CLUSTERING OF SUBMILLIMETER-SELECTED GALAXIES

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ABSTRACT

Using accurate positions from very deep radio observations to guide multiobject Keck spectroscopy, we have determined a substantially complete redshift distribution for very luminous distant submillimeter-selected galaxies (SMGs). A sample of 73 redshifts for SMGs in seven fields contains a surprisingly large number of "associations": systems of SMGs with Mpc-scale separations and redshifts within 1200 km s^{-1}. This sample provides tentative evidence of strong clustering of SMGs at $z \simeq 2$–3 with a correlation length of ~(6.9 ± 2.1) h^{-1} Mpc, using a simple pair-counting approach that is appropriate to the small, sparse SMG samples. This is somewhat greater than the well-determined correlation lengths for both $z \simeq 3$ optical-UV color-selected Lyman break galaxies (LBGs) and $z \simeq 2$ QSOs. This could indicate that SMGs trace the densest large-scale structures in the high-redshift universe and that they may either be evolutionarily distinct from LBGs and QSOs or subject to a more complex astrophysical bias.

Subject headings: cosmology: observations — galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: starburst — large-scale structure of universe

1. INTRODUCTION

Since 1997 several hundred galaxies have been discovered using imaging arrays at millimeter and submillimeter wavelengths (Blain et al. 2002; Smail et al. 2002; Scott et al. 2002; Borys et al. 2003; Webb et al. 2003; Greve et al. 2004). The difficulties of identifying these galaxies at other wavelengths, and moreover determining their redshifts, are significant, owing both to the coarse positional accuracy ($\simeq 8''$) of the discovery images and to the faint optical magnitudes of their proposed counterparts. By exploiting the high-redshift analog of the far-infrared–radio correlation between hot dust and radio synchrotron emission, which are powered by young, hot stars and their associated supernovae, respectively, sub-arcsecond radio positions can be found for a substantial fraction of submillimeter-selected galaxies (SMGs). This enables efficient multiobject optical spectroscopy to search for redshifts, given that the surface density of radio-detected SMGs on the sky is ~300 deg^{-2} (Chapman et al. 2003a), and thus is well matched to the field of view and multiplex gain of current spectrographs. This technique was first tried using the Keck LRIS-B spectrograph, which counterintuitively detected identifiable rest-frame ultraviolet spectral lines and features in many of these galaxies. The redshift distribution of a large sample of 73 of these galaxies in the seven independent fields listed in Table 1 is presented by Chapman et al. (2004a). The spectroscopic completeness for redshift determinations is ~50% for SMGs selected purely on the grounds of submillimeter flux density greater than 5 mJy at a wavelength of 850 μm and ~70% for SMGs with the same submillimeter flux density and radio detections at 1.4 GHz brighter than 30 μJy.

The remaining ~30% of radio-detected SMGs without redshifts are likely split between those at higher redshifts and any with cooler dust temperatures and lower luminosities, neither of which yield radio detections; and galaxies in the redshift range $1.2 < z < 1.8$, whose optical continua are generally too faint for the detection of rest-frame UV absorption lines, and for which any rest-frame UV emission lines are not redshifted into the wide spectral range of LRIS (Chapman et al. 2004a).

This reasonably complete redshift distribution confirms absolutely that the SMGs are an important high-redshift galaxy population and that galaxies within a factor of 5 in submillimeter flux density of the 5 mJy 850 μm detection limit of this sample dominate the luminosity density from galaxies at redshifts $z \simeq 2$. The redshift distribution can be represented adequately by a Gaussian with $\bar{z} = 2.4$ and $\sigma = 0.65$, with almost all SMGs found over the redshift range $1.5 < z < 3$. SMGs are found in relatively small fields on the sky, less than 10' across, but are spread very widely in redshift from at least 0.8 to 3.4. This means that the SMG survey volumes have a uniquely long thin pencil geometry, which extends in depth by 2–3 Gpc but across the sky only as far as ~5 Mpc.

