Section C

The galaxy melting pot

Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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On the age-radius relation and orbital history of cluster galaxies

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Abstract. We explore the region of influence of a galaxy cluster using numerical simulations of cold dark matter halos. Many of the observed galaxies in a cluster are expected to be infalling for the first time. Half of the halos at distances of one to two virial radii today have previously orbited through the cluster, most of them have even passed through the dense inner regions of the cluster. Some halos at distances of up to three times the virial radius have also passed through the cluster core. We do not find a significant correlation of "infall age" versus present day position for substructures and the scatter at a given position is very large. This relation may be much more significant if we could resolve the physically overmerged galaxies in the central region.

1. Introduction

Are the morphologies of galaxies imprinted during an early and rapid formation epoch or are they due to environmental processes that subsequently transform galaxies between morphological classes? The gravitational and hydrodynamical mechanisms that could perform such transformations were proposed in the 1970's, before the key observational evidence for environmental dependencies was provided - the morphology-density relation and the Butcher-Oemler effect. Many recent numerical simulations support these theoretical expectations. However, until we have self-consistent numerical simulations that can follow the structural evolution of galaxies within a large computational volume, we must resort to semi-analytic treatments or to studying the evolution of galaxies within idealised numerical calculations.

In this paper we study the orbits and infall history of substructure halos within a cold dark matter galaxy cluster. When we observe a cluster today we see a single frame of its entire cosmic evolution. What we would like to know for a given galaxy at a given position is: what is its likely orbit? Is it infalling for the first time? What are the environments that may have pre-processed the galaxy? If it has already passed the pericenter at what epoch did it enter a cluster-like environment? What was its impact parameter and velocity with respect to the cluster center? Are clusters built up in an "onion shell" scenario such that the observed galaxies trace an age-radius relation? We shall use the largest and highest resolution calculations of cold dark matter galaxy clusters to address some of these questions. With over 60 million particles in the high resolution region, up to 25 million particles within the virial radius and high force resolution, we can resolve the orbital histories of many thousands of substructures and halos both within the cluster and in the suburbs. Related studies have been carried out recently: Balogh, Navarro, & Morris (2000) followed *particle* orbits in N-body simulations while Mamon *et al.* (2004) used analytical calculations and the $z = 0$ snapshots of simulations to estimate rebound radii. Shortly after this meeting, other groups (Gill, Knebe & Gibson 2004, Gao *et al.* 2004a) have published results that were also obtained by following *subhalo* orbits and their results are very similar to those presented here.

2. Accretion redshift of cluster subhalos

It is interesting to know how much time today's cluster galaxies spent in dense environments and if the accretion time into a more massive halo is correlated with the current position in the cluster. One could expect that subhalos which fell into the cluster (or one of it progenitors) early have less orbital energy and tend to end up closer to the cluster center. We analyze the redshift of accretion of cluster subhalos in ΛCDM simulations. Note that as accreted structures we count both subhalos of the final cluster and subhalos of the cluster progenitor groups.

We take 20 outputs of run D6h and 10 of run C9, equally spaced in time. The simulations are described in Diemand, Moore & Stadel (2004b) and the properties of their subhalos are presented in Diemand, Moore & Stadel (2004a). Run C9 resolves a $M_{\rm virial} = 5.0 \times 10^{14} {\rm M}_\odot$ cluster with 10 million particles within $r_{\rm virial}$ and D6h resolves a smaller $M_{\rm virial} = 3.1 \times 10^{14} {\rm M}_\odot$ cluster with 2 million particles.

The subhalos were identified with SKID (Stadel 2001) and here we consider only structures with at least 32 bound particles. For each snapshot we construct a halo catalogue with FOF using a comoving linking length of 0.164 Δx_0 and trace back in time all subhalos within the virial radius of todays cluster. In Figure 1 the redshift before accretion is plotted, that is the last time a halo is identified as individual field halo. There is a large scatter in the accretion redshifts and no strong correlation with radius.

