

## Clusters of Galaxies at $1 < z < 2$ : The *Spitzer* Adaptation of the Red-Sequence Cluster Survey

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### Abstract.

As the densest galaxy environments in the universe, clusters are vital to our understanding of the role that environment plays in galaxy formation and evolution. Unfortunately, the evolution of high-redshift cluster galaxies is poorly understood because of the “cluster desert” that exists at  $1 < z < 2$ . The SpARCS collaboration is currently carrying out a 1-passband ( $z'$ ) imaging survey which, when combined with the pre-existing  $\sim 50 \text{ deg}^2$   $3.6\mu\text{m}$  Spitzer SWIRE Legacy Survey data, will efficiently detect hundreds of clusters in the cluster desert using an infrared application of the well-proven cluster red-sequence technique. We have already tested this 1-color ( $z' - [3.6]$ ) approach using a  $6 \text{ deg}^2$  “pilot patch” and shown it to be extremely successful at detecting clusters at  $1 < z < 2$ . The clusters discovered in this project will be the first large sample of “nascent” galaxy clusters which connect the star-forming proto-cluster regions at  $z > 2$  to the quiescent population at  $z < 1$ . The existing seven-passband Spitzer data ( $3.6, 4.5, 5.8, 8.0, 24, 70, 160 \mu\text{m}$ ) will allow us to make the first measurements of the evolution of the cluster red-sequence, IR luminosity function, and the mid-IR dust-obscured star-formation rate for  $1 < z < 2$  clusters.

## 1. Introduction

Galaxy clusters are unique, high-density regions in the universe and are therefore important testbeds for theories of galaxy formation and evolution. Within the last decade, significant amounts of observational resources have been invested in finding clusters to  $z \sim 1$  using X-ray (Rosati et al. 1998; Pierre et al. 2004) and optical (Gladders & Yee 2000; Gilbank et al. 2004) techniques. Simultaneously, surveys which employ the Lyman-break technique have begun to uncover a population of vigorously star-forming proto-cluster regions at  $2 < z < 5$  (e.g., Kurk et al. 2004; Ouchi et al. 2005; Steidel et al. 2005). Tantalizingly, the

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crucial stages in cluster galaxy evolution, where star-forming Lyman- $\alpha$  galaxies transform into the quiescent early-type population seen at  $z \sim 1$  (Blakeslee et al. 2003; Holden et al. 2004) appear to occur in the hard to access redshift range  $1 < z < 2$ , the “cluster desert”. Currently, there are fewer than 15 spectroscopically-confirmed clusters at  $1 < z < 2$ <sup>1</sup> (with the highest-redshift being  $z = 1.41$ ; Stanford et al. 2005)

## 2. The (Infrared) Cluster Red-Sequence Method

The Cluster Red-Sequence (CRS) technique requires imaging in only two filters which span the 4000Å break feature in early types, and is a well-tested and observationally efficient method for detecting clusters (Gladders & Yee 2005; Wilson, Muzzin & Lacy 2005). The CRS algorithm selects clusters by using the fact that the cluster galaxy population is dominated by ellipticals and that they lie along a linear relation in the color-magnitude plane. If two filters that span the rest-frame 4000Å break are used to construct the color-magnitude diagram, cluster ellipticals are always the brightest, reddest galaxies at a given redshift, and therefore provide significant contrast with the field. The original technique was first developed by Gladders & Yee and is being used very successfully to target clusters in the  $0.2 < z < 1.1$  range where the blue-red  $R - z'$  filter combination spans the 4000Å break.

Fig. 1 shows the observed spectral energy distribution (SED) of an early type at  $z = 0.0, 1.0, 1.5$  and  $2.0$ . Also shown are the portions of the SED sampled by the  $r', i', z', K$  and  $[3.6]$  passbands. At  $z \sim 1.1$ , the 4000Å-break is shifted into the infrared (IR). To carry out a cluster survey at  $1 < z < 2$  requires deep IR observations over a large area - observations that are very difficult to obtain from the ground.

The only deep, large area (tens of square degrees) IR dataset currently available (or indeed available for the foreseeable future) is the Spitzer SWIRE Legacy Survey<sup>2</sup>.

## 3. The SpARCS Survey

The SWIRE Survey is comprised of six fields, and is well-suited to searching for high redshift clusters. Four fields (34.2 deg<sup>2</sup>) are accessible from the North, and two fields (14.8 deg<sup>2</sup>) from the South (totalling 49 deg<sup>2</sup>). Rich clusters are very rare so it is important to search over as large an area as possible. We expect to find only about 30 *rich* clusters (Abell Class 1) in the *entire* SWIRE survey.

