A Large Population of High Redshift Galaxy Clusters in the IRAC Shallow Cluster Survey

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Abstract.

We have identified 335 galaxy cluster and group candidates spanning $0 < z < 2$, using a 4.5$\mu$m selected sample of galaxies in a 7.25 deg$^2$ region in the Spitzer/IRAC Shallow Survey. Using full redshift probability distributions for all galaxies, clusters were identified as 3-dimensional overdensities using a wavelet algorithm. To date 12 clusters at $z > 1$, and over 60 at $z < 0.5$ have been spectroscopically confirmed. The mean I-[3.6] color for cluster galaxies up to $z \sim 1$ is well matched by a $z_f = 3$ passively evolving model. At $z > 1$, a wider range of formation histories is needed, but higher formation redshifts (i.e. $z_f \geq 4-5$) are favored for most clusters. The cluster autocorrelation function, measured for the first time out to $z = 1.5$, is found not to have evolved over the last 10 Gyr, in agreement with the prediction from ΛCDM. The average mass of the IRAC Shallow Cluster Survey sample, inferred from its clustering, is $\sim 10^{14}M_\odot$.

1. Introduction

The bulk of the stellar mass in the universe is created at $1 < z < 3$ (Dickinson et al. 2003; Rudnick et al. 2006) in very massive luminous and ultraluminous galaxies (LIRGs and ULIRGs, Le Floc’h et al. 2003; Papovich et al. 2006). Recent studies show that the SFR at $z = 1$ increases with increasing local density (Elbaz et al. 2007; Cooper et al. 2008), a reversal of the local SFR-density relation (Lewis et al. 2002; Brinchmann et al. 2004). To obtain a complete census of massive galaxy formation at $z > 1$ we need to study it across a range of environments, not least because most massive galaxies are found in very rich environments. Here we describe the IRAC Shallow Cluster Survey (ISCS;
Eisenhardt et al. 2008, hereafter E08), the largest, best-studied sample of stellar mass selected clusters at \( z > 1 \).

2. The IRAC Shallow Cluster Survey

The ISCS is a sample of 335 galaxy clusters spanning \( 0.1 < z < 2 \) in the IRAC Shallow Survey (ISS, Eisenhardt et al. 2004) area of the NOAO Deep-Wide Field Survey (NDWFS, Jannuzi and Dey 1999; Jannuzi et al. in prep) in Boötes. The clusters are selected using a wavelet detection algorithm which identifies peaks in cluster probability density maps constructed from accurate photometric redshift probability functions for 175,431 galaxies brighter than 13.3\( \mu \)Jy at 4.5\( \mu \)m in a 7.25 deg\(^2\) region (Brodwin et al. 2006, hereafter B06, E08). The redshift distribution is shown in Fig. 1.

![Figure 1](image)

Figure 1. Observed redshift distribution of 335 galaxy clusters in the ISCS. The curve, a fit to the distribution, is used in the clustering analysis in §4.

The AGES survey (Kochanek et al. in prep) in Boötes provides spectroscopic confirmation for over 60 clusters at \( z \leq 0.5 \) (E08). At higher redshift, a multi-year Keck spectroscopic campaign has to date confirmed 12 \( z > 1 \) clusters, many with \( \sim 10 - 20 \) members, at redshifts from 1.06 to 1.41 (Stanford et al. 2005; Elston et al. 2006; B06; E08).

3. Formation of Massive Galaxies

The extensive redshift baseline of the ISCS sample permits a test of various plausible star formation histories (E08). Fig. 2 (left) plots the average k-corrected I-[3.6] color for galaxies within 1 Mpc of each cluster center whose integrated redshift probability distribution in the range \( z_{cl} \pm 0.06(1 + z_{cl}) \) exceeds 0.3 (circles; filled symbols indicate \( z > 1 \) spectroscopically confirmed clusters. The red
curve is not a fit, but rather a Bruzual and Charlot (2003) population synthesis model in which the stars formed in a 0.1 Gyr burst at $z_f = 3$ and evolved passively thereafter. This scenario clearly describes the data better than a no-evolution model. Also plotted are the average k-corrected colors for galaxies more massive than a passively evolving $L^*$ galaxy (red boxes). These are systematically redder than the full cluster population, showing the persistence of the color-magnitude relation in clusters out to $z \approx 1.5$, and suggesting the early existence of a mass-metallicity relation in clusters and/or providing evidence of downsizing.