From the scatter plot and also from the histogram of accretion redshifts in three radial bins (Figure 2) one can see that the accretion rate is not a simple function of time but there are epochs of very rapid or of very slow accretion. Both clusters show very little accretion around redshift 0.4, which seems to be a coincidence.

The inner subhalos were accreted slightly earlier on average, in run D6h the mean and standard deviation of expansion factors at accretion is $a = 0.59 \pm 0.14$ for subhalos that end up in the inner 33 percent of the cluster and $a = 0.80 \pm 0.16$ for the outer 33 percent. For run C9 however all three radial bins give a mean of about $a = 0.7$. More halos must be analyzed to see if there really is a correlation of accretion redshift with cluster-centric radius, but we can already say that such a correlation must be weak and have a very large scatter.

3. Pericenters of halos in the outskirts of clusters

How many galaxies in the outskirts of clusters have passed through the inner, hot dense part of the cluster and how many are approaching the system for the first time? This question is interesting since some spiral galaxies in the outskirts of the Virgo cluster are observed to be deficient in neutral Hydrogen. First attempts to answer this questions include tracing back *particles* in cosmological Nbody simulations (Balogh *et al.* 2000) and analytical, spherical infall and rebound calculations (Mamon *et al.* 2004).

We traced back all subhalos and halos around the cluster D6h and measured the distance to the cluster core going back to the formation epoch of the cluster ($z \simeq 0.6$) with a time resolution of 0.6 Gyr.

Figure 3 shows the pericenter distance of the (sub)halos versus cluster-centric distance today. The points on the diagonal are halos that have their pericenter at $z \simeq 0$, the halos just below the diagonal in the upper right corner of the Figure are orbiting two satellite groups at distances of about 2 $r_{\rm virial}$. In the lower left corner ($< r_{\rm virial}$) we see todays subhalos. For ($r > r_{\rm virial}$) there is a large population of halos that have pericenters well within the cluster. These are halos in the outskirts of the cluster which have passed through the cluster earlier. About half of the halos between $r_{\rm virial}$ and 2 $r_{\rm virial}$ have a

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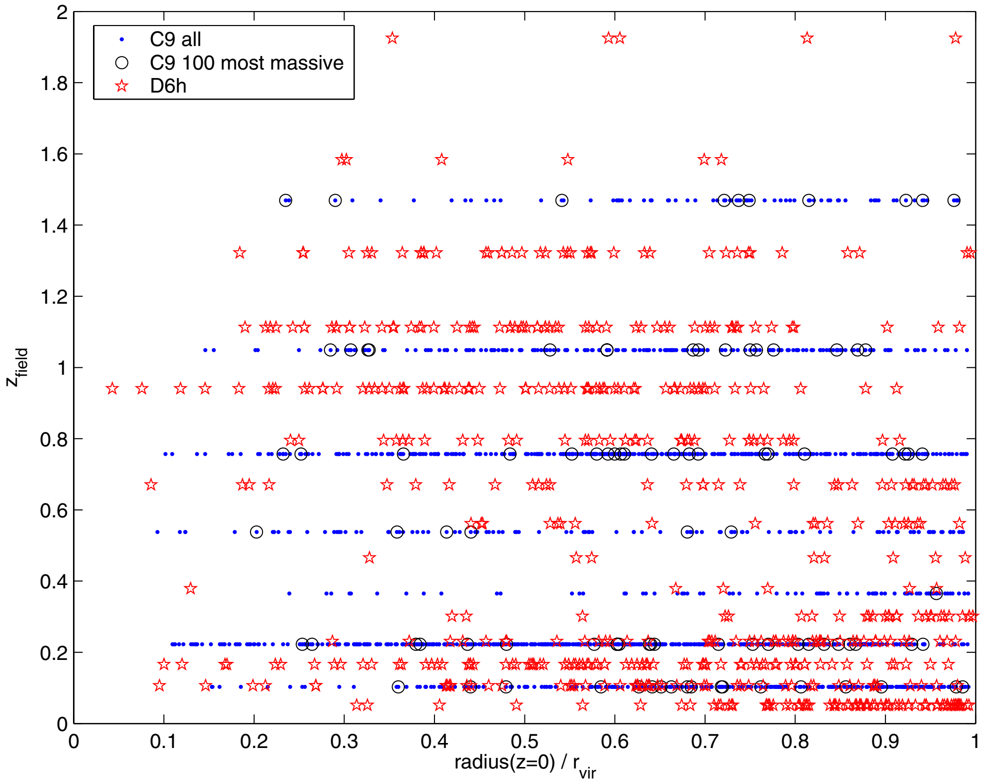

