A DEFINITIVE OPTICAL DETECTION OF A SUPERCLUSTER AT $z \approx 0.91$

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ABSTRACT

We present the results from a multiband optical imaging program that has definitively confirmed the existence of a supercluster at $z \approx 0.91$. Two massive clusters of galaxies, Cl 1604+4304 at $z = 0.897$ and Cl 1604+4321 at $z = 0.924$, were originally observed in the high-redshift cluster survey of Oke, Postman, & Lubin. They are separated by 4300 km s$^{-1}$ in radial velocity and 17' on the plane of the sky. Their physical and redshift proximity suggested a promising supercluster candidate. Deep BRI imaging of the region between the two clusters indicates a large population of red galaxies. This population forms a tight, red sequence in the color-magnitude diagram at $(R-i) \approx 1.4$. The characteristic color is identical to that of the spectroscopically confirmed early-type galaxies in the two member clusters. The red galaxies are spread throughout the $5 h^{-1}$ Mpc region between Cl 1604+4304 and Cl 1604+4321. Their spatial distribution delineates the entire large-scale structure with high concentrations at the cluster centers. In addition, we detect a significant overdensity of red galaxies directly between Cl 1604+4304 and Cl 1604+4321 which is the signature of a third, rich cluster associated with this system. The strong sequence of red galaxies and their spatial distribution clearly indicate that we have discovered a supercluster at $z \approx 0.91$.

Subject headings: cosmology: observations — galaxies: clusters: individual (Cl 1604+4304, Cl 1604+4321) — large-scale structure of universe

1.INTRODUCTION

Superclusters comprise the largest known systems of galaxies, containing 2–5 massive clusters and extending over 10–20 Mpc (e.g., Bahcall & Soneira 1984; Postman, Geller, & Huchra 1988; Quintana et al. 1995; Small et al. 1998). Since the dynamical timescales of superclusters are comparable to the Hubble time, large-scale structures observed today are cosmic fossils of conditions that existed in the early universe. As a result, studies of these systems can be used to measure the cosmological density parameter $\Omega_m$ to constrain the large-scale variation of the mass-to-light ratio, and to test theories of the formation and evolution of galaxies and clusters (e.g., Hoffman, Shaham, & Shaviv 1982; Shaya 1984; Peebles 1986; Cen 1994). Large-scale structures have been studied at low redshift via the local, Shapley, and Corona Borealis superclusters (e.g., Davis et al. 1980; Postman et al. 1988; Quintana et al. 1995; Small et al. 1998). At higher redshifts of $z \approx 0.4$, weak lensing studies of MS 0302+16 (Kaiser et al. 2000) provide a direct measure of the projected mass distribution on 10 Mpc scales. These studies indicate that supercluster masses are $M \sim 10^{16} - 10^{17} h^{-1} M_\odot$, their mass-to-light ratios are $ML_L \sim 200 - 600 h M_\odot/L_\odot$, and the density parameter measured on supercluster scales is $\Omega_m \sim 0.1-0.4$. This work can be extended to higher redshift, but until recently no such systems were known.

Such a high-redshift system has been discovered in a study of nine candidate clusters at $z \geq 0.6$ by Oke, Postman, & Lubin (1998). Two clusters, Cl 1604+4304 at $z = 0.897$ and Cl 1604+4321 at $z = 0.924$, were observed as part of this survey. They are separated by 4300 km s$^{-1}$ in radial velocity and by 17' on the sky. This implies a projected separation of only 5 $h^{-1}$ Mpc. We have already analyzed the spectra of a nearly complete sample of galaxies with $R \leq 23.5$ in a $2.2' \times 7.2'$ field centered on each cluster. The top panel in Figure 1 shows the combined velocity histogram of the 63 confirmed members in the two clusters (21 in Cl 1604+4304 and 42 in Cl 1604+4321). Cl 1604+4304 and Cl 1604+4321 have velocity dispersions of $1226^{\pm 155}_{\pm 145}$ and $935^{\pm 126}_{\pm 141}$ km s$^{-1}$ and masses of $3.1 \times 10^{15}$ and $1.6 \times 10^{15} h^{-1} M_\odot$, respectively (Postman, Lubin, & Oke 1998; M. Postman, L. M. Lubin, & J. B. Oke 2000, in preparation). All of the observational data suggest that Cl 1604+4304 and Cl 1604+4321 are typical of Abell richness class 1–3 clusters (Lubin et al. 1998; L. M. Lubin, M. Postman, J. B. Oke, R. Brunner, J. E. Gunn, & D. P. Schneider 2000, in preparation).

