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# THE STANFORD CLUSTER SEARCH (StaCS): PROGRESS REPORT

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We present a progress report for StaCS. Our aim is a complete catalog of optically selected clusters in the range $0.3 \lesssim z \lesssim 1.0$ with well-understood selection effects to derive $n(M, z)$ for cosmological and evolutionary studies. StaCS cluster candidates are found on existing deep images, and we use the Hobby-Eberly Telescope to confirm redshifts and measure velocity dispersions. The catalog will be made available to the community for follow-up observations of the X-ray properties, the S-Z effect, and weak and strong lensing. Multiwavelength observations are necessary for the derivation of accurate mass profiles which are needed to model the cluster mass function accurately.

## 1 Introduction

Optically selected cluster catalogs have advantages over X-ray and S-Z catalogs. First, existing optical images can be used to probe higher redshifts and identify poorer clusters. Our limitation is the substantial optical spectroscopy needed to confirm and analyze the velocity structure of interesting candidates, whereas X-ray and sub-mm surveys both need substantial telescope time to search large volumes of space but their detection criteria are more closely related to the potential well that indicates a virialized cluster. Another advantage is that we will be sensitive to proto-clusters and rich groups that may not be found using X-rays or the S-Z effect due to the state of the intra-cluster gas. Identification of such structures is essential if we wish to follow the evolution of clusters.

We give here an introduction to StaCS and a progress report. In brief, we use deep optical images to generate galaxy catalogs, analyze these with a matched filter algorithm to search for candidate clusters, confirm these spectroscopically, and plan further observations in the optical, X-ray, and sub-mm regions of the spectrum. Our analysis of the image data base from the Supernova Cosmology Project is in progress, and we have a growing list of spectroscopically confirmed clusters. This contribution is a synopsis of a paper in preparation, to be submitted to PASP. See also our website at `http://redshift.stanford.edu/StaCS/`.

[a] Deceased.

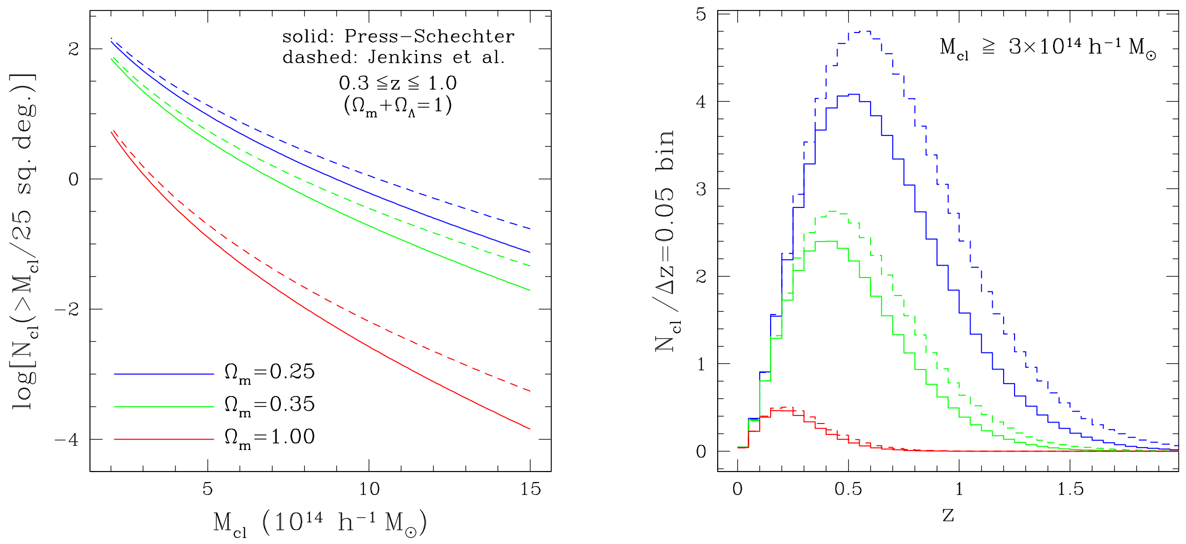


Figure 1: The expected number of clusters per square degree of sky, with redshifts $z \le 1$, and mass $\ge M$, for two representative low-density, flat cosmologies. The calculations are made using both the Press-Schechter formalism and a fitting formula for the Virgo Consortium mass function (Jenkins et al. astro-ph/0005260). The rms mass fluctuations are normalized to present-day cluster abundance. See talk by Mathiesen & Willick.