The spatial distribution of SMGs is important, as the detection of any clustering signal can provide information about the distribution of galaxies as a function of dark matter density. In principle, in a dark matter–dominated universe the strength of clustering should correlate with the mass of halos (Bardeen et al. 1986), and thus its measurement provides an insight into the masses of the dark halos that host luminous galaxies (e.g., Overzier et al. 2003 and references therein).

TABLE 1
Correlation Lengths r_0 for Radio-pinpointed SMGs

Field	R.A.	Decl.	Size (arcsec)	N_{gal}	N_{pair}	z_{as}	N'_{pair}	r_0 (h^{-1} Mpc)
All fields................	. . .	. . .	. . .	. . .	. . .	. . .	. . .	6.9 ± 2.1
All but SA22.........	. . .	. . .	. . .	. . .	. . .	. . .	. . .	5.5 ± 1.8
03 hr......................	03 02	00 06	240×280	5	0	. . .	0.20	. . .
Lockman................	10 52	57 20	360×450	12	2	2.1, 2.7	1.2	4.3 ± 3
HDF......................	12 36	66 10	720×900	21	9	1.9, 2.0[a]	3.65	9.5 ± 3.3
SA13	13 12	42 40	470×540	11	2	1.5, 2.6	0.99	6.1 ± 4
14 hr......................	14 18	52 29	320×210	7	1	2.1	0.40	5.3 ± 5.3
N2..........................	16 37	40 55	480×750	8	1	2.4	0.53	6.4 ± 6.4
SA22	22 18	00 12	820×650	9	3	3.1[b]	1.0	15 ± 9

Notes.—The total number of spectroscopic redshifts N_{gal} and the numbers of pairs of galaxies N_{pair} within 1200 km s^{-1} in radial velocity at redshift z_{as} in each field are listed, along with the pair abundance predicted in the absence of clustering N'_{pair}. Units of right ascension are hours and minutes, and units of declination are degrees and arcminutes.

[a] This is a five-galaxy association.

[b] These three SMGs lie in the richest spectroscopically confirmed high-redshift large-scale structure (Steidel et al. 2000), which contains 29 of the 76 LBGs in this field. If the width of the LBG redshift distribution matched that of the SMG surveys, then only 15% of the SMGs would lie in this structure, not the 3/9 found in the SMG survey. The comoving density of LBGs in the best-sampled Westphal 14 hr field is 4.6×10^{-4} Mpc^{-3}, while the comoving density of SMGs in all the survey fields is $(2.7 \pm 0.4) \times 10^{-5}$ Mpc^{-3}, and in the HDF it is 2.5×10^{-5} Mpc^{-3}.

The clustering strength of many types of high- and low-redshift galaxies has been probed by a wide variety of methods. At redshifts less than those of SMGs, $z < 1.3$, the large-scale structure of galaxies is being mapped in great detail by the DEEP2 survey (Coil et al. 2004). At higher mean redshifts, the clustering of many hundreds of rest-frame UV/optically selected, spectroscopically confirmed Lyman break galaxies (LBGs) can be measured (Adelberger et al. 1998). Recent values of correlation lengths[1] are $r_0 = 4$ h^{-1} Mpc (Porciani & Giavalisco 2002) and $r_0 = 2.7$ h^{-1} Mpc (Ouchi et al. 2001). The published samples of LBGs lie at higher redshifts than most SMGs, which could on its own explain the lack of observed correlation between the positions of LBGs and SMGs (Peacock et al. 2000; Chapman et al. 2000; Webb et al. 2003), even if they are drawn from a common underlying population of galaxies described by the same form of evolution. Lower redshift counterparts to LBGs can be isolated by varying the color selection conditions (see Steidel et al. 2004). Spectroscopically confirmed samples of these galaxies can be compiled in parallel to surveys for SMG redshifts using the same multiobject slit masks and should ultimately provide an excellent opportunity to determine the relative three-dimensional distribution of LBGs and SMGs. The clustering of much rarer QSOs and relatively faint ($\simeq 10$ mJy) radio galaxies at redshifts that overlap with the SMGs has been probed by Croom et al. (2002) and Overzier et al. (2003), who report correlation lengths $r_0 = 5$ and 6 h^{-1} Mpc, respectively. However, these surveys are more sparsely sampled and cover larger areas of sky (of order thousands of square degrees), so the typical source separation is much greater than the correlation length.