Our collaboration, SpARCS<sup>3</sup> (The *Spitzer* Adaptation of the *Red-Sequence Cluster Survey*) has developed an IR adaptation of the two-filter cluster red-sequence technique which utilizes IRAC’s 3.6 $\mu$ m channel as the “red” filter (Fazio et al. 2004). A good choice of “blue” filter (better than e.g.,  $R$  or

<sup>1</sup>NASA Extragalactic Database (NED)

<sup>2</sup><http://swire.ipac.caltech.edu/swire/swire.html>

<sup>3</sup><http://spider.ipac.caltech.edu/staff/gillian/SpARCS>

$i'$ ), is the  $z'$  filter. This is because  $z'$  samples blueward of rest-frame  $4000\text{\AA}$  at  $z > 1.1$ , and yet becomes only as blue as rest-frame  $U$  at  $z = 2$ .

Fig. 2 shows red-sequence models constructed using the code of Bruzual & Charlot (2003), assuming a galaxy undergoing a burst of star-formation at  $z_f = 4.0$  and evolving passively thereafter. Based on these models, we can detect  $M_\star$  early types to  $z \sim 2$ .

To date, we have combined  $6 \text{ deg}^2$  of MegaCam  $z'$  and SWIRE [3.6] data in the XMM-LSS field, and detected about 70 moderately-rich clusters at  $0.05 < z < 1.85$ . Figs. 3 & 4 show examples of clusters at  $z > 1$ . We are currently extending this analysis to the remaining SWIRE fields.

## Science Goals

By searching for clusters over  $50 \text{ deg}^2$ , our aim is to detect a *representative* sample of clusters at  $1 < z < 2$ . This will allow the study of cluster galaxy evolution over a range of cluster richnesses and redshifts.

We plan to measure the IR luminosity function (e.g., Muzzin, Wilson & Lacy 2005, 2006), the mid-IR dust-obscured star-formation rate (using the SWIRE  $24\mu\text{m}$  data), the red-sequence, and the relative color distribution. In particular, the evolution of the color distribution will allow us to study the star-formation properties of the cluster galaxies as a function of mass and redshift and understand how the star-forming proto-cluster regions at  $z > 2$  connect to the quiescent clusters at  $z < 1$ . Furthermore, by measuring the evolution of both the IR luminosity function and the slope, scatter and color of the red-sequence to higher redshift than previous studies, we hope to put precise constraints on the epoch when stellar mass is assembled in cluster galaxies (Holden et al. 2004; Kodama et al. 2004).

Our goal is to release our cluster catalogs to the community as soon as possible, so that this sample can serve as a basis for numerous other science projects which require follow-up observations (e.g. mass determination, enrichment history).

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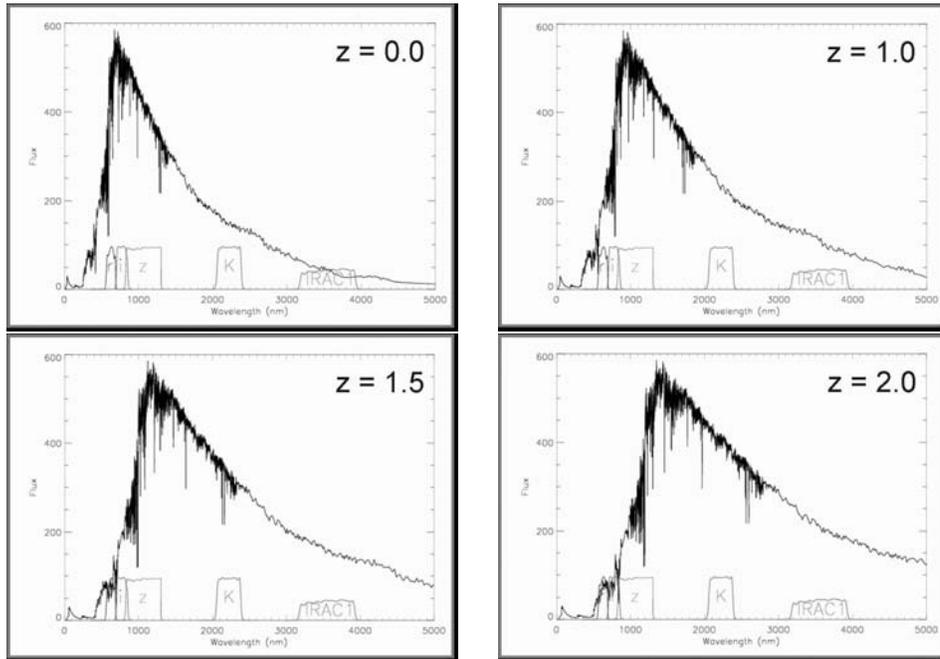


