

SUPERCLUSTERING AT REDSHIFT $z = 0.54$

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Received 1996 May 21; accepted 1996 October 3

ABSTRACT

We present strong evidence for the existence of a supercluster at a redshift of $z = 0.54$ in the direction of Selected Area 68 (SA68). From the distribution of galaxies with spectroscopic redshifts, we find that there is a large over density of galaxies (a factor of 4 over the number expected in an unclustered universe) within the redshift range $0.530 < z < 0.555$. By considering the spatial distribution of galaxies within this redshift range (using spectroscopic and photometric redshifts), we show that the galaxies in SA68 form a linear structure passing from the Southwest of the survey field through to the Northeast (with a position angle of approximately 35° east of north). This position angle is coincident with the positions of the X-ray clusters CL 0016+16, RX J0018.3+1618 and a new X-ray cluster, RX J0018.8+1602, centered near the radio source 54W084. All three of these sources are at a redshift of $z \sim 0.54$ and have position angles, derived from their X-ray photon distributions, consistent with that measured for the supercluster. Assuming a redshift of 0.54 for the distribution of galaxies and a FWHM dispersion in redshift of 0.020, this represents a coherent structure with a radial extent of $31 h^{-1}$ Mpc, transverse dimension of $12 h^{-1}$ Mpc, and a thickness of $\sim 4 h^{-1}$ Mpc. The detection of this possible supercluster demonstrates the power of using X-ray observations, combined with multicolor observations, to map the large-scale distribution of galaxies at intermediate redshifts.

Subject headings: galaxies: distances and redshifts — large-scale structure of universe — techniques: photometric

1. INTRODUCTION

By mapping the spatial distribution of galaxies, we can determine the intrinsic scales on which galaxies cluster, from poor groups through rich clusters to superclusters. Quantifying the abundance of these clusterings and their evolution with time should provide important constraints on the multifarious cosmological models (Liddle et al. 1996). In the local universe, extensive redshift surveys have been undertaken to map the distribution of galaxies to $B \sim 15.5$ that reach to a redshift of $z \sim 0.05$. Such surveys have uncovered coherent structures that extend over many tens of megaparsecs, such as the Perseus-Pisces filament (Giovanelli & Haynes 1993) or the sheetlike Great Wall (Geller & Huchra 1989). These structures appear to be common in other and even deeper ($B < 20$) surveys that extend beyond redshifts $z \sim 0.1$ (Landy et al. 1996; Willmer et al. 1996).

At even fainter magnitudes, redshift surveys have been undertaken to a limit of $B \simeq 24$ (Cowie et al. 1996; Glazebrook et al. 1995; Lilly et al. 1995). Because of the long exposures required to reach such faint limits, these surveys have been restricted to a few pointings that cover tiny regions of sky, typically $\leq 10'$ in diameter. Consequently, while large

over densities of galaxies are visible in the deep redshift surveys (Broadhurst et al. 1990; Le Fevre et al. 1994; Cohen et al. 1996), the angular distribution of these structures and, therefore, their transverse spatial extent, have yet to be well studied.

In this Letter, we consider the distribution of galaxies in the direction of Selected Area 68 (SA68) (Kron 1980). We identify this region as a potential site of an intermediate redshift supercluster because of the coherent distribution of very red galaxies, estimated to be at $z \sim 0.5$, found by Koo (1985), as well as the presence of two X-ray clusters at the same redshift (Hughes, Birkinshaw, & Huchra 1995). The over density of galaxies is quantified using a small sample of spectroscopic redshifts in § 2 and then improved using a larger sample of photometric redshifts in § 3. The coincidence of this structure with the position and orientation of three X-ray clusters is discussed in § 4. Finally, we show that the galaxies and clusters are consistent with a Great Wall-like supercluster, at $z = 0.54$, that is almost edge-on with respect to the line of sight. For this Letter, we assume an $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega = 1$ cosmology; at redshift $z \sim 0.54$, the lookback time is nearly one-half the age of the universe and 1° spans $13.5 h^{-1}$ Mpc.