Without redshifts to trace three-dimensional structure, only limits to the projected clustering strength of SMGs in two dimensions have been obtained (Carilli et al. 2001; Scott et al. 2002; Borys et al. 2003; Webb et al. 2003; see Fig. 1). This is

unsurprising given the narrow, deep geometry of SMG surveys: multiple structures along the line of sight overlap and dilute the clustering signal. Note that even the best possible photometric redshifts derived from deep multicolor optical and near-IR imaging with $\Delta z \simeq 0.1$ are not sufficiently accurate to provide useful three-dimensional clustering information in the deep narrow pencil-beam geometries of SMG surveys, which include very significant projection effects (see Fig. 2). The availability of a large number of spectroscopic redshifts means that we can now remove these projection effects and investigate the clustering of the SMG population directly.
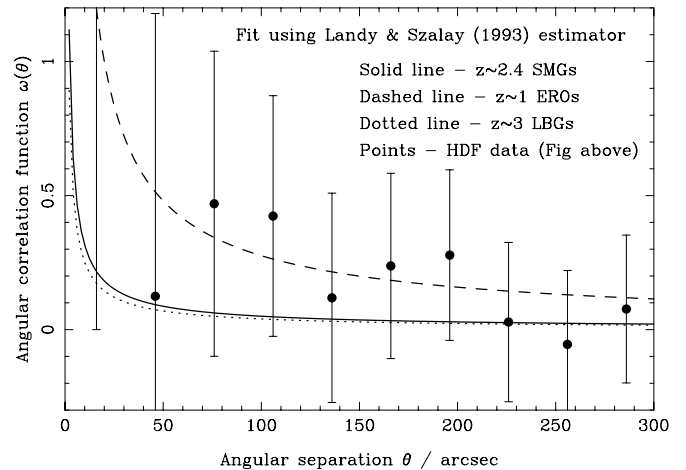

Fig. 1.—ACF observed for 47 SMGs in the extended HDF field shown in Fig. 2 (Borys et al. 2003; Chapman et al. 2003a, 2004a). Other results for two-dimensional clustering of SMGs have been discussed by Carilli et al. (2001), Scott et al. (2002), Borys et al. (2003), and Webb et al. (2003). The errors on existing ACF data are much too great to measure the clustering signal without much larger SMG samples: redshifts are essential to discern the clustering of SMGs. The observed correlation functions of $z \simeq 1$ EROs (Daddi et al. 2001; $r_0 \simeq 12$ h^{-1} Mpc), $z \simeq 3$ LBGs (Adelberger et al. 1998; Porciani & Giavalisco 2002; $r_0 \simeq 4$ h^{-1} Mpc), and $z \simeq 2.5$ SMGs assuming the correlation length $r_0 \simeq 7$ h^{-1} Mpc determined in § 3 (Table 1) are also shown. After projection, the SMGs and LBGs have similar ACFs, which are much weaker than the ACF for the lower redshift EROs.