Figure 1. Accretion redshift of subhalos versus distance form the cluster center today. We use the redshift of the snapshot where the halo was identified as a field halos for the last time. The trend that central subhalos are older is weak and there is a large scatter in accretion redshifts at all radii.

pericenter smaller than $r_{\rm virial}$. Most of them (at least 70 percent†) have even passed through the inner part of the cluster ($r < 0.5 r_{\rm virial}$). Finally the points in the lower right part of the plot show that in some rare cases halos that passed through the cluster can rebound out to 3 $r_{\rm virial}$, which is a little larger than the maximal distance of 2.5 $r_{\rm virial}$ obtained from analytical, spherical infall and rebound calculations (Mamon *et al.* 2004).

4. Spatial distribution of subhalos

Ghigna et al. (1998) showed that the spatial distribution of subhalos is antibiased with respect to the mass. Diemand *et al.* (2004a) confirmed that this was not a resolution effect but most likely due to physical overmerging of dark matter halos as they entered the central cluster region. In order to reproduce the observed spatial distribution of galaxies (see Figure 4), dissipation is likely to play a key role (Gao *et al.* 2004b). It is not expected that dissipation will greatly alter the internal structure of galactic halos hosting disks with type later than Sb. These galaxies will suffer the same fate as the infalling subhalos and become tidally disrupted by the cluster environment. This immediately leads to the

† Note that in the inner part of the cluster the dynamical times become comparable to the interval between outputs, so the real pericenters will be smaller.

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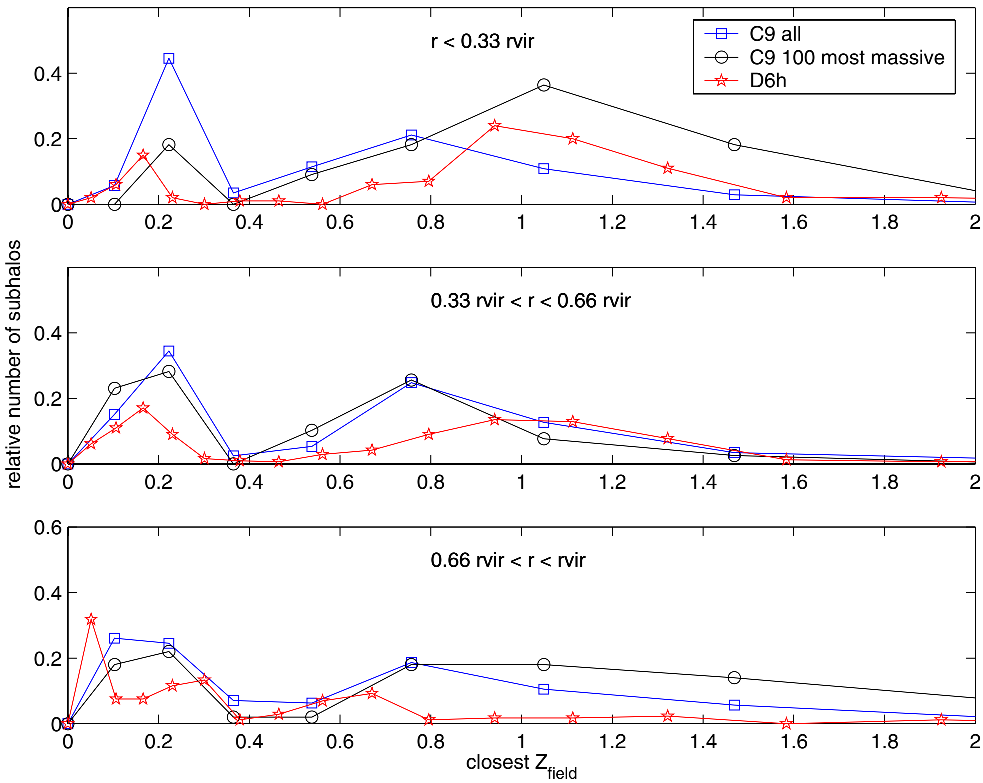