More interestingly, these two clusters may comprise an even larger system of galaxies. The bottom panel of Figure 1 shows the north-south position of the confirmed cluster members versus redshift. There is a clear trend in which the redshift on the north side of Cl 1604+4304 approaches the redshift of Cl 1604+4321. The apparent alignment in redshift space and the physical proximity of the clusters indicate that this may be a high-redshift supercluster. The estimated mass of this structure is $\geq 5 \times 10^{15} M_\odot$, and the spatial overdensity is $\sim 40$. These numbers imply that the system is bound and has likely reached turnaround for reasonable cosmologies (Small et al. 1998).

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In this Letter, we provide new evidence from multiband optical imaging which strongly favors the supercluster hypothesis. Unless otherwise noted, we use $H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}$ and $q_0 = 0.1$.

2. THE OBSERVATIONS

All of the optical imaging was completed with the Carnegie Observatories Spectroscopic Multislit and Imaging Camera (COSMIC; Kells et al. 1998) at the 200 inch (5 m) Hale telescope at Palomar Observatories. We have used the instrument in direct imaging mode, which provides a pixel scale of $0.7$ pixel$^{-1}$ and a field of view of $9.7 \times 9.7$. Two individual pointings were made in order to cover the region between Cl 1604+4304 and Cl 1604+4321. Each pointing covered a portion of one cluster. The overlap between the pointings was $35^\circ$. The photometric survey was conducted in three broadband filters $B$, $R$, and Gunn $i$. The total integration times on each pointing were 2 hr in $B$ and 1 hr in $R$ and $i$. The data were calibrated to the standard Cousins-Bessell-Landolt system through exposures of Landolt standard-star fields (Landolt 1992). Variations about the nightly photometric transformations are $0.03$ mag or less.

Source detection and photometry were performed using SExtractor version 2.1.0 (Bertin & Arnouts 1996). SExtractor was chosen for its ability to detect objects in one image and analyze the corresponding pixels in a separate image. When applied uniformly to multiband data, this technique generates a matched aperture data set. Our detection image was constructed from the $BRi$ images using a $x^2$ process (Szalay, Connolly, & Szokoly 1999). Briefly, this process involves convolving each input image with a Gaussian kernel matched to the seeing. The convolved images were squared and normalized so that the background had zero mean and unit variance. The three processed images (corresponding to the original $BRi$ images) were co-added, forming a $x^2$ detection image. A histogram of the pixel distribution in the $x^2$ image was created and compared to a $x^2$ function with 3 degrees of freedom (which corresponds to the sky pixel distribution). The difference between the actual pixel distribution and the $x^2$ function provides an optimal estimate for the actual object pixel distribution. The Bayesian detection threshold was set equivalent to the intersection of the “sky” and “object” distributions (i.e., where the object pixel flux becomes dominant). To convert this empirical threshold for use with SExtractor, we scale the threshold (which is a flux per pixel value) into a surface brightness threshold (which is in magnitudes per square arcsecond) by defining a detection zero point using the desired detection threshold and the pixel scale. Approximately 4800 galaxies were detected in the combined fields.

For the color analysis, we use the total magnitudes as calculated by SExtractor. These magnitudes are variable-diameter aperture magnitudes measured in an elliptical aperture of major-axis radius $2r_e$, where $r_e$ is the Kron radius (see Bertin & Arnouts 1996). Because we have used a matched aperture analysis, the total magnitudes in the three bands are measured within the same physical radius for a given galaxy. The limiting magnitudes of our survey are $B = 25.8$, $R = 24.6$, and $i = 23.5$ for a $5 \sigma$ detection.

