Galaxy Cluster Assembly and Environmental Effects on Galaxy Morphology

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Abstract

We study the formation of galaxy cluster-size dark matter halos ($M > 10^{14.0} M_\odot$) formed within a set of cosmological Λ cold dark matter N-body simulations, and track the accretion histories of cluster subhalos. By comparing the observed morphological fractions in cluster and field populations, we estimate an approximate timescale for morphological transformation within the cluster environments. Galaxy clusters provide an interesting environment for the study of several astrophysical phenomena. They are the largest collapsing objects in the universe, and, as such, they are an observable constraint of hierarchical structure formation. Through understanding the formation of clusters, we probe key parameters in cosmology; such studies allow us to place constraints on several processes in the formation and evolution of galaxies as well as large scale structure. Simulations provide us with tools to interpret the growth and assembly of these objects, allowing us to probe the effects that the cluster environment may have on galaxies that have been accreted into the cluster. We examine the formation of galaxy cluster sized dark matter halos in simulations and examine the possible effects on the morphologies of galaxies accreted into the cluster environment, as well as the timescales necessary to affect this change. Comparisons with observed samples of galaxy clusters allow simple models to be tested.

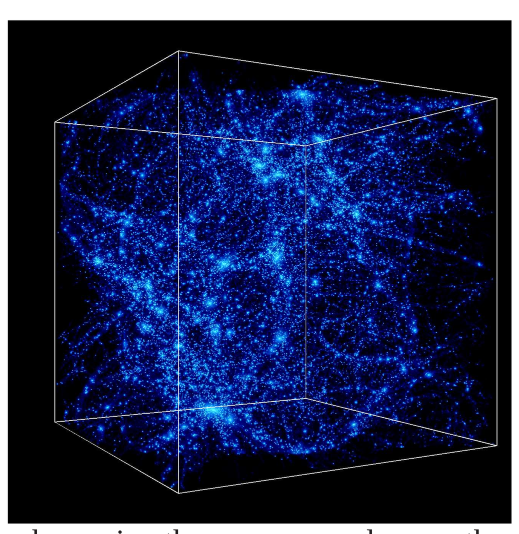

FIGURE 1: A simulation box using the same cosmology as the original N-Body simulations. This box is only $60h^{-1}$Mpc on a side, while those used in our analysis are $80h^{-1}$Mpc and $120h^{-1}$Mpc cubes. This image was provided by Andrey Kravtsov.

1 Method

We study the formation histories of 47 cluster-size dark matter halos, with $z = 0$ masses $M > 10^{14} h^{-1} M_\odot$, extracted from two cosmological N-body simulations with comoving cubic volumes of $120h^{-1}$Mpc and $80h^{-1}$Mpc on a side. Each simulation corresponds to a flat ΛCDM cosmology with $\Omega_M = 1 - \Omega_\Lambda = 0.3$, $h = 0.7$, and $\sigma_8 = 0.9$ and was performed using the Adaptive Refinement Tree (ART) code of Kravtsov et al. (1997). The populations of the clusters, or protoclusters at higher redshift, are examined in three different redshift bins, $z = 0, 0.5, 1$. We use 48 snapshot outputs from the $80h^{-1}$Mpc simulation, 91 for the $120h^{-1}$Mpc box, spaced roughly equally in expansion factor $a = 1/(1+z)$ to a maximum redshift of $z = 21.6$ in the $80h^{-1}$Mpc simulation and $z = 10.1$ for the $120h^{-1}$Mpc simulation, to generate merger histories for halos and subhalos (Stewart et al., 2008). This work is an extension of Berrier et al. (2009).

There are two categories of halos in the simulation. The first are discrete halos which are not contained within a larger structure - these are referred to as "host" halos. The second type of halo is a halo which has been accreted into a larger halo and is now substructure in that larger body. These are called "subhalos". The mass of a halo at the time of accretion is labeled M_{in}. For halos that are discrete field "host" halos we set $M_{in} = M_{vir}$ of the halo at that epoch. Galaxies whose masses fall below a critical mass, $M_{cr} = 10^{11.0} h^{-1} M_\odot$, are removed from our catalog. The choice for M_{cr} allows us to define a sample cleanly at a mass scale where our halo finder is complete and our simulations are not strongly affected by over-merging. We assume that halos with M_{in} larger than a $10^{11.5} h^{-1} M_\odot$ will host one galaxy at their center. If a halo contains one or more subhalos, it is assigned one "central" galaxy in addition to one galaxy for each of its subhalos. The term *host* is used to describe the largest halo that contains a galaxy. We use the term protocluster as any host halo which will meet our mass criteria as a cluster at $z = 0$, but does not have sufficient mass to be considered a cluster at the observed epoch.