Figure 1. Observed SED of an early type at various redshifts. At  $z \sim 1.1$ , the traditional “red”  $z'$  filter no longer samples redward of the rest-frame  $4000\text{\AA}$  break. To detect clusters at higher redshift, an IR “red” filter is necessary.  $z'$ , however, is a good choice of “blue” filter for high redshift cluster surveys.

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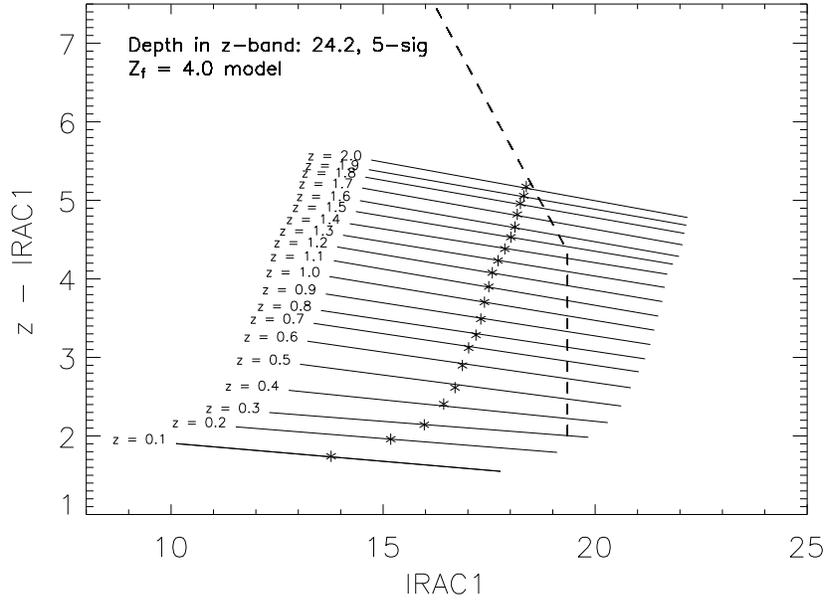


Figure 2. Simulated red-sequences for a  $z' - [3.6]$  filter combination assuming a Bruzual & Charlot (2003) model where a galaxy undergoes a burst of star-formation at  $z_f = 4.0$  and evolves passively thereafter. The dashed line is the depth of our survey.  $M_*$  the characteristic magnitude at each redshift is denoted by an asterisk. Photometric redshifts can be determined from the red-sequence ( $z' - [3.6]$ ) color) to an accuracy of 10%.

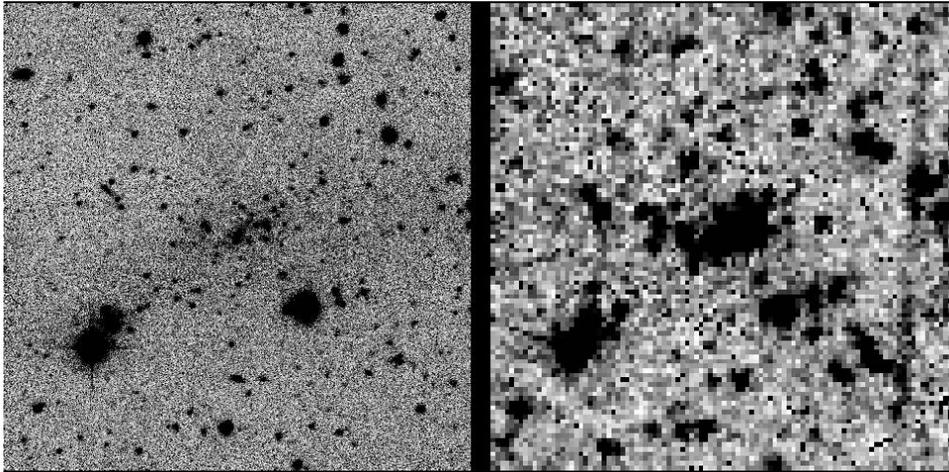


Figure 3.  $z'$  (left) and  $[3.6]$  (right) image of a  $z = 1.22$  cluster in the  $6 \text{ deg}^2$  “pilot patch” (the redshift is estimated from the color). The FOV is 1 Mpc at the cluster center. For a color image and more examples see (<http://spider.ipac.caltech.edu/staff/gillian/SpARCS>). Note: This cluster was discovered independently by the XMM-Newton Large Scale Structure Survey (Pierre et al. 2004).