2. THE DISTRIBUTION OF SPECTROSCOPIC REDSHIFTS IN SA68

To determine whether there exist intermediate redshift counterparts to the locally detected superclusters, we consider the spectroscopic and photometric galaxy catalog of Koo and

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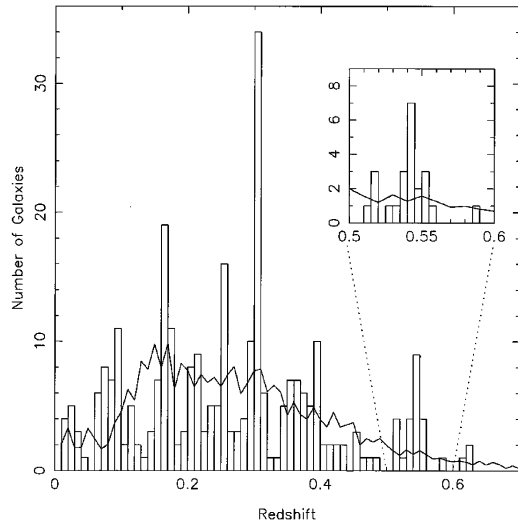


FIG. 1.—Redshift distribution of galaxies in the SA68 for those galaxies in the Koo and Kron spectroscopic sample with $B_J < 23$. Solid line represents the expected distribution of redshifts for this sample assuming no clustering. Expectation value for the number of galaxies between $0.530 < z < 0.555$ is 3.54 ± 3.7 . Observed number of galaxies within this redshift range is 14, a factor of 4 larger.

Kron (Kron 1980; Koo 1986; Munn et al. 1996) in the direction of SA68 ($00^{\text{h}}14^{\text{m}} + 15^{\circ}30'$). These data comprise a total of 1750 galaxies, $B_J < 23.0$, with multicolor photometry in the U , B_J , R_F , and I_N passbands. Of these galaxies, 286 have spectroscopically measured redshifts.

In Figure 1, we show the redshift distribution of the spectroscopic sample of galaxies. The most striking features of this redshift distribution are the regular set of peaks. Such overdensities have been interpreted as the intersection of the narrow-pencil beam surveys with large-scale coherent structures in the galaxy distribution (Broadhurst et al. 1990; Szalay et al. 1991; Le Fevre et al. 1994; Cohen et al. 1996). For later discussions, we consider only the spatial and redshift distribution of those galaxies lying between $0.530 < z < 0.555$.

To test whether this feature, at $z = 0.55$, represents a significant perturbation from a number of galaxies expected from an unclustered distribution of galaxies, we calculate the

selection function for the spectroscopic sample of galaxies. As the spectroscopic sample is not formally magnitude limited, we must calculate the expected redshift distribution using the models of Gronwall & Koo (1995). These models were derived to match the observed redshift distribution of SA68 to a limit of $B < 24$. Taking the observed B_J magnitude distribution of the spectroscopic galaxy sample, we construct the expected dn/dz (Fig. 1, solid line). The expectation value for the number of galaxies with $0.530 < z < 0.555$ is 3.54.

To account for a clustered distribution, we calculate the variance of the expectation value by integrating the local spatial correlation function, $\xi(r)$, over this redshift volume. Assuming a projected area of 706 arcmin^2 for SA68, we estimate the variance in the expectation value to be 3.7. It should be noted that this is a conservative value (an upper limit), as we assume no evolution of the spatial correlation function, with redshift. Therefore, we would expect to detect

$$\langle N \rangle = 3.54 \pm 3.7 \quad (1)$$

galaxies with spectroscopic redshifts within the redshift range $0.530 < z < 0.555$. The observed number of galaxies in this redshift peak is 14, representing a factor of 4 over the unclustered expectation value. Fitting a Gaussian to the spectroscopic redshifts, we determine the dispersion of the redshift distribution to be 0.0083. If the dispersion in redshift were the result of the internal velocity of a cluster, this would equate to a velocity dispersion of $\sim 2500 \text{ km s}^{-1}$ —far in excess of local observations (Zabludoff et al. 1993; Collins et al. 1995). The radial distance corresponding to the FWHM of the redshift distribution is then $31 h^{-1} \text{ Mpc}$.