In Fig. 2 (right) the average k-corrected color of $L > L^*$ cluster galaxies is plotted relative to the $z_f = 3$ PE model (horizontal line). Overplotted are models with formation redshifts of $z_f = [1.5, 2, 4, 5, 30]$, as well as a no-evolution model. The offset between all models and the data at low redshift is primarily due to the redder colors of these massive galaxies discussed above. Nevertheless we can draw two robust conclusions from this figure regarding the star formation histories of $z > 1$ clusters. First, the variation in the average cluster colors increases markedly at $z > 1$. Second, we find that the stars in most high-redshift clusters, particularly those above $z > 1.2$, formed at $z \sim 4 \sim 5$ or even earlier.

4. Clustering of Galaxy Clusters to $z = 1.5$

The large, uniformly selected ISCS cluster sample has permitted the first measurement of the galaxy cluster autocorrelation function in the first half of the Universe (Brodwin et al. 2007). Specifically, the autocorrelation function was measured in two broad bins, at $0.25 \leq z \leq 0.75$ and $0.75 < z \leq 1.5$, with result-
ing clustering amplitudes of \( r_0 = 17.40^{+3.98}_{-3.10} \) and \( r_0 = 19.14^{+5.65}_{-4.56} \) h\(^{-1}\) Mpc, corresponding to average halo masses of \( \log[M_{200}/M_\odot] \sim 13.9^{+0.3}_{-0.2} \) and \( \sim 13.8^{+0.2}_{-0.3} \), respectively. Errors are computed via bootstrap resampling of the cluster catalog and are therefore rather conservative.

These correlation lengths are quite similar to the values for local clusters (e.g. Abell, APM, SDSS) as well as those at \( z \approx 0.5 \) (Gonzalez et al. 2002). This constancy with redshift is a key prediction of \( \Lambda \)CDM, as shown in Fig. 3 (left). Measurements of the cluster clustering amplitude, \( r_0 \), are plotted vs. intercluster distance, \( d_c \), for several different surveys spanning redshifts up to \( z \approx 0.5 \). Overplotted are the present measurements, at effective redshifts of 0.5 and 1.0 (filled symbols). The hashed regions shows the prediction from a high-resolution numerical simulation (Younger et al. 2005) that over \( 0 < z < 1.5 \) very little evolution is expected, in agreement with our results.

In Figure 3 (right) we plot a compilation of recent clustering amplitudes for various cluster surveys, as well as for highly clustered galaxy populations. Following Moustakas and Somerville (2002), we overplot the halo conserving model of Fry (1996) normalized to our two measurements in order to explore possible evolutionary connections with structures at other redshifts. The shaded area (dotted lines) shows the 1\( \sigma \) region for the \( z_{\text{eff}} = 0.53 \) (0.97) measurement. In this model the ISCS clusters will evolve into typical present–day massive clusters, such as those in the SDSS, APM or Abell surveys. In the stable–clustering picture, in which clustering is fixed in physical coordinates (Groth and Peebles 1977, dashed lines), the \( z_{\text{eff}} = 0.97 \) ISCS clusters grow into the most massive clusters in the local Universe, typically identified in X–ray surveys.
Most of the plotted high redshift galaxy clustering measurements are rather uncertain due to both small number statistics and poorly known redshift distributions. Several authors also find clustering amplitudes for galaxy populations which are inconsistent with their space densities (e.g. [Quadri et al. 2007]). Indeed, only obscured ULIRGs have space densities similar to the present cluster sample, a prerequisite for drawing evolutionary connections from these particular models. Their clustering is consistent with that of the ISCS clusters, providing a measure of support for recent studies (e.g. Magliocchetti et al. 2007) indicating that they may be associated with, or progenitors of, groups or low–mass clusters.

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