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The Evolving Shape of Galaxy Clusters

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Abstract. We present the first measurement of the evolution of the apparent projected shape of galaxy clusters from $0.2 \lesssim z \lesssim 2$. We measure the ellipticities ($\epsilon_{\rm cl}$) of homogeneously selected galaxy clusters over this wide redshift range. We confirm the predictions of N-body simulations that clusters are more elongated at higher redshift, finding the mean projected ellipticity changes linearly from 0.36 ± 0.01 to 0.25 ± 0.01 over that range. The fraction of relaxed clusters (defined as having $\epsilon_{\rm cl} < 0.2$) is 9^{+5}_{-3}% at $z \sim 1.8$, steadily increasing to 42^{+7}_{-6}% by $z \sim 0.3$. Because more spherical clusters have a higher degree of virialization, our result shows significant evolution in the degree of cluster virialization over cosmic time.

Keywords. galaxies: clusters: general

1. Introduction

Galaxy clusters are the largest virialized structures in the Universe, and play important roles in our understanding of both cosmology and galaxy evolution. The aspherical shapes of clusters and groups has long been recognized tending to be preferentially prolate with cluster ellipticities ($\epsilon_{\rm cl}$) of $\sim$ 0.2–0.5. In a hierarchical structure formation scenario, clusters are predicted to exhibit more elongated shapes when infall and merging rates are higher, as they are at earlier times in the Universe. With galaxy infall preferentially occurring along a few filaments that feed the cluster, the distribution of galaxies takes an elongated shape. As the Universe becomes more rarefied, clusters find themselves cut off from significant inflow and have the opportunity to gravitationally relax to a more spherical shape with a higher degree of virialization (Tsai & Buote 1996).

In this paper, we present the first measurement that tracks the mean cluster ellipticity from $0.2 \lesssim z \lesssim 2$ using homogeneously selected galaxy clusters. The low redshift clusters come from the Red-Sequence Cluster Survey-2 (RCS-2; Gilbank *et al.* 2011), with higher redshift clusters from the Spitzer Adaptation of the RCS (SpARCS; Wilson *et al.* 2009),

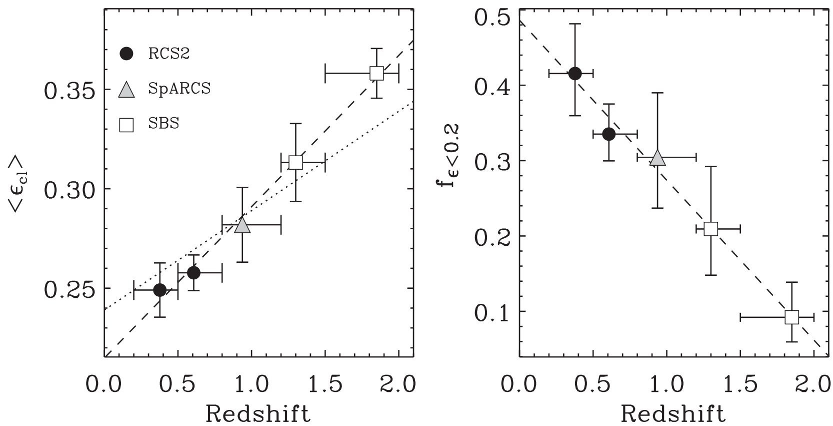

Figure 1. (*Left panel*) The mean ellipticity ($\langle\epsilon_{\rm cl}\rangle$) as a function of redshift. Horizontal error bars show the bin sizes. The dotted line uses the slope from Hopkins *et al.* (2005), with the intercept fitted to the data: $\langle\epsilon_{\rm cl}\rangle = 0.240 + 0.05z$. The dashed line is the best-fit based on the data. (*Right panel*) The fraction of clusters with $\epsilon < 0.2$ as a function of redshift.

including clusters identified with the stellar bump sequence method (SBS; Muzzin *et al.* 2009).

2. Results

We determine projected cluster shapes by assigning a probability that a given galaxy belongs to the cluster red sequence based on its color (Gladders *et al.* 2000, Muzzin *et al.* 2013). We construct probability maps by smoothing the spatial distribution of galaxies with a 0.5 Mpc gaussian kernel and measure $\epsilon_{\rm cl}$ from the second moment of the probability contours containing 60% of the peak probability in the map.

In Fig. 1 we present $\langle\epsilon_{\rm cl}\rangle$ and the fraction of "relaxed" clusters (defined by $\epsilon_{\rm cl} < 0.2$; $f_{\epsilon_{\rm cl}<0.2}$) as a function of redshift. The former quantity tracks how the shape of the clusters changes over redshift, while the latter quantifies the mix of "relaxed" and more elongated clusters over cosmic time. We compare to the N-body simulation of Hopkins *et al.* (2005).

Both are strong functions of redshift, with the best linear fit to both trends having slopes > 5 standard deviations from zero. The rate of change in $\langle\epsilon_{\rm cl}\rangle$ is steeper than predicted, although the difference in measuring cluster shape between observations and simulations can account for this. Our result shows the evolving degree of cluster virialization over ≈ 7.5 Gyr of cosmic time and agreement with the ΛCDM cosmology.

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