The projected angular distribution of the spectroscopic sample of galaxies within this redshift range is shown in Figure 2a; they form a linear structure passing from the southwest of the SA68 field through to the northeast. The angular distribution extends to the limits of the survey field. From the second moments of the galaxy distribution, we find that this structure can be represented by an ellipse with a position angle oriented 29° east of north and centered on $00^{\text{h}}14^{\text{m}}40 + 15^{\circ}33'58$ (B1950).

While the number of galaxies with observed spectroscopic redshifts is small, we can estimate whether they are consistent

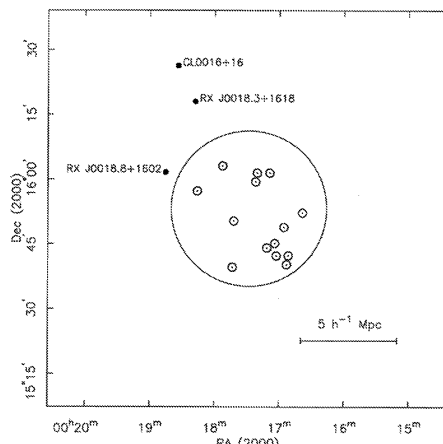


FIG. 2a

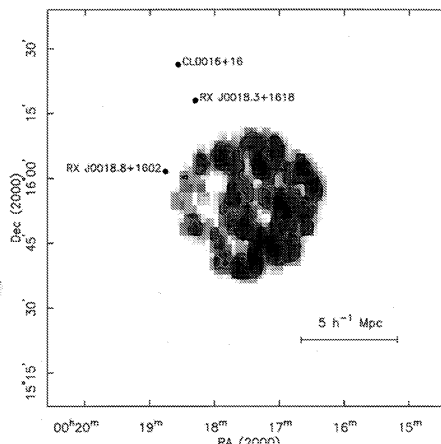


FIG. 2b

FIG. 2.—(a) Spatial distribution of those galaxies with spectroscopic redshifts between $0.530 < z < 0.555$, in SA68; solid line shows the extent of the SA68 survey field. (b) Distribution of galaxies with photometric redshifts in the range $0.49 < z < 0.59$. Spectroscopic and photometric samples of galaxies form a linear distribution passing from the southwest of SA68 through to the northeast with position angles of $27^{\circ}2$ and $40^{\circ}3$ (east of north), respectively. Positions of the previously identified X-ray clusters CL 0016+16 and RX J0018.3+1618 are shown in both figures, together with the new cluster RX J0018.8+1602. Position angle of the photon distribution for these X-ray clusters are 39° , 29° , and 30° , respectively.

with a uniform distribution of galaxies across the SA68 survey field. We do this by applying a two-dimensional Kolmogorov-Smirnov test (Peacock 1983; Fasano & Franceschini 1987). For a sample size of 14, the probability that the galaxies with spectroscopic redshifts are consistent with a uniform distribution is only 15%.

3. THE DISTRIBUTION OF GALAXIES ACROSS SA68

Since the spectroscopic sample is so small, we adopt another technique to increase the redshift sample—namely, we estimate the redshift of a galaxy from its broadband magnitudes. The effectiveness of this technique for deriving galaxy redshifts to the limit of our photometric data has been demonstrated by Connolly et al. (1995). By fitting the U , B_J , R_F , and I_N magnitudes with a second order relation to the spectroscopic redshifts, redshifts can be estimated to an accuracy of $\sigma_z \leq 0.05$.