Figure 2. Histograms of accretion redshifts in the inner (top panel), intermediate (middle) and outer part(bottom) of two ΛCDM clusters.

morphology-density/radius relation since only ellipticals and Sa/Sb galaxies can survive near the cluster centre. Ellipticals will be especially dense since the multiple merging of gas rich proto-galaxies will undoubtedly lead to strong gas inflow into the central regions. The inter-galactic medium will rapidly be stripped from the central Sa/Sb galaxies and combined with a moderate amount of disk heating from tides these galaxies will rapidly turn into S0's. However it is hard to distinguish this scenario from one in which disk formation is suppressed within the proto-cluster environment.

5. Conclusions

Numerical simulations that follow only the dark matter component have provided numerous insights into the dynamical evolution of substructures. From these simulations we can infer a great deal about the environmental processes that may have affected galaxies both within the cluster and in the surrounding regions. However it is also clear that dissipation must play an important role in enabling galaxies to survive in the harsh environment within the inner regions of the virialised cluster. We summarise some of the results of our CDM cluster simulations here and look forward to enormous progress over the next decade in hydro-dynamical simulation of galaxy formation in different environments.

• The average accretion redshift of subhalos does not change significantly with the final time cluster-centric distance, i.e. there is no strong age-radius correlation in ΛCDM *subhalos* (however this does not exclude an age-radius correlation for *cluster galaxies*,

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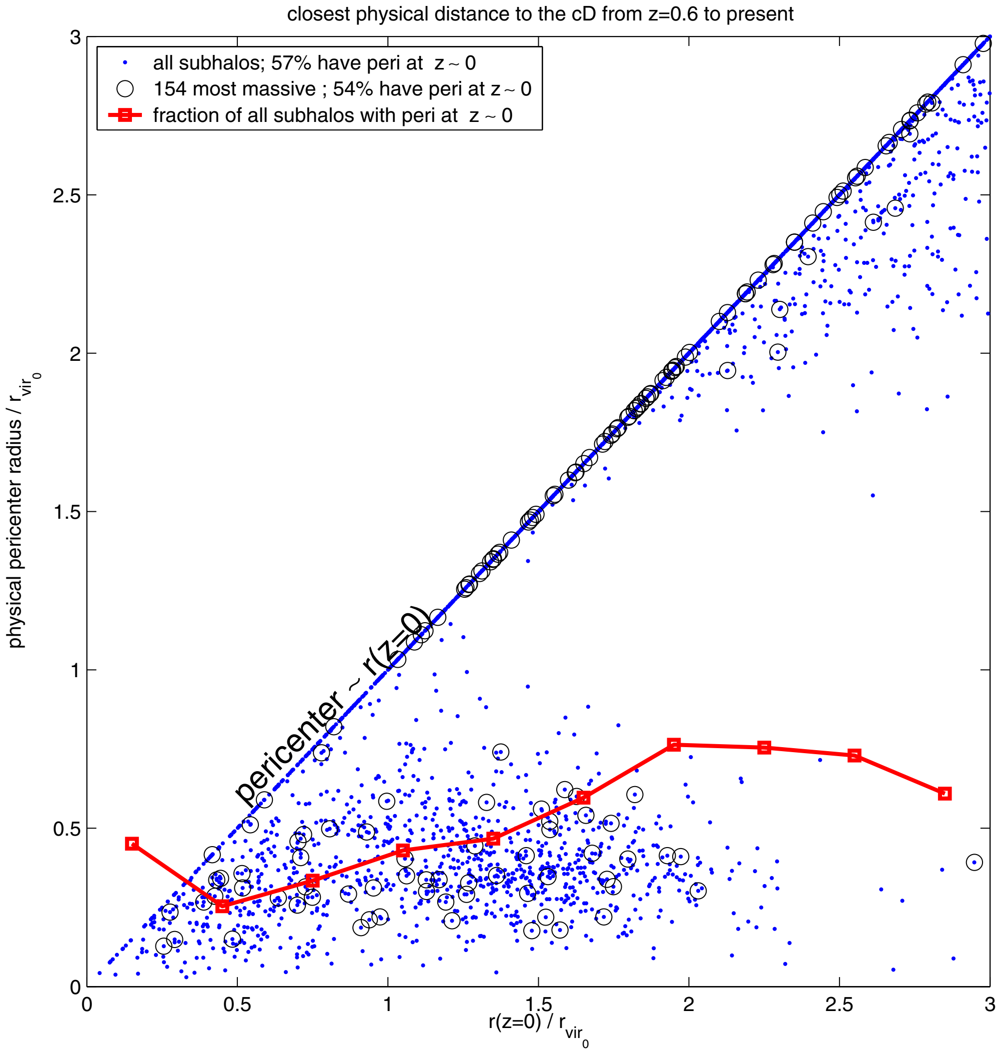