## 2 Science Objectives

The most glamorous goal for StaCS is to constrain $\Omega_m$ and non-gaussianity by probing $n(M, z)$ at high redshifts (Figure 1). While this is a strong motivation, the history of observational cosmology suggests that our catalog will contribute more to the investigation of cluster formation, evolution, and merger histories than the elusive cosmic parameters. Two short-term goals are to constrain scaling relations at intermediate redshifts ($0.4 \lesssim z \lesssim 1$), and to examine clusters in the context of surrounding large-scale structure. StaCSwill be an excellent starting point for tracing the evolution of cluster dynamics and the intracluster medium.

## 3 The Catalog

StaCS will be a large catalog of confirmed, optically selected clusters in the range $0.3 \lesssim z \lesssim 1$, to establish the comoving density $n(M, z)$ and provide a target list for follow-up observations. We cover three essential elements in the design of the project. First, cluster candidates must be confirmed with Hobby-Eberly telescope spectroscopy, resulting in measured redshifts. We do not consider the estimated cluster characteristics by our image analysis (see Sec. 3.1)—or indeed the cluster identification itself—to be reliable, and spectroscopic confirmation is essential to make the catalog useful for science. Second, the catalog completeness will be modeled through Monte-Carlo analysis to characterize the algorithm efficiency for finding clusters with a broad range of properties that deviate from the assumed model cluster. Third, robust mass measurements are planned via a combination of high resolution imaging for lensing analysis for all the clusters and multi-object spectroscopy, X-ray imaging, and Sunyaev-Zel'dovich observations for subsets of the catalog. Finally, the algorithm demonstrates a sensitivity to medium and low luminosity clusters, allowing investigation of cluster properties all the way down the scale to groups.

### *3.1 Procedure*

We begin with a deep image database. Currently we are concentrating on images taken by the Supernova Cosmology Project (SCP) of Lawrence Livermore Laboratory. [1] We co-add $R$-band images to a limiting magnitude of $\sim$ 23.5 or deeper and feed these to a sequence of FOCAS procedures [2] and locally written photometry and astrometry routines to generate a galaxy catalog. The galaxy catalogs from adjacent images are combined into one large catalog, removing duplicates in the overlap regions. We then apply a matched filter algorithm (MFA) to generate a likelihood map of the existence of clusters over RA, Dec, and $z$, along with the associated richness map. [3,4]

Once we have a likelihood map ($\mathcal{L}_{fine}$), we search for peaks, identifying those that project above the 95$^{\rm th}$ percentile for each redshift plane, and determine the most likely redshift and richness ($\mathcal{R}$) for each ($\mathcal{R}$ is the optical luminosity in units of $L^*$ at the estimated redshift, according to the assumed cosmology). Further criteria for cluster candidates are somewhat subjective: they must have a reasonable local galaxy luminosity function (excess above the background distribution) and be visually apparent on the images. Such criteria eliminate spurious candidates with various causes—the real data are imperfect—but identifications are only ambiguous for the poorest clusters, and a more sophisticated algorithm (approximating those in our heads) might be coded into the software in future.

Following the generation of the candidate list, we prioritize the targets. We are currently aiming for $z \sim 0.6 - 0.8$ to fill in the intermediate-redshift (called "high" redshift a few years ago) sample of known optically selected clusters (see Sec. 5). The highest redshift candidates are too faint for regular targeting with HET at this time, though upgrades in progress will allow multi-object slit spectroscopy [5] out to $z \sim 1$.

Further observations must be used to measure the mass of these clusters. Perhaps the least telescope-time-intensive method is weak lensing analysis, requiring a few hours of 4-m class telescope time in good conditions (the available images in the SCP database are not deep enough and mostly do not have good enough seeing). However, given the uncertainties associated with weak lensing, we also plan on searching for strong lensing arcs with HST and ground-based adaptive optics instruments (giving a much more accurate core mass, if arcs are found), performing thorough spectroscopic surveys (i.e. $>100$ redshifts per cluster), and making X-ray and Sunyaev-Zel'dovich effect measurements for subsets of the catalog. This will enable us to determine the systematic offsets and uncertainties of the methods in a uniform manner, hopefully allowing us to adopt accurate masses based on weak lensing alone for most of the clusters.