We calculate the photometric redshift relation for the galaxies in the photometric sample using the prescription given by Connolly et al. (1995). Comparing those galaxies with spectroscopic redshifts with their estimated photometric redshifts, we derive a dispersion in the relation of $\sigma_z = 0.049$. We select a $1 \sigma_z$ range around the peak in the spectroscopic redshift distribution. In Figure 2b, we show the distribution of the 146 galaxies within the redshift range $0.49 < z < 0.59$. These data have been smoothed with a kernel of diameter $2.5 (0.55 h^{-1} \text{ Mpc at } z = 0.54)$; equivalent to the core diameter of a King cluster profile).

The galaxy distribution is again seen to form a coherent linear structure passing from the southwest to the northeast of SA68. The second moments of the distribution of galaxies gives a position angle of $40^\circ.3$ centered on $00^{\text{h}}14^{\text{m}}41^{\text{s}} + 15^\circ37'16''$. Clearly this represents an underestimate of the over density of galaxies within the supercluster (caused by the contamination from foreground and background galaxies). The two-dimensional Kolmogorov-Smirnov test yields only a 2% probability that the photometric-redshift sample is drawn from a uniform distribution. A comparison of the angular distributions of those galaxies with spectroscopic redshifts with those from the photometric redshift sample shows that the probability that they are drawn from *different* intrinsic populations is only 45% (i.e., less than a 1σ deviation). The angular distribution of the spectroscopic and photometric redshift samples, therefore, display the same large-scale clustering properties. They show a linear structure of at least $0^\circ.5$ in extent (equivalent to $6.5 h^{-1} \text{ Mpc at } z = 0.54$).

4. THE DISTRIBUTION OF X-RAY CLUSTERS AROUND SA68

Just beyond one-half a degree from the center of SA68 lies the X-ray luminous cluster CL 0016+16 at a redshift of $z = 0.5455$ (Koo 1981; see Fig. 2), which was the target of one of the deepest *ROSAT* PSPC pointed observations (Hughes et al. 1995). The efficacy of using deep *ROSAT* pointings to serendipitously identify X-ray clusters has been demonstrated by Hughes et al. (1995). As part of the serendipitous high-redshift archival *ROSAT* cluster (SHARC) survey (Nichol et al. 1996; Burke et al. 1996) we have, therefore, reanalyzed this deep pointing using a detection algorithm based on the wavelet transform.

In the SHARC survey, an X-ray source is flagged as a candidate distant cluster if the observed X-ray emission is significantly extended ($>3 \sigma$) compared to the radial-dependent PSPC point-spread function. Furthermore, the

source is required to have no optical counterpart on the Palomar Digital Sky Survey Plates. In addition to CL 0016+16 ($00^{\text{h}}18^{\text{m}}33.2 + 16^\circ26'18''$) and RX J0018.3+1618 ($00^{\text{h}}18^{\text{m}}16.8 + 16^\circ17'45''$; Hughes et al. 1995)—both of which satisfy these criteria—we have discovered a further such X-ray source: RX J0018.8+1602 ($00^{\text{h}}18^{\text{m}}45.5 + 16^\circ01'41''$). This source lies $25'$ from the center of the PSPC pointing and is within $1'$ of the radio galaxy 54W084 (Neff, Roberts, & Hutchings 1995).

