Probing Satellite Quenching With Galaxy Clustering

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1 INTRODUCTION

Astronomical surveys have long established a correlation between galaxy properties and environmental density (e.g., Oemler 1974; Davis & Geller 1976; Dressler 1980; Postman & Geller 1984). At fixed luminosity or stellar mass, high-density environments like groups and clusters exhibit a higher fraction of quiescent galaxies, whereas more isolated environments have a larger fraction of galaxies that are actively star-forming (e.g., Balogh et al. 1997, 2004; Kauffmann et al. 2004; Blanton et al. 2003). For example, among galaxies in the local universe with stellar mass near $10^{10} M_\odot$, the red fraction within massive groups and clusters is around 70%, while in the field, the red fraction is far smaller, closer to around 25% (Weinmann et al. 2006). This relationship is known to persist at least as far back as $z \approx 1$ (Cucciati et al. 2006; Cooper et al. 2007; Peng et al. 2010), over seven billion years into the cosmic past.

Historically, proposals for the physical origin of these phenomenological trends have focused on processes that are specific to the interior regions of particularly massive dark matter halos. For example, the hot, diffuse gas belonging to a satellite may become unbound as the galaxy orbits within the virial radius of some larger host halo; after a delay time $t_{\text{delay}}$, the satellite first passes through the central region of its host halo. This process is referred to as the "quenching timescale", $t_{\text{quench}}$, which is the time it takes for a satellite to lose its gas reservoir upon infall, resulting in the quenching of star formation in the satellite. The quenching timescale is defined as the time it takes for the satellite to lose its gas reservoir upon infall, resulting in the quenching of star formation in the satellite. The quenching timescale is a critical parameter in understanding the evolution of satellite galaxies.

Emphasis on the host halo playing the dominant role in satellite quenching can also be seen in contemporary empirical models of galaxy evolution. In the model introduced in Wetzel et al. (2013), satellite galaxies evolve as centrals until the time $t_{\text{delay}}$ that the satellite first passes within the virial radius of some larger host halo; after a delay time $t_{\text{delay}}$, the satellite becomes a central of the group.

Early attempts at the semi-analytical modeling of galaxy evolution (SAMs) also focused on the extreme environmental conditions inside massive host halos. For example, the SAMs introduced in Kauffmann et al. (1993) and Cole et al. (1994) assumed instantaneous stripping of a satellite’s gas upon infall, resulting in satellites that were predicted to be significantly redder than those observed in the local universe (Weinmann et al. 2006; Baldry et al. 2006). Updates to these early models have consistently involved more gradual implementations of satellite-specific processes, and have brought predictions into broader agreement with observational data (see, e.g., Font et al. 2008; Weinmann et al. 2010; Guo et al. 2011; Somerville et al. 2012). However, significant tension between the predicted and observed satellite trends remains (Lu et al. 2013; Kauffmann et al. 2013), and there are several indications that this tension is due, at least in part, to an overestimate of the efficiency of intra-host processes (Kimm et al. 2009; Wang et al. 2012; Hearin et al. 2014).
confirmed by multiple groups (e.g., De Lucía et al. 2012; Wheeler et al. 2014).

Although intra-host quenching is a natural explanation for the observed relation between local environment and quiescent fraction, quenching of star formation might not necessarily be driven by the halo environment. Recently, Watson et al. (2014) have argued that it is possible to reproduce many statistical properties of galaxies, including the relation between local density and red fraction, using the ‘age-matching’ prescription of Hearin & Watson (2013). As shown in Hearin et al. (2013b), age matching is a variant of subhalo abundance matching (Conroy et al. 2006), in which dark matter halos and subhalos are associated with galaxies with stellar populations whose ages are related to the assembly history of the (sub)halos. At fixed stellar mass, quiescent galaxies are placed in relatively older halos than actively star-forming galaxies. This correspondence between stellar age and halo age could arise if the transition from fast growth to slow growth in halos cuts off the supply of gas needed to form stars (Pfeffermann & Mayer 2014).