### *3.2 Example: SCP field*

As an example, we show the stages of analysis of a $0.67\Box^\circ$ SCP field near $01^{\rm h}$, $+04^\circ$(the "01+04" field). This field consists of 12 positions of CTIO prime focus $R$-band images ($\geq$ 720 s net integration time per co-added frame). Figure 2 shows the galaxy positions, totalling 38633 galaxies, with a limiting magnitude $m_{lim} \sim 23.23$. From this, the MFA generated the 3-D $\mathcal{L}_{fine}$ map (RA, Dec, $z$), shown as a 2-D tiled map in Figure 3. Each section indicates the $\mathcal{L}_{fine}$ value in RA and Dec for a fixed $z$.

Figure 4 shows the $\mathcal{L}_{fine}(z)$ plots for a semi-random selection of the $\mathcal{L}_{fine}$ local maxima which is the first criterion in generating a cluster candidate list. There were 19 such candidates in this field, although a few were found to be spurious upon inspection of the images and/or the local luminosity function. Figure 5 shows the local luminosity functions at the same positions. The luminosity functions are from the excess galaxy counts above the background level, previously determined by measuring the entire $0.67\Box^\circ$ galaxy catalog for this field. For example, the J0104.2+0416 luminosity function is unconvincing, but inspection of the image shows that a

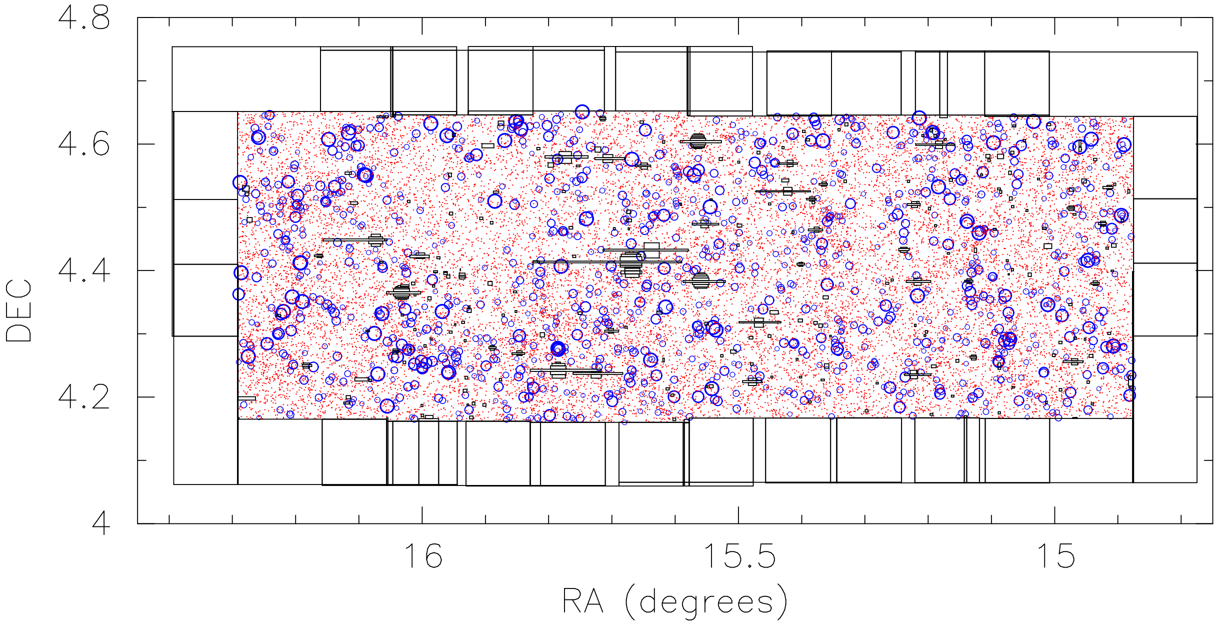


Figure 2: Positions of a subset of the galaxies detected in the CTIO prime CCD frames of the 01+04 field. Blue markers are sized according to the magnitudes of those galaxies with $m_R \leq 20$ and galaxies with $m_R > 20$ are shown with red dots. Exclusion boxes are in black, indicating the edges of the galaxy catalog and regions of spurious or missing data such as those caused by saturated stars or image defects, used by our modified MFA.