The PSPC X-ray contours of RX J0018.8+1602 are overlaid on a B_J photographic plate (# 1286) observed by R. Kron with the KPNO 4 m telescope. The peak in the X-ray photon distribution is coincident with an over density of faint, $B_J < 23$, galaxies in the optical data. The color of the central optical galaxy is consistent with that of an elliptical galaxy at a redshift of 0.5. Within the X-ray contours lies the radio galaxy 54W084 at a redshift of $z = 0.544$ (R. Windhorst 1996, private communication), indicated by an arrow in Figure 3 (Pl. L10). If we assume a redshift of 0.544, RX J0018.8+1602 has a luminosity in the 0.500–2.0 keV energy range of $4.25 \times 10^{43} \text{ ergs s}^{-1}$. This compares with an X-ray luminosity of $2.5 \times 10^{43} \text{ ergs s}^{-1}$ measured by Hughes et al. (1995) for the cluster RX J0018.3+1618. The *ROSAT* PSPC spectrum of RX J0018.3+1618 is consistent with a thermal plasma. Assuming a Raymond-Smith model with heavy metal abundance of 0.3 solar and the Galactic N_{H} value at the cluster position, the temperature of the plasma is $kT = 1.6_{-0.4}^{+0.7} \text{ keV}$. This source has also been detected by *ASCA*, and a preliminary analysis shows a spectrum consistent with that derived from the *ROSAT* data. This is indicative of an intermediate redshift X-ray cool cluster of galaxies.

The redshifts of CL 0016+16 and RX J0018.3+1618 are 0.5455 and 0.5506, respectively. All three X-ray clusters are, therefore, consistent with the redshift distribution observed in SA68. CL 0016+16 and RX J0018.3+1618 have been suggested to be a bound system and possibly linked with the over density of red galaxies in SA68 found by Koo (Hughes et al. 1995). Below we show in fact that the space distribution of the three clusters and those galaxies in SA68 with spectroscopic redshifts are consistent with a supercluster viewed edge-on with respect to the line of sight.

The orientation of clusters of galaxies has been suggested as a means of identifying coherent large-scale structures (Binggelli 1982). Results derived from the optical distribution of galaxies remain inconclusive, with West (1989) finding evidence for a correlation between cluster position angles on scales of up to $45 h^{-1} \text{ Mpc}$ while Struble & Peebles (1985), using similar data, find no significant signal. Much of these uncertainties arise from the difficulty in separating cluster galaxies from contamination caused by background sources (especially in the outer regions of a cluster). Determining the orientation of a cluster from the distribution of its X-ray-emitting gas provides a more objective measure (Ulmer, McMillan, & Kowalski 1989), since the gas better traces the cluster potential.

The position angles of the three X-ray sources were determined from the second moments of the outer isophotes of the X-ray photon distribution. The derived values for CL 0016+16, RX J0018.3+1618, and RX J0018.8+1602 were 39° , 29° , and 30° east of north, respectively. All three sources are, therefore, aligned with the galaxy distribution of SA68. As has been noted by Bond, Kofman, & Pogosyan (1996), the signature of superclustering will be strongest when the individual clusters are aligned.

