total stellar mass within observed clusters at $z \sim 0$. This provides further support to our identification of halos with mass $> 10^{13}\, M_\odot$ as being host to LRGs and suggests that disrupted LRGs deposit their stars into a combination of the central galaxy and ICL. Increasing or decreasing $M_{\rm min}$ by a factor of two would result in substantial disagreement with the observations shown in Figure 4. This is due to the fact that the number of accreted halos does not scale linearly with the accreted halo mass, and provides further support for our choice of $M_{\rm min} = 10^{13}\, M_\odot$.

The simple model presented here also provides a straightforward means for understanding the observed trend of decreased scatter in $M_{\rm star}/M_{\rm host}$ with increasing $M_{\rm host}$.

This arises because the number of accreted halos with mass $> 10^{13}\, M_{\odot}$ is a weak function of $M_{\rm host}$. This is in contrast to the observed number of satellites, which appears to be closer to linear in $M_{\rm host}$ (Lin et al. 2004; Popesso et al. 2007). The difference implies that fractionally more halos/LRGs are merging in lower mass halos compared to higher mass halos.

Interestingly, we find that it is not uncommon for $z = 0$ host halos to contain disrupted LRGs that did not disrupt within the host halo (and hence were not counted in the above figure) but rather disrupted in a smaller halo that later accreted onto the host (and remained as a satellite to $z = 0$). If these disrupted LRGs are depositing some fraction of their stars into ICL, then this suggests that there could be a significant amount of ICL that is not centered on the central galaxy but is instead centered on cluster satellites. Such a scenario is corroborated by recent observations of the Virgo cluster that show significant amounts of ICL surrounding several of the most massive satellites (Mihos et al. 2005).

5 DISCUSSION

The results of the previous sections suggest the following picture. If LRGs are associated with halos more massive than $10^{13}\, M_{\odot}$ at the time when they are accreted onto more massive host halos, then the observed multiplicity function of LRGs at $z \sim 0.3$ implies that LRGs must merge and/or disrupt on timescales of ~ 2 Gyr. Such a merger rate implies that $2 - 3$ such LRGs have disrupted in halos more massive than $10^{14}\, M_{\odot}$ by $z = 0$. This merger timescale is consistent with classical dynamical friction arguments and suggests that a rather simplistic dynamical prescription for the evolution of LRGs is applicable when considering ensemble averages.

Moreover, the amount of total stellar mass in clusters that was at one point associated with these infalling LRGs (ignoring for the moment whether or not this stellar mass is locked up in satellite galaxies) is consistent with observations when the observed amount of stars in the intracluster light (ICL) is accounted for. This in turn suggests that the disrupting LRGs are depositing their stars into a combination of the ICL and central galaxy, which is consistent with previous modeling (Monaco et al. 2006; Murante et al. 2007; Purcell et al. 2007; Conroy et al. 2007). Finally, there appears to be a significant number of LRGs that have disrupted within halos that only later accreted onto (but did not merge with) what would become the $z = 0$ host halo. This suggests that there could be a significant amount of ICL surrounding cluster satellites, in addition to what is known to be associated with the central galaxy.

It has been historically challenging to constrain the merger rate of galaxies. Previous studies have relied on either morphological disturbances (e.g. Conselice et al. 2003; van Dokkum 2005; Bell et al. 2006) or close pair counts (e.g. Masjedi et al. 2006) as probes of the merger rate of massive galaxies. Unfortunately, both methods are rather indirect since the connection between either morphological disturbances or close pair counts and merger rates is uncertain. The most recent inferred LRG-LRG merger rate is from Masjedi et al. (2006) who find a rate of 0.6×10^{4} Gyr^{-1} Gpc^{-3}. Averaging over all halos between $z = 0.5$ and $z = 0.2$, the model presented herein implies an LRG-LRG merger rate of $(1.0 - 1.3) \times 10^{4}$ Gyr^{-1} Gpc^{-3}, depending on whether the constant 2 Gyr or dynamical friction timescale is used. The agreement with Masjedi et al. (2006) is encouraging, especially given the (different) uncertainties in both approaches. These rates are also consistent with current predictions from cosmological hydrodynamic simulations (Maller et al. 2006).