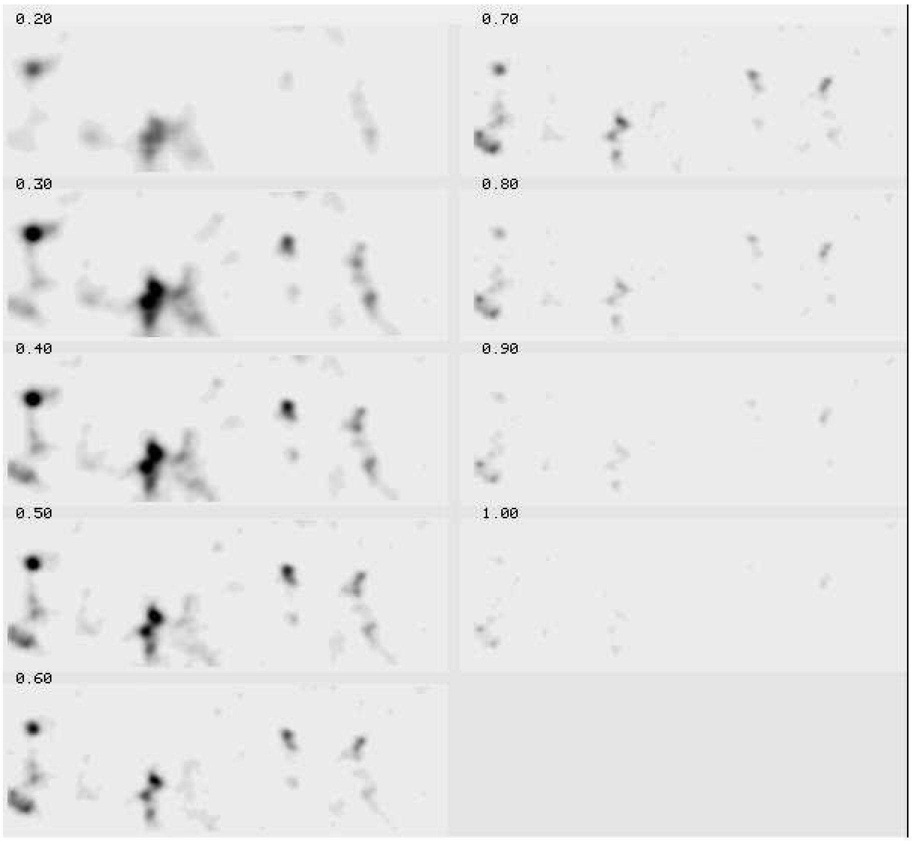


Figure 3: The 2-dimensional tiling of the 3-D $\mathcal{L}_{fine}$ map resulting from a run of CLUSTERFIND on the 01+04 field galaxy catalog. The redshift for each RA-DEC plane is shown in the upper left hand corners; North is up and East to the left. The reverse greyscale indicates values from $\sim 0$ to $\sim 50$. Values of $\mathcal{L}_{fine}$ are suppressed (set to -1 in the plot) where $\mathcal{R} < 0$, i.e. where there is an underdensity of galaxies. The confirmed cluster (STACS J0104.8+0430) is represented by the strong, nearly circular peak near the north-east corner.

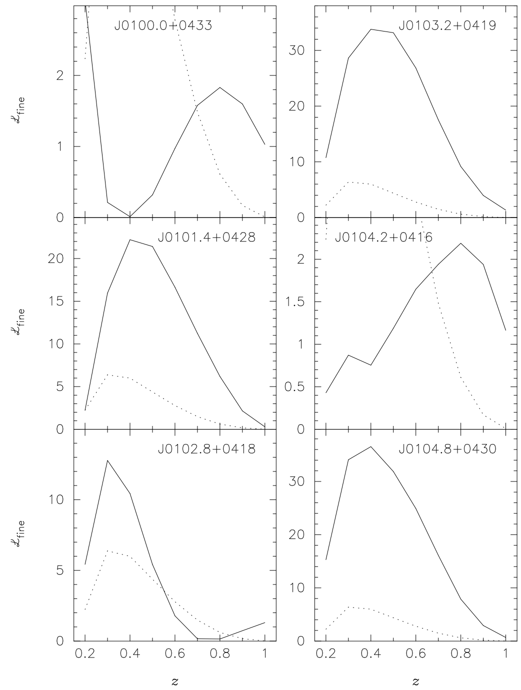


Figure 4: Likelihood $\mathcal{L}_{fine}$ versus redshift for six candidate clusters obtained from the 01+04 field. The peak of each curve indicates the most probable redshift of the candidate cluster, and the $\mathcal{R}$ value (not shown) at redshift of the $\mathcal{L}_{fine}$ peak represents its estimated richness. The dotted lines represent the 95$^{\rm th}$ percentile $\mathcal{L}_{fine}$ value as a function of redshift, used as a threshold.