[1] The two-point correlation function of galaxies that describes the excess probability of finding a pair of galaxies separated by r over an unclustered distribution is observed to be a decreasing power law with distance $\xi(r) = (r/r_0)^{\simeq -1.8}$ (Coil et al. 2004).
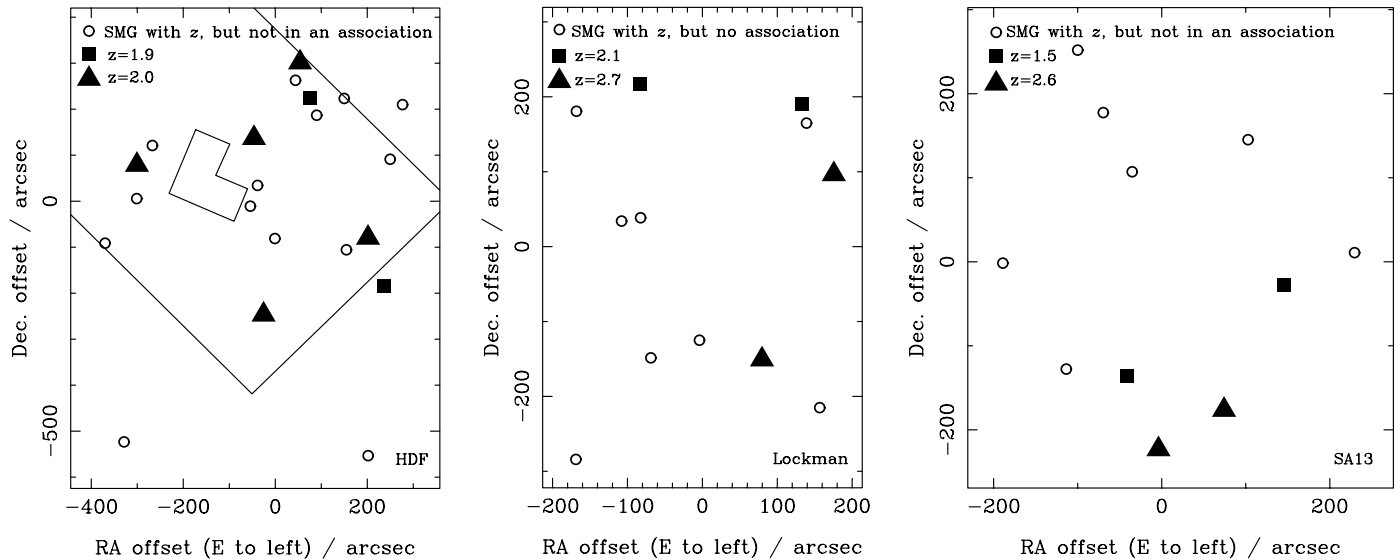
Fig. 2.—Positions of radio-pinpointed SMGs in the richest three fields in our redshift survey: from left to right these are the HDF (the boundaries of the HDF-N and GOODS fields are also shown), Lockman Hole, and SA13 fields. SMGs in our catalog with spectroscopic redshifts are represented by open circles. Those in the redshift associations present are shown by different filled symbols. These figures demonstrate the typical wide separation of the associations, which span the whole of the fields.

Throughout this paper we assume a post–*Wilkinson Microwave Anisotropy Probe* cosmology with $\Omega_0 = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, with $h = 0.71$.

2. SIGNS OF CLUSTERING IN SMG SURVEYS

There have been serendipitous detections of SMGs clustered in close proximity to other classes of high-redshift galaxies. For example, there are detections of optically selected galaxies at redshifts matching those of known SMGs and with separations of only ~100 kpc in the backgrounds of two gravitational lensing clusters of galaxies: at $z = 2.80$ in A370 (Ivison et al. 1998; Santos et al. 2004), and at $z = 2.55$ in A2218 (Kneib et al. 2004). SMGs were identified by Chapman et al. (2001) in the most overdense structure of LBGs at $z \simeq 3.1$ (Steidel et al. 2000). Overdensities of bright SMGs found near the targeted positions of some of the most extreme high-redshift radio galaxies at redshifts as great as $z = 3.8$ (Ivison et al. 2000; Stevens et al. 2003) also provide evidence for strong overdensities in the spatial distribution of SMGs, some confirmed by spectroscopy (Smail et al. 2003a, 2003b). Can we find direct spectroscopic evidence of clustering in the general population of SMGs?

In order to demonstrate the crucial importance of obtaining redshifts for the SMGs before attempting to measure their clustering properties, in Figure 1 we determine the projected two-dimensional angular correlation function (ACF) of 47 SMGs in the biggest available survey field (Borys et al. 2003; Chapman et al. 2004a). To measure a significant ACF for the SMGs, the large fractional errors on the results shown in Figure 1 indicate that a *much* larger sample of several hundred SMGs would be required, a challenge for the next generation of sensitive wide-field submillimeter telescopes.

We indeed find spectroscopic evidence for clustering of SMGs. In six of the seven fields containing SMGs with redshifts, "associations" of galaxies are found, with redshifts separated by less than 1200 km s^{-1} in radial velocity (Table 1). This velocity is an approximate upper limit to the velocity dispersion of the richest clusters of