The Hearin & Watson prescription quantitatively reproduces the correlation between quiescent fraction and local density, without invoking any physics related to the infall of satellites into larger halos. In this model, environmental trends arise because (sub)halos in high density environments tend to assemble their mass earlier than (sub)halos in low density environments. And yet, the age matching prescription is able to reproduce the same observational statistics deriving from galaxy group catalogs as those used to fine-tune the empirical and semi-analytic models discussed above. This directly implies that traditional group-based measurements are incapable of discriminating between models predicated upon radically different assumptions, and highlights that the well-known correlation between halo assembly and environment (e.g., Gao et al. 2003; Dalal et al. 2008) represents a fundamental degeneracy in satellite quenching models. This degeneracy is also unbroken by the two-point correlation function split on broadband color, which limits the ability of this traditional statistic to robustly constrain models of galaxy evolution, particularly satellites (see Zentner et al. 2013, figure 11).

Fortunately, it is possible to distinguish observationally between these two classes of scenarios. If infall into massive halos is responsible for all quenching of star formation in the galaxies inside massive groups and clusters, then most of the cluster galaxies that have been red and dead since high redshift (e.g. z ~ 1) have been inside massive halos since $z \gtrsim 1$. While inside those massive halos, satellite galaxies experience significant tidal forces. In this paper, we argue that tidal effects can provide a simple signature of the amount of time that a population of galaxies has typically resided inside of their host halos. More specifically, measurements of satellite clustering can be used to determine the fraction of satellites that have been in their current hosts for multiple dynamical times. If quenching is indeed a slow process that requires massive hosts, such measurements can place interesting constraints on quenching models.

\section{2 Galaxy Clustering Beyond the Tidal Radius}

Galaxies are spatially correlated with each other (e.g., Peebles 1980), a fact that is also true of the galaxies that fall into massive clusters and become satellite galaxies. For example, a significant fraction ($\approx 30-40\%$) of galaxies enter clusters via bound groups (Berrier et al. 2009; McGee et al. 2009). Once inside the clusters, tidal gravity can unbind these groups, and once galaxies become unbound from each other, their spatial correlations decay on a timescale of order a few dynamical times.

We might naively expect that satellite galaxies inside massive groups and clusters would exhibit little if any spatial correlations with each other past their tidal radii. This would be incorrect, however, because a large fraction of cluster galaxies have not been inside their hosts for many dynamical times. This is because the dynamical time inside a halo can be a large fraction of the Hubble time (especially for large cluster-centric radii, $r \sim r_{\text{vir}}$), and also because massive clusters tend to assemble much of their mass relatively late, $z < 1$. Therefore, the spatial correlations of many satellite galaxies at separations $r > r_{\text{tidal}}$ do not have sufficient time to decay completely, leading to observable spatial correlations of galaxies within clusters (Cohn 2012).

To illustrate this, we plot in Figure 4 the 2-point correlation function of selected subhalos in the Bolshoi simulation (Klypin et al. 2011; Hite et al. 2013). Halos and subhalos were obtained from the publicly available Rockstar (Behroozi et al. 2013) catalogs and merger trees available at the Multidark website. Following Reddick et al. (2013), we stack subhalos of similar peak circular velocity, under the assumption that $V_{\text{peak}}$ is the subhalo property that correlates most tightly with stellar mass. We selected samples of subhalos in bins of $V_{\text{peak}}$ and cluster-centric radius $R$, and then computed the average number density $\bar{n}(r)$ of neighboring subhalos as a function of separation $r$, as well as the average mass density profile $\bar{\rho}(r)$. Uncertainties in the stacked profiles were estimated using bootstrap errors. Note that because these are correlation functions in real space, the errors in the profile are themselves highly correlated, which is why the profiles may appear smoother than one might expect from the size of the error bars. Also note that this figure plots the clustering of subhalos relative to each other; this is distinct from the radial profile of satellites within clusters. The latter corresponds to the satellite-cluster 2-point correlation function, whereas Figure 3 plots the subhalo-subhalo correlation function within cluster-sized halos.