Figure 3. Closest physical distance to the cluster center form $z = 0.6$ to present vs. distance form the cluster center today. The red line gives the fraction of (sub)halos that have their pericenter today (within the time resolution of 0.6 Gyr). The points in the lower right corner show that many halos well outside the cluster today passed deep through it earlier.

since they do not trace the subhalos in a simple one-to-one correspondence: the subhalo number density profile are much shallower).

• About 50 percent of the galaxies that have a distance between one and two virial radii form the cluster center today have passed through the cluster earlier.

• Most of them (at least 70 percent) even approached the cluster center to less than half of the virial radius.

• There are some (rare) cases where a halo passes through the inner part of the cluster and then rebounds out to three virial radii.

• Dissipation must play an important role in enabling galaxies to survive in the central cluster regions. The morphology-density relation may be due to the disruption of disks at the cluster centre.

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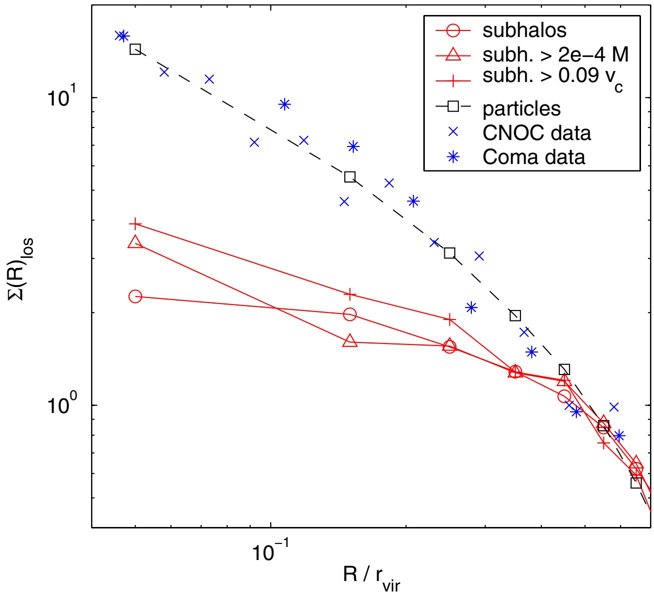

Figure 4. The distribution of subhalos plotted against the smooth dark matter component. The symbols show the radial distribution of galaxies from a sample of CNOC clusters (Carlberg, Yee & Ellingson 1997) and the Coma cluster (Lokas & Mamon 2003).

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