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The formation histories of galaxy clusters

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Abstract

A sample of hundreds of simulated galaxy clusters is used to study the statistical properties of galaxy cluster formation. Individual assembly histories are discussed, the degree of virialization is demonstrated and various commonly used formation times are measured and inter-compared. In addition, the fraction of clusters which have "recently" undergone a major merger or significant mass jump is calculated as a function of lookback time and interval. The fraction of three- and four-body mergers is also studied.

Keywords: Cosmology; Galaxy clusters; Mergers; Formation times

1. Introduction

Due to their immense size, galaxy clusters can be easily identified with their dark matter halos, and their clustering and number counts can be reliably predicted by dark matter simulations. However in order to find or "weigh" galaxy clusters observationally, assumptions of dynamical equilibrium and less understood astrophysics usually come into play.[1] Since halos form via the accretion and mergers of smaller units, and for clusters this process is occurring to the present time, such assumptions need to be specified precisely. For example, how well a galaxy cluster is described by equilibrium properties depends upon whether it has recently undergone a major merger (where "major" means disrupting equilibrium) and upon the specific methods used for its detection and mass measurement. Thus even if one is

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[1] Weak gravitational lensing measures mass without equilibrium assumptions, but only in projection (see e.g. Ref. [1]).

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only interested in galaxy clusters as "test particles" or peaks in the density field, the history of cluster growth is important in order to make contact with observations. Cluster growth histories are also important for understanding other cluster properties. For example, several observational phenomena (see below) are associated with clusters which have recently undergone mergers. A related question is which cluster properties have the least sensitivity to cluster assembly histories.

In this paper we study the assembly history and degree of virialization of high-mass halos in large N-body simulations. A cluster assembly history can be characterized either by events with specific occurrence times, such as mergers or large mass changes, or by properties of its entire history, e.g. a parameterization of the mass as a function of time. We calculate several such quantities for a statistically significant sample of halos. We consider several popular formation time definitions and cluster history parameterizations and statistics. We also calculate the fraction of "recently" merged galaxy clusters as a function of redshift, back to $z \sim 1$.

The definitions of both "merger" and "recently" depend on the cluster property of interest and we explore several choices. We also find the fraction of galaxy clusters which have had a recent large mass gain (including accretion) for several choices of interval and two final/initial mass ratios. Merger histories can be reliably extracted from N-body simulations, and as such these recently merged fractions are implicit in earlier work. However, it can be difficult to obtain specific numbers from the literature for ΛCDM models, especially if one has a particular relaxation time in mind. In part this is because previous studies of different quantities at different times have been published over several years, often using different cosmological models. Here we compute several of these quantities for a much larger sample than used in earlier work, for ΛCDM cosmologies, and present them in a homogeneous manner in the hope that this will be a useful reference for the community.

The outline of the paper is as follows. Section 2 is a review, including pointers to earlier work on formation times and examples of observed merger phenomena. Section 3 describes the simulations and methods. A reader interested primary in the results can skip directly to Section 4, which has comparisons and distributions of some cluster formation properties, and the fractions of clusters which have recently merged or had a large mass increase, as a function of time. Three- and four-body major mergers are also studied. Finally, Section 5 presents our conclusions.

2. Background

The growth of structure by mergers and accretion is key to the hierarchical paradigm of structure formation, and thus mergers and mass gains have been studied intensively. Previous work on cluster formation histories includes Refs. [2–9]. While cluster assembly is a complex and ongoing process in hierarchical models, it is often useful to have some measure of when the cluster "formed". Refs. [5,7,8], each with 10–20 clusters, considered formation time definitions including the redshift, $z_{\rm jump}$, of the most recent large ΔM over a short time. Both [7,8] also found a characteristic formation time $z_{\rm f}$ associated with the entire cluster growth curve using the parameterization of Ref. [10]. This parameterization works extremely well for galaxy sized halos and correlates with other properties such as concentration. For galaxy clusters, Ref. [8] introduced a generalization to help better match the more recently active formation histories of galaxy clusters. Ref. [6] had a sample similar to ours and found a "turning point" time where halos went from a quickly growing phase to a more slowly growing phase, this turning point was correlated with concentration. There are other formation times considered in the literature. For instance Ref. [11] found the average mass accretion history of halos generated by extended Press-Schechter. Ref. [7] also looked at the amount of mass gain coming from large ΔM "jumps" as fraction of cluster mass. We consider these properties and their distribution for our large sample of over 500 clusters for a ΛCDM $\sigma_8 = 0.8$ model in Section 4.

Our second set of results is the frequency of recent mergers and recent large mass gains for some fixed lookback time and definition of "recent."