large area near the presumed cluster center was blanked out with an exclusion box surrounding a saturated star. Our modified MFA did its best to interpolate the signal so that a marginal overdensity of galaxies became a "significant" peak in $\mathcal{L}_{fine}$. While ideally a renormalization of the values could be done to avoid such false identifications, in practice there are diminishing returns for the small data set we are using. There are other potential improvements we feel are more important, such as a system for fitting the background galaxy density with a smooth function rather than a constant value for each field (cf. Bramel *et al.*[6]).

Our first confirmed cluster (October 1999) is STACS 0104.8+0430. Figure 6 shows the region. Its estimated $\mathcal{R}$= 38. Figure 7 shows the 9 galaxy spectra we have in this field with measured redshifts, 6 of which are presumed cluster members. The average of those 6 yields $\langle z \rangle = 0.400$, which is closer to the MFA-estimated $z_{est} = 0.4$ than we have any right to expect ($\mathcal{L}_{fine}$ was calculated only in increments of $\Delta z = 0.1$).

## 4 Progress

The preparatory work for StaCS is all but complete: the data analysis procedure is established, the processing of the SCP data base images is well along, the MFA has been developed to deal with specific issues in our data set, and high priority candidates are in the HET queue for spectroscopic confirmation. We have submitted several proposals to other telescopes (Chandra, HST, Gemini) for follow-up observations, and have been discussing collaborations with other groups. The StaCS naming convention (STACS JHHMM.m+DDSS in J2000 coordinates) has been registered with the *IAU Commission 5 Task Group on Astronomical Designations* (see `http://cdsweb.u-strasbg.fr/Dic/iau-spec.htx`) and conforms to their recommendations.

Four clusters have been confirmed with the HET as of July 2000. While this number seems small, note that the HET is still in its first year of semi-regular science operations, and Stanford's share is only 7%. We do expect efficiency to improve over the next year as improvements are

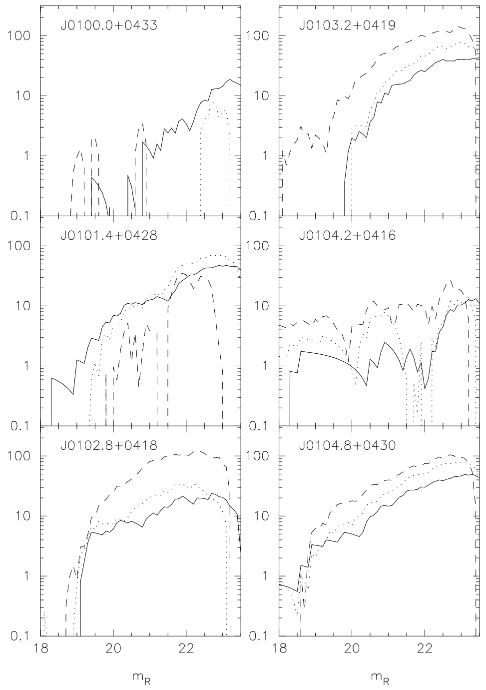


Figure 5: Luminosity functions for the candidates indicated in Figure 4. The horizontal axes are $R$-magnitude and the vertical axes are the integrated excess number counts $(N(< m) - N_{background}(< m))$ within circles centered on the cluster candidate. The solid lines indicate the counts within $r_{core}$ of the center, dotted within $2r_{core}$, and dashed within $4r_{core}$. The background distribution is assumed to be the straight power law used in CLUSTERFIND, and exclusion boxes were ignored.

implemented aimed at decreasing the seeing size and reducing observing overhead, as well as the permanent installation of the 13-slitlet multi-object unit on the Marcario Low Resolution Spectrograph.