2 Results

Figure 2 illustrates the fraction of cluster/protocluster *galaxies* that were accreted as members of host halos of a given mass. The lines are the cumulative frequency of galaxies accreted into the cluster from a halo of a given mass. The blue line is the $z = 0$ sample, the black line is the $z = 0.5$ sample, and the red line is the $z = 1$ sample. Note that the populations of the individual cluster halos that will not necessarily be the same as the $z = 0$ population as galaxies that fall below M_{cr} are removed from the sample and new objects are accreted into the cluster. Only $\sim 25\%$ of the $z = 0$ galaxies in clusters are accreted into the cluster from halos with group masses, $M \geq 10^{13} h^{-1} M_\odot$. For our sample of clusters and protoclusters at $z = 0.5$ and $z = 1$ we find a similar result as the $z = 0$ sample, with $\sim 80\%$ of galaxies in our sample being accreted from environments less massive then groups.

These results suggest that most cluster galaxies experienced no evolution in a group environment prior to their accretion into the cluster, lending support to the idea that internal cluster processes are responsible for the differences seen between cluster galaxies and those in field environments. If this is so, then the distribution of time spent in the cluster environment can provide insight into the timescales required for morphological transformation or the truncation of star formation.

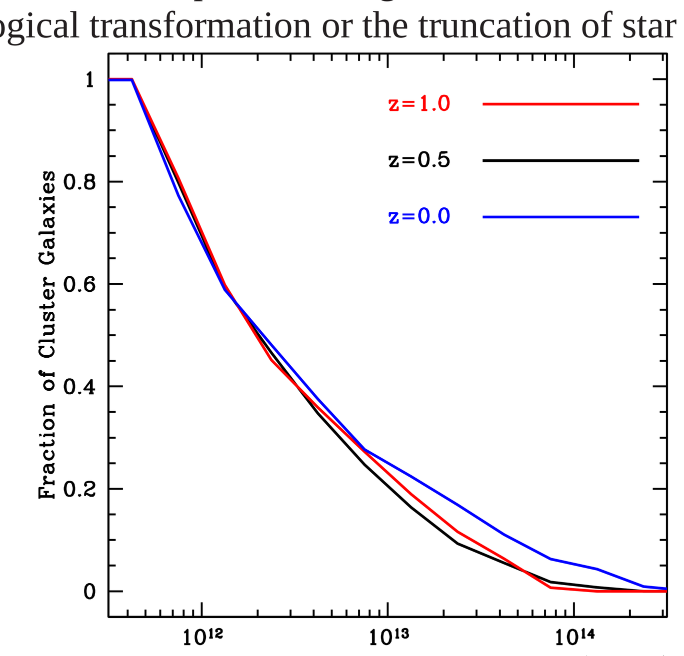

FIGURE 2: Cumulative fraction of cluster galaxies accreted into their respective clusters, or protocluster, as part of a host halo of a given mass. Three different populations are shown here. The blue line represents the final cluster populations at $z = 0$. The black line illustrates the cluster and protocluster populations at $z = 0.5$. The data in red demonstrates the cluster and protocluster populations at $z = 1$.

Figure 3 shows the distribution of accretion times for surviving cluster galaxies in our main cluster sample. Here the blue line is our $z = 0$ sample, the black is the $z = 0.5$, and the red is our $z = 1$ sample. We see that the accretion rate has been fairly uniform over the past ~ 8 Gyr, with the median lookback time to accretion at $\sim 4-5$ Gyr. The median time since accretion for the higher redshift samples are approximately 3 Gyr and 1.5 Gyr for the $z = 0.5$ and $z = 1$ samples respectively. In all three redshift bins the median time since accretion is longer then the dynamical time for the dark matter halo, ~ 2 Gyr at $z = 0$, ~ 1.25 Gyr at $z = 0.5$, and ~ 0.9 Gyr at $z = 1$ Stewart et al. (2009).