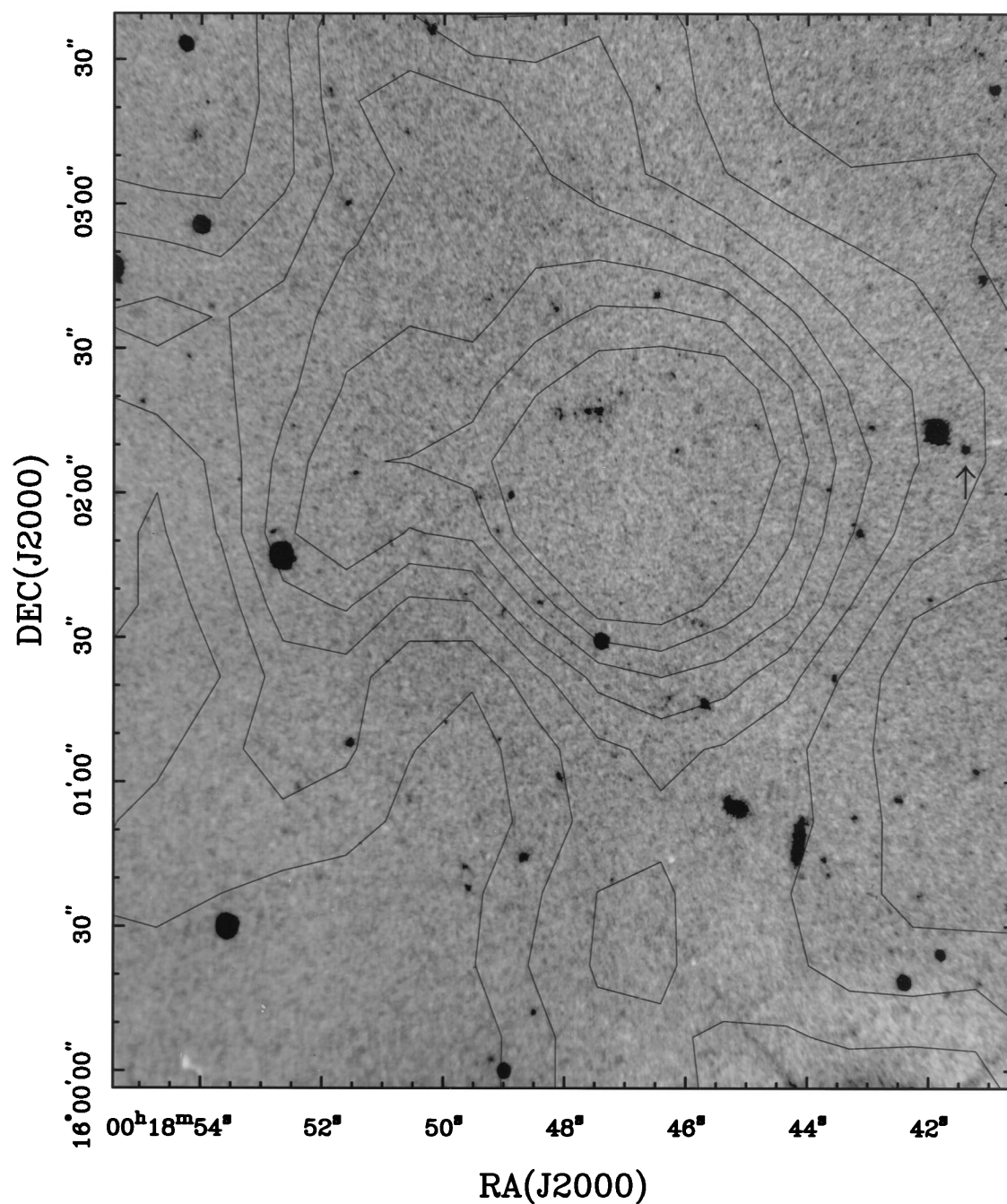


FIG. 3.—*ROSAT* PSPC X-ray contours for RX J0018.8+1602 are overlaid on a 4 m B_J photographic plate of SA68. A local bore sight correction has been applied to the X-ray data based on the position of three stars. Wavelet analysis of the field shows the X-ray distribution to be more extended than the radially dependent PSF at greater than the 3σ level. Peak in the X-ray photon distribution is coincident with an over density of faint galaxies ($B_J \sim 23$) with the central galaxy appearing elliptical. Arrow indicates the position of the radio galaxy 54W084 at a redshift of $z = 0.544$. Position of this radio source is within $1'$ of the center of the X-ray cluster and is contained within the outer isophotes. If we assume the radio galaxy is a member of the cluster the X-ray luminosity corresponds to 4.25×10^{43} ergs s^{-1} . This is approximately 13% of the luminosity of CL 0016+16.

CONNOLLY et al. (see 473, L69)

5. DISCUSSION: A GREAT WALL AT $z = 0.54$

Combining the optical and X-ray data, we have strong evidence for a coherent structure, at a redshift of $z = 0.54$, extending about 1° across the sky from the survey field SA68 through the cluster CL 0016+16. At this redshift, this translates to a tangential size of $12 h^{-1}$ Mpc, a radial depth of $31 h^{-1}$ Mpc, and a “thickness” of $4 h^{-1}$ Mpc. The positions of the galaxies and clusters within this volume are not randomly distributed but appear to lie in a planar distribution (i.e., their redshifts and angular distribution are strongly correlated).