The stacked profile plotted in Figure 4 requires some explanation, since it contains two distinct contributions. First, there is a contribution associated with the mean radial profile of the host cluster. When we stack on galaxies at cluster-centric radii $R$, then we would expect the average number of other nearby satellites at distances $r \lesssim R$ to be about $n(R)$, nearly independent of $r$. We can think of this as the ‘background’ density of galaxies at cluster-centric radius $R$. In addition to this term, however, there are also possible satellite-satellite pairwise correlations. For example, two sub-subhalos that are both bound to the same substructure.
will be spatially correlated with each other, above and beyond the correlations provided by the host profile \( n(R) \). It is this second contribution that we are interested in, since tidal gravity will tend to diminish such correlations for satellites that are not bound to each other. We would therefore like to subtract the background contribution to the stacked profile, in order to measure the excess correlation of unbound material. One simple way to estimate the background, suggested by Pastor Mira et al. (2011), is to compute the average profile stacked on the antipodal point to each subhalo, relative to the host centroid. The difference between the subhalo stacked profile and the opposite stacked profile reveals the excess correlations of subhalos with each other.

As Figure 1 illustrates, there are significant correlations of subhalos persisting to large radii. Similar behavior holds true for the mass correlated with subhalos. The average mass profiles were computed in a similar way as the average number profiles, by stacking dark matter particles as a function of distance relative to subhalos. Because there are many more particles than subhalos, the statistical errors on the stacked mass profiles are far smaller than the errors on the satellite profile. In both cases, there is a clear, significant and positive excess of mass persisting to large radii. From the stacked mass profiles, we can also roughly estimate the approximate tidal radius: the Hill radius will occur where the density associated with subhalos (blue curve) becomes comparable to the background density (green curve). For the subhalo sample plotted in Figure 1, the Hill radius is of order 50 kpc, implying that the excess correlations seen at much larger radii are with material that is unbound.

The presence of significant correlations with unbound material implies that many of the subhalos in our cluster sample have not been inside their host halos for long, compared to the dynamical time. We can verify this by splitting our subhalo sample based on age. From the publicly available merger trees for Rockstar subhalos provided by Behroozi et al. (2013), we can determine the redshift at which each subhalo entered its \( z = 0 \) host halo; we denote this redshift as \( z_{\text{acc}} \). We then split the subhalo samples into groups of different \( z_{\text{acc}} \), and plot their respective stacked profiles in Figure 2. As the figure illustrates, the oldest subsample of satellites, with \( z_{\text{acc}} > 0.75 \), indeed exhibit no significant correlations with mass at large distances well beyond the estimated Hill radius. The excess observed in the combined sample (Figure 1) is driven by the more recently accreted subhalos. If we estimate the dynamical time as the orbital timescale for a circular orbit at radius \( r \), then \( t_{\text{dyn}} = 2\pi r/v_{\text{circ}}(r) = 2\pi(GM/r^3)^{-1/2} \approx (\pi/G\rho)^{1/2} \), where the last approximate equality is only valid for nearly isothermal profiles, \( \rho \propto r^{-2} \). For the background density \( \rho \approx 3 \times 10^{13} M_\odot/\text{Mpc}^3 \) at this location \( (R \sim 500 \text{ kpc}) \), the dynamical time is \( t_{\text{dyn}} \approx 5 \text{ Gyr} \), corresponding to a lookback redshift \( z \sim 0.5 \). As we can see, subhalos that have been inside their hosts for only \( \lesssim 1 \) dynamical times retain significant correlations with unbound material.

### 3 IS QUENCHING ASSOCIATED WITH INFALL?

The result shown in Figure 2 suggests an immediate test of environmental quenching models for satellite galaxies. By measuring 2-point statistics of satellites within host halos, we can determine the fraction of those satellites that have been inside their hosts for multiple dynamical times. By examining regions within clusters where the local dynamical time is less than the \( \gtrsim 6 \) Gyr quenching timescales found by previous analyses, we can thereby determine the...
fraction of quiescent satellites that were quenched by their current hosts. This fraction is expected to be large, especially for satellites in massive groups and clusters with $M_{\text{host}} \sim 10^{14} M_\odot$ (Wetzel et al. 2013). If a large fraction of quiescent satellites have been inside their hosts for long amounts of time, then their 2-point correlations will resemble the oldest subset shown in Figure 4. Conversely, if quenching of star formation is completely unrelated to infall into massive halos, then satellites with old or young stellar populations will not necessarily show significantly different correlations with unbound material.