We have found an important issue that needs attention in the field of cluster identification. While the MFA algorithm has demonstrated a sensitivity to poor clusters, and we have no doubt the technique can generate a complete catalog down through moderate masses and redshifts approaching 1, intermediate and poor clusters often have ambiguous characteristics. We often suspect a projected overlap between more than one cluster, or the chance projection of rich groups or large scale structures. We are only sensitive to redshift as it affects the angular size and the luminosity function (with a characteristic $m^*$) of the overdensity, since we use only one filter. While multi-color imaging may assist in discerning such structure by providing rough redshift information during the galaxy catalog analysis (cf. Kepner *et al.*[4]), there is no substitute for a thorough redshift mapping of the field. The latter is especially true as we probe to redshifts beyond 1 where our understanding of cluster galaxy characteristics is incomplete.

## 5 Final Note

One final note is in order. A tragic event has cast uncertainty on the future of StaCS. Jeff Willick, the leader and originator of our project, died shortly before the conference (see memorial page to be included with these proceedings). In the near-term, StaCS is continuing as planned, but we have a commitment for a share of Stanford's HET time only until the summer of 2001. We plan on processing the best of the SCP data base images, perhaps 15–20$\Box^\circ$. For the most scientific impact, we will then get spectra with HET of the most promising candidates with intermediate richness and $0.6 \lesssim z \lesssim 0.8$. We also will try to get redshifts for rich $z > 0.8$ candidates as it becomes possible, although these are not numerous in our candidate lists. We