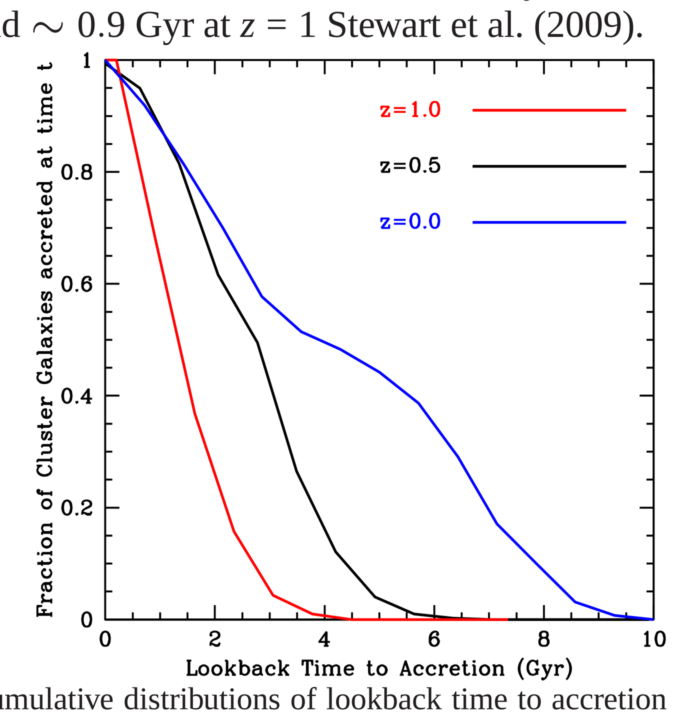

FIGURE 3: Cumulative distributions of lookback time to accretion for our primary sample of N-body cluster galaxies at $z = 0$, as well as for cluster and protocluster populations at $z = 0.5$ and $z = 1$. Please note that all lookback times are calculated relative to the redshift in question. The solid blue line shows the distribution of sample at $z = 0$. The black line represents the population at $z = 0.5$ while the red line illustrates the lookback time to accretion times for the galaxies at $z = 1$.

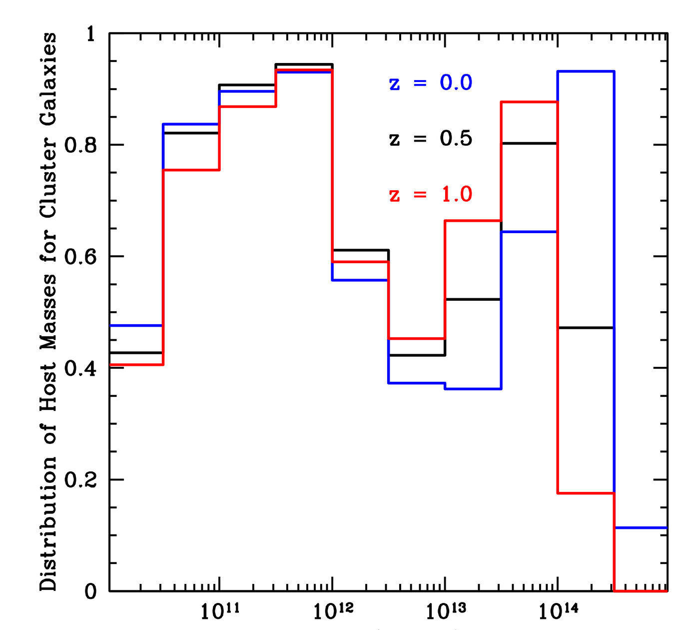

FIGURE 4: Fraction of $z = 0$ cluster and protocluster galaxies (with $M_{in} > 10^{11.5} h^{-1} M_\odot$) that have spent *any time* in a host of mass M_{host}. We allow objects to appear in multiple mass bins as long as they have any time in a host halo of a given mass. The $z = 0$ sample is presented by the blue line, the $z = 0.5$ by the black line, and the $z = 1$ by the red line.

In Figure 4 we plot the fraction of galaxies that have spent *any* time within a halo within a given mass bin. In this figure, a value of unity implies that every galaxy has spent at least some time in a halo of this size. As can be seen in this figure, a larger portion of the high redshift cluster/protocluster galaxy population has spent time in a group environment. This is to be expected since the majority of the protocluster population are group mass halos, $M_{host} \sim 10^{13.0}$, during these eras. This can be seen from the fact that less than 50 per cent of the galaxies have spent time in clusters at $z = 0.5$, and less than 20 per cent at $z = 1$. A significant portion of the population still spends *no time* in the group mass scale at both $z = 0.5$ and $z = 1$.

3 Conclusions

- **Figure 2**: The populations of cluster/protocluster galaxies show similar fractions of galaxies accreted into the cluster/protocluster environment from group mass, $M \geq 10^{13.0} h^{-1} M_\odot$, halos. In all cases less then 25 per cent of galaxies are accreted into the cluster from group mass halos.
- **Figure 3**: The median lookback time to accretion for galaxies within clusters is ~ 4.5 Gyr for the $z = 0$ sample. The median time since accretion for cluster/protocluster galaxies was approximately $3.0, 1.5$ Gyr for the populations at $z = 0.5, 1$ respectively, all are greater then the relevant dynamical times.
- **Figure 4**: A significantly larger fraction of cluster/protocluster galaxies have spent time in the group mass scale at higher redshift. Only ~ 35 per cent of $z = 0$ cluster galaxies have spent time in groups, compared to over 50 per cent at $z = 0.5$, and over 65 per cent at $z = 1$. This is driven by the fact that protoclusters at the higher redshifts are in fact groups at those epochs. There is still a strong bi-modality in all three distributions.

References

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