We illustrate this point by repeating the stacking analysis of Figure 1 but for various other age estimates instead of accretion time. We consider two examples in figures 3 and 4. In the first example (Figure 3), we use $z_{\text{starve}}$ from Hearin & Watson (2013) as an age estimate. In this model, quenching of star formation is typically not associated with infall into massive hosts. Instead, $z_{\text{starve}}$ is taken to be the redshift when a subhalo first enters any host ($z_{\text{sub}}$) as an age estimate. This would correspond to a model in which all quenching of star formation is completely unrelated to infall into massive halos, then satellites with old or young stellar populations will not necessarily show significantly different correlations with unbound material.

The figures illustrate the behavior we would expect. At large cluster-centric radii, the subhalos have typically not resided in their present-day hosts for enough time to dissipate any correlations with unbound material. At small cluster-centric radii ($R \sim 500$ kpc), however, the dynamical time is short enough for tidal effects to become noticeable, and the two different models produce significantly different behavior. If quenching is associated with infall (Figure 3), then the correlations with unbound material should be nearly absent for the oldest galaxies. On the other hand, if satellite quenching is not associated with infall (Figure 4), then a large fraction of even the oldest galaxies have not resided in their current hosts for enough time to destroy correlations with unbound material.

In practice, 3D density profiles cannot be observed around galaxies. Instead, we measure projected profiles. The projection from 3 dimensions to 2 can wash out some of the signal, since satellites at large 3D radii can occasionally project onto small 2D radius. Despite this mixing of different radial bins, the difference in behavior of various quenching models survives even in the projected 2D profiles (compare middle panels of Figures 3 and 4). This demonstrates that spatial clustering of satellites may be used to constrain the amount of time that a population of satellites has resided inside of their current hosts, which can help to distinguish satellite quenching models.

In Figures 3 and 4, we only plot stacked mass profiles, because the small number of subhalos in the Bolshoi simulation limits our ability to measure subhalo-subhalo clustering. Observationally, however, upcoming surveys like DES and HSC will observe much larger volumes than that simulated in Bolshoi, meaning that they will detect much larger numbers of satellite galaxies. For example, most of the figures in this paper were generated by stacking samples of $\sim 300$ subhalos, while for comparison, the existing SDSS
2.0 4 0.25 12 3.0 6 0.5 12 1.0 2.0 8 3.0 2 2 5.0 5.0 4 6 900–1200 kpc (N = 293)

satellite quenching predict different accretion histories for remnants to be seen, however, if broad band photometry is simulated in the Bolshoi simulation used in this paper. It remains to be seen, however, if broad band photometry is sufficient to determine the ages of the stellar populations of galaxies in cluster fields, or if spectra will be required to select appropriate samples. For example, if we are unable to distinguish quenched galaxies from dusty, reddened star-forming galaxies, then difference in the the stacked profiles of supposedly ‘old’ and ‘young’ galaxies will be diminished. Line of sight interlopers present a related concern. Because they have not experienced significant tidal gravitational forces, interlopers could dilute the stacked signal if they are mistaken for old cluster members. Spectroscopic data could help reduce contamination by interlopers, and provide more accurate age estimates.

The observation proposed here involves measurement of 2-point correlations of satellites within clusters, and is therefore a 3-point correlation function (the cluster-satellite-satellite 3-point function). As noted above, this is a distinct measurement from clustering statistics previously used to constrain quenching models, like average radial profiles or abundances, which involve 2-point and 1-point functions. With the advent of deep imaging surveys like DES, HSC and LSST, the measurement of 3-point and higher correlation functions is now becoming practical over a range of spatial scales. Our estimates indicate that ongoing surveys like DES and HSC should be able to provide significant constraints on quenching models of the form examined here, which can complement other probes previously considered.
in the literature (Cohn & White 2014). In this work, we have considered only one particular sum over possible triangles, but there is clearly additional information encoded in galaxy N-point functions beyond the tidal effects that we have focused on.

ACKNOWLEDGMENTS

We thank Joanne Cohn, Surhud More, Eli Rykoff and Risa Wechsler for helpful discussions. ND is supported by NASA under grants NNX12AD02G and NNX12AC99G, and by a Sloan Fellowship. The MultiDark Database used in this paper and the web application providing online access to it were constructed as part of the activities of the German Astrophysical Virtual Observatory as result of a collaboration between the Leibniz-Institute for Astrophysics Potsdam (AIP) and the Spanish MultiDark Consolider Project CSD2009-00064. The Bolshoi and MultiDark simulations were run on the NASA’s Pleiades supercomputer at the NASA Ames Research Center.

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