To determine the true geometry of the galaxy distribution—i.e., whether it is better represented by an extended filament or a sheet of galaxies—we fitted a two-dimensional surface to the spectroscopic redshifts. The redshifts of the galaxies in SA68 and the three clusters are transformed to comoving distance and treated as independent points; we do not weight the cluster redshifts by the number of galaxies that have spectroscopic observations. The best fit to these data is a plane with an orientation $40^\circ \pm 10^\circ$ east of north and an angle $12^\circ \pm 2^\circ$ from the line of sight. Given that the redshift dispersion of the galaxies exceeds that expected for a cluster, we suggest that the structure we are observing is a sheet of galaxies oriented almost orthogonally to our line of sight.

As noted in § 3, the dispersion in the photometric-redshift relation results in a dilution of the supercluster as a result of contamination by foreground and background galaxies. We cannot, therefore, map the full three-dimensional distribution of the supercluster. We can, however, determine whether the galaxy distribution is comparable to that observed in the local universe (i.e., if a structure similar to the Great Wall were to exist at $z = 0.54$, what would its signature be). If we correct for the orientation of the galaxy distribution and determine the width orthogonal to the plane of the supercluster, we derive a dispersion of 433^{+85}_{-61} km s $^{-1}$. This is consistent with the mean value of 300 km s $^{-1}$ determined by Ramella, Geller, & Huchra (1992) for the Great Wall. Furthermore, if we assume that 30% of the galaxies within the redshift range $0.5 < z < 0.6$ are indeed members of the supercluster, as suggested by the results of de Lapparent, Geller, & Huchra (1991) from their analysis of the CfA redshift survey, we can estimate the surface density of the galaxies in the supercluster. Allowing for an inclination angle of 10° to the line of sight and a luminosity

distance of $1837 h^{-1}$ Mpc, we estimate the surface density of galaxies to be approximately $0.6 h^2$ Mpc $^{-2}$. This is only slightly higher than the values of 0.25 – $0.4 h^2$ Mpc $^{-2}$ determined for the individual slices in the CfA redshift survey (de Lapparent et al. 1991). It would appear, therefore, that we have identified an intermediate redshift counterpart to the sheetlike supercluster structures observed in redshift surveys of the local universe.

Clearly the available data, while providing tantalizing evidence for large-scale clustering at intermediate redshifts, do not map the full extent of this supercluster. The over density in the spectroscopic redshifts encompasses the full extent of the survey field SA68. To determine the tangential distribution of galaxies at a redshift of 0.54 , and, therefore, the true size of this supercluster, we are engaged in follow-up photometric and spectroscopic observations of this region.

We would like to thank the referee for helpful comments that improved the clarity of this paper. We thank Richard Kron for providing the photographic plate for SA68 and for help in the identification of the new X-ray cluster. We are grateful to Kron, Jeffrey Munn, Steven Majewski, Matthew Bershad, and John Smetanka for prepublication access to the KPGRS catalogs, and to Rogier Windhorst for the redshift of 54W084. We acknowledge Piero Rosati and Jack Hughes for useful discussions on the X-ray distributions in CL 0016+16, and Gerry Luppino, Gordon Richards, Dan Vanden Berk, and Michael Strauss for attempting optical follow-ups of the SA68 region. A. J. C. and A. S. acknowledge partial support from NSF grant AST-9020380, an NSF-Hungary Exchange Grant, the US-Hungarian Fund, and the Seaver Foundation. D. C. K. acknowledges support from the NSF grant AST 88-58203. A. K. R. acknowledges support from NASA grant NAGS-2432. B. H. was supported in part by the National Science Foundation under a cooperative agreement with the Center for Astrophysical Research in Antarctica (CARA), grant NSF OPP 89-20223. CARA is a National Science Foundation Science and Technology Center. T. M. appreciates the hospitality of NASA Goddard Space Flight Center and the Johns Hopkins University during his visit. His visit was partially supported by USRA.

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