3. THE RESULTS

3.1. The Galaxy Colors

With the multiband imaging, we have generated photometry on a complete sample of galaxies in a contiguous area of $10.3 \times 18.3$ or $3.1 \, h^{-1}$ Mpc $\times 5.5 \, h^{-1}$ Mpc at the supercluster redshift of $z \approx 0.91$. We show the resulting $(B-R)$ and $(R-i)$ color-magnitude diagrams (CMDs) in Figure 2. In both diagrams, we see a well-defined color-magnitude sequence that is redder than the vast majority of galaxies that comprise the field population. This red sequence of galaxies is considerably tighter in the $(R-i)$ CMD where it is observed at $(R-i) \approx 1.4$. In the $(B-R)$ CMD, the larger color scatter in this red sequence is a result of the fact that many of these galaxies lie at or beyond the completeness limits of this survey. Figure 3 shows a histogram of $(R-i)$ colors. In this figure, the red sequence of galaxies can be clearly distinguished from the field population where it is a red peak superposed on the large distribution of bluer field galaxies. Fitting two Gaussian functions to this distribution, we find that the standard deviation of the red peak is $0.15$ mag.

A tight, red color-magnitude relation is typical of the central regions of massive clusters both in the local universe and at intermediate and high redshift (e.g., Dressler 1980; Butcher & Oemler 1984; Stanford, Eisenhardt, & Dickinson 1995, 1998). The galaxies contained in this “red locus” are the elliptical and S0 galaxies, which comprise the majority of the cluster population. The early-type galaxies are characterized by their red color and their small color scatter, typically less than $0.2$ mag. Studies of clusters from $z \sim 1$ to the present epoch imply that the observed color trend in this red envelope of galaxies is consistent with passive evolution of an old stellar population formed in a relatively synchronized burst of star formation at $z \geq 2$ (e.g., Ellis et al. 1997; Stanford et al. 1995, 1998; Bower, Kodama, & Terlevich 1998).

![Image](image_url)
and are spectroscopically confirmed members of either absorption spectrum which is typical of an early-type galaxy galaxies. Within this field, there are 21 galaxies that have an supercluster field corresponds to a population of old, early-type galaxies. Based on a control field, we find the number density of red field galaxies, as defined by our color selection, is $0.7 \pm 0.1$ galaxies arcmin$^{-2}$. Within a radius of $0.2$ h$^{-1}$ Mpc, the new concentration is overdense in red galaxies by a factor of $\sim 20$ compared to this control field. This overdensity is equivalent to that observed in the two original clusters; Cl 1604+4304 and Cl 1604+4321 are overdense by a factor of 20 and 13, respectively. At half an Abell radius, the overdensity of red galaxies in the three clusters is a factor of $\sim 6$. These data clearly indicate that we have detected a third, massive cluster associated with this large-scale structure. We also observe at least one other, although more marginal, overdensity in this field, suggesting that this supercluster may contain additional clusters beyond the three discussed here. The spatial distribution of red galaxies provides further confirmation of a large-scale structure spanning at least $5.5$ h$^{-1}$ Mpc.

4. CONCLUSIONS

We have confirmed the existence of a supercluster at $z = 0.91$ with deep, multiband imaging taken at the Palomar 200 inch telescope. In the resulting color-magnitude diagrams, we find a relatively tight, color-magnitude sequence of red galaxies. The characteristic color of this sequence corresponds directly to the colors of the confirmed early-type galaxies in the two member clusters, Cl 1604+4304 and Cl 1604+4321. Therefore, we have identified a large population of early-type galaxies within the redshift range of $z \sim 0.89-0.93$. These red galaxies cover the entire $5.5$ h$^{-1}$ Mpc region which separates the two member clusters. They delineate the full extent of the large-scale structure while clearly encompassing the two clusters. Based on the distribution of red galaxies over this field, we have identified another rich cluster associated with this system. It lies directly between Cl 1604+4304 and Cl 1604+4321, and its overdensity of red galaxies is approx-
Fig. 4.—Same \((R-i)\) color-magnitude diagram as shown in Fig. 2. The circles indicate all of the spectroscopically confirmed, early-type galaxies in the two clusters which lie within the field of view of our supercluster observations. The color of these galaxies are consistent with the color of the red locus, indicating that there exists a large population of red, early-type galaxies at the supercluster redshift.

Fig. 5.—Composite \(i\)-band image of the supercluster field (north is up, and east is to the right). The cluster centers of Cl 1604+4304 and Cl 1604+4321 are at the bottom and top, respectively, of this image. Large circles indicate those confirmed cluster members with spectra that are consistent with early-type galaxies. The likely supercluster members based on our color selection (see § 3.2) are indicated by small circles. Their spatial distribution clearly shows the presence of a large-scale system of galaxies encompassing the two rich clusters, as well as a new cluster concentration in the center of the field at the coordinates (0, +100).

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