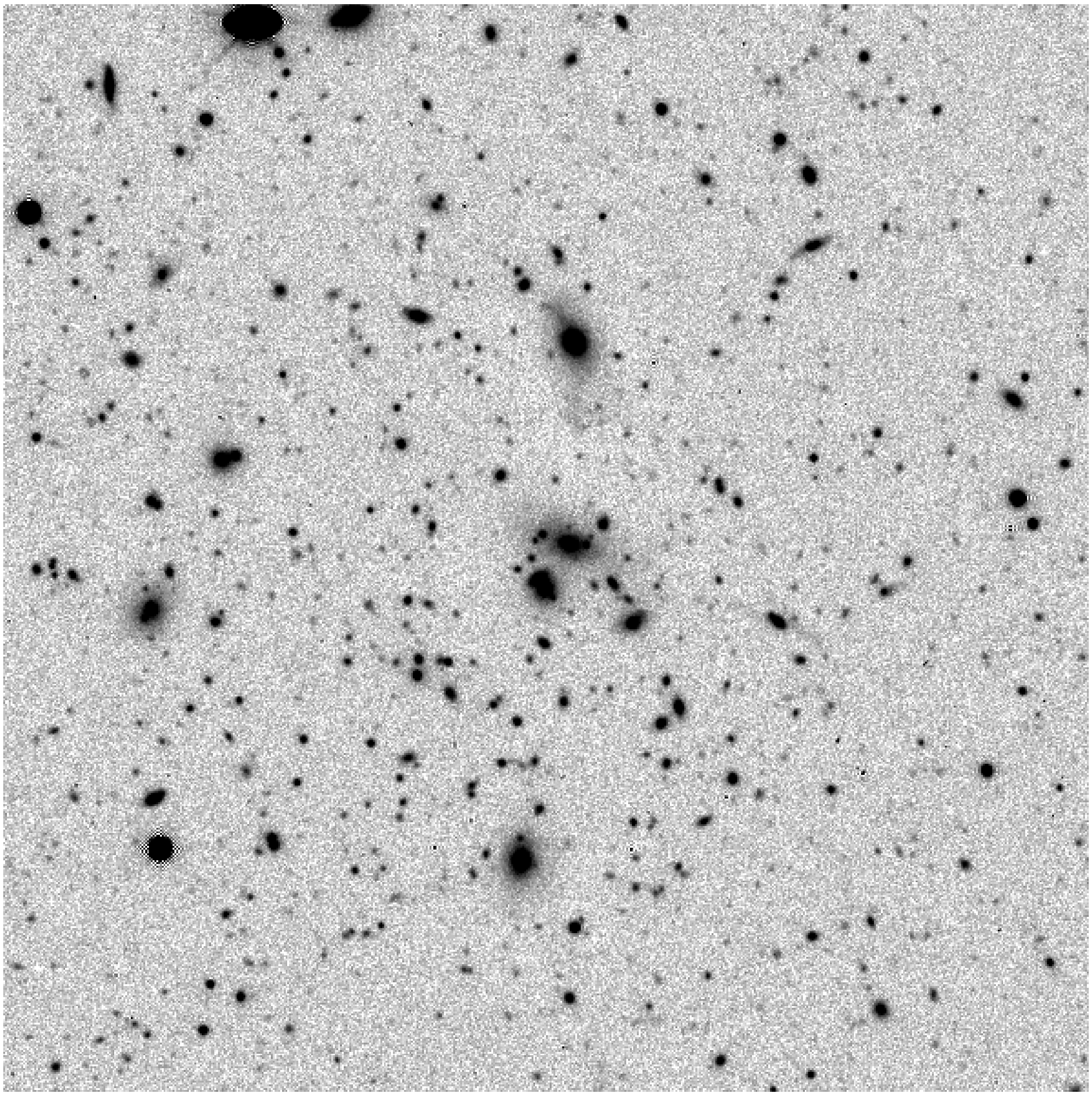

Figure 6: The $R$-band image centered on STACS J0104.8+0430.

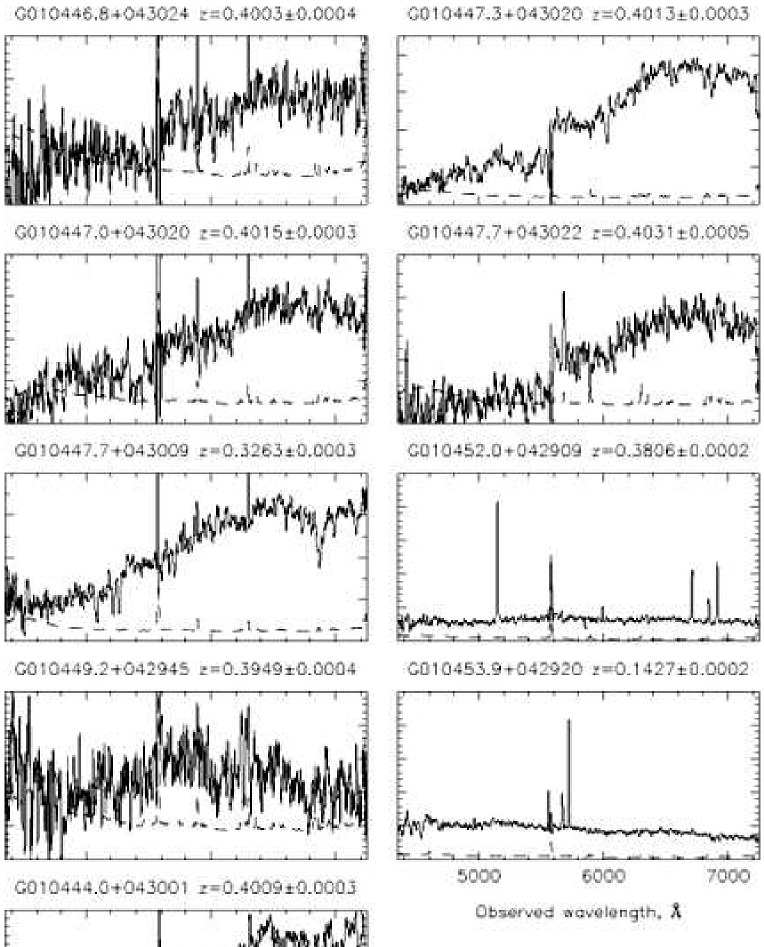


Figure 7: Spectra of galaxies in the field of STACS J0104.8+0430. The solid lines are the spectra, smoothed with a 5-pixel boxcar filter (approximately the size of the resolution element, R $\sim$ 600), and the dashed lines are the approximate pixel uncertainties. The vertical axes are roughly calibrated $F_\lambda$. The H+K absorption features are just short of the $\lambda$5577 sky emission line subtraction residuals in the cluster members.

are also pursuing X-ray, Sunyaev-Zel'dovich effect, and deep optical imaging of our clusters, though with lower priority. We expect to have up to $\sim 20$ clusters confirmed by June of 2001, more than an order of magnitude fewer than the complete catalog we envisioned. However, even this number of optically selected, confirmed clusters in this redshift range will be useful to the community, even if not part of a complete catalog. At the end of the program we will provide our candidate list to interested parties (contact KLT), and will always make available our growing catalog of confirmed clusters.


**Acknowledgments**

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