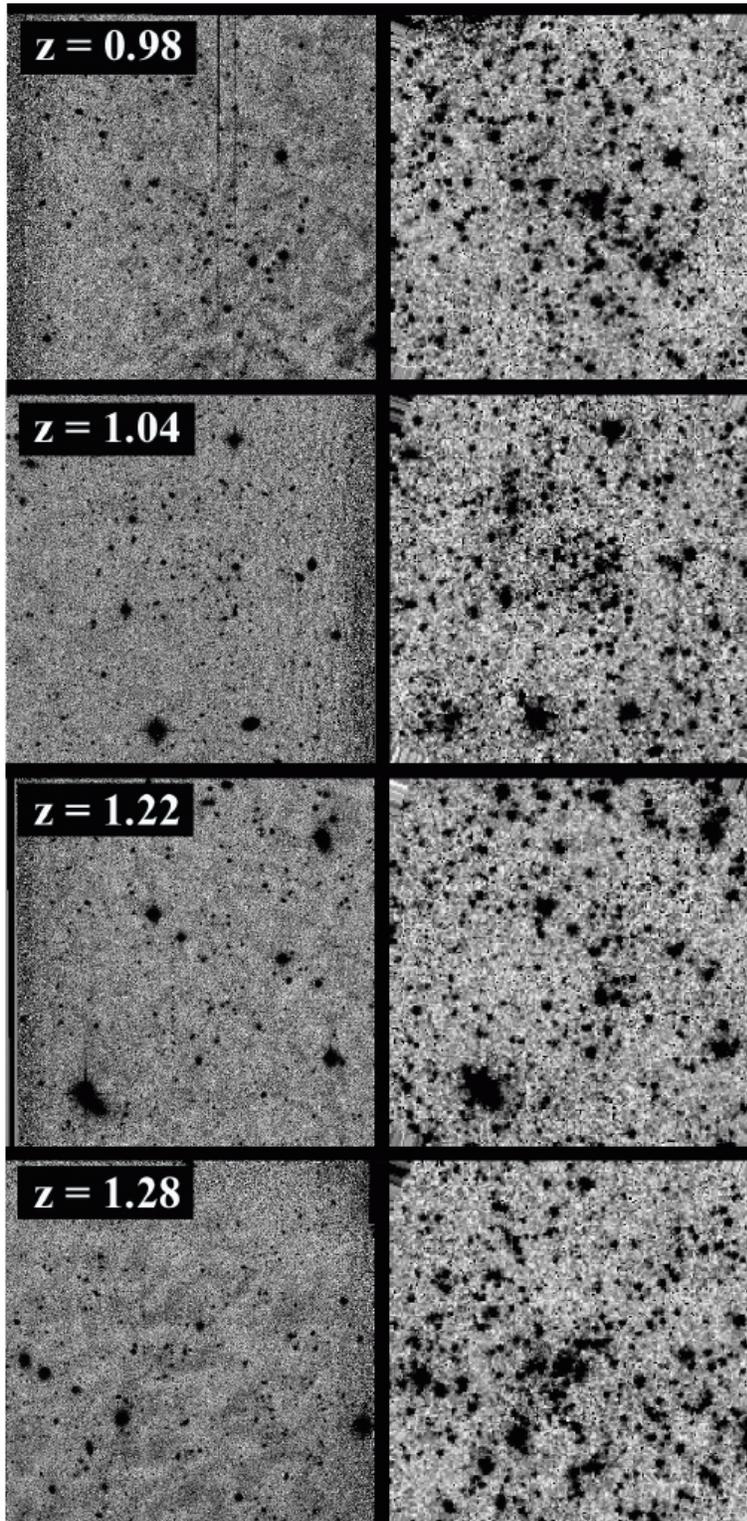


Figure 4. As for Fig. 3 but for a 2 Mpc FOV.