Many studies have attempted to constrain the stellar mass growth of massive galaxies from their inferred merger rates. However, as argued in Conroy et al. (2007) and herein, the merging of massive galaxies will often not correspond to significant growth of the resulting galaxy because a substantial amount of stars can be transfered to the ICL. We hence caution against using merger rates to constrain the stellar mass growth of galaxies.[4] In fact, significant growth of the ICL via merging at late times provides a means for reconciling two apparently contradictory facts: one the one hand, observations at $z < 1$ indicate that central massive red galaxies grow little in mass (e.g. Brown et al. 2007; Fontana et al. 2006; Bundy et al. 2006; Wake et al. 2006), while on the other hand, merging/disruption of galaxies within groups and clusters at late times appears relatively common (e.g. White et al. 2007).

White et al. (2007) outlined an approach for measuring the merging rate of massive galaxies similar to the one presented herein. Using the observed evolution in the clustering of massive galaxies, these authors concluded that $\sim 1/3$ of massive satellites merge/disrupt between $z \simeq 0.9$ and $z \simeq 0.5$. In the present work we find roughly 50% of massive satellites have disrupted over similar epochs. Our fraction is slightly higher because we have focused on more massive galaxies than in White et al. (2007). The more general conclusion from these two studies is, however, robust — the population of massive galaxies experiences significant amounts of merging/disruption, even at $z < 1$.

There is an important implication of considering the evolution of galaxies within the context of the hierarchical growth of halos. At first glance, the lack of evolution in the observed correlation function of massive galaxies and their halo occupation distribution at $z < 1$ suggests that massive galaxies do not disrupt or merge over this epoch. However, these galaxies are embedded within dark matter halos that are continually merging and accreting new galaxies, which instead suggests that massive galaxies *must* merge in order that these observed quantities not evolve appreciably at late times. This statement is further corroborated by dissipationless simulations which show explicitly that the average number of subhalos within host halos does not evolve appreciably at $z < 1$ because the accretion and disruption rate of subhalos are approximately equal (Reed et al. 2005; Conroy et al. 2006). If satellite galaxies reside within these subhalos then the observed non-evolution of the clustering and halo occupation of massive galaxies at $z < 1$ is in fact consistent with significant amounts of merging at late times.

Our results highlight the power of using purely dissipationless simulations coupled to simple relations between

[4] This issue is intimately related to the way in which one counts galaxy light. Of course the *combined* light of both the central galaxy and its ICL will increase after a merger event.

galaxies and dark matter to infer the evolution of galaxies and their relation to the underlying dark matter with time. The approach outlined herein can easily be extended to other datasets to provide additional constraints on the merger rate of galaxies.

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APPENDIX A: THE SIMULATION, HALO CATALOG, AND MERGER TREES

We use a high resolution simulation of a ΛCDM cosmology ($\Omega_M = 0.25 = 1 - \Omega_\Lambda$, $\Omega_B = 0.043$, $h = 0.72$, $n_s = 0.97$ and $\sigma_8 = 0.8$). The linear theory power spectrum is computed by evolution of the coupled Einstein, fluid and Boltzmann equations using the code described in White & Scott (1996). This code agrees well with *CMBfast* (Seljak & Zaldarriaga 1996), see e.g. Seljak et al. (2003). The simulation employs 1024^3 particles of mass $8 \times 10^9\,h^{-1}M_\odot$ in a periodic cube of side $500\,h^{-1}$Mpc using a *TreePM* code (White 2002). The Plummer equivalent softening is $18\,h^{-1}$kpc (comoving).

The phase space data for the particles exists at 50 outputs, spaced equally in conformal time between $z \simeq 3$ and $z = 0$. For each output we generate a catalog of halos using the Friends-of-Friends (FoF) algorithm (Davis et al. 1985) with a linking length of 0.168× the mean inter-particle spacing. This procedure partitions the particles into equivalence classes, by linking together all particle pairs separated by less than a distance b. The halos correspond roughly to particles with $\rho > 3/(2\pi b^3) \simeq 100$ times the background density. For each halo we compute a number of properties, including the mass M_{200} interior to r_{200} within which the mean density is 200× the critical density. M_{200} is computed from a fit of an NFW profile (Navarro et al. 1997) to the particles in the FoF group.

Merger trees are computed from the set of halo catalogs by identifying for each halo a "child" at a later time. The child is defined as that halo which contains, at the later time step, more than half of the particles in the parent halo at the earlier time step (weighting each particle equally). For the purposes of tracking halos this simple linkage between outputs suffices (note that we do not attempt to track subhalos within larger halos, which generally requires greater sophistication). From the merger trees it is straightforward to compute the time when a halo 'falls in' to a larger halo, the number and masses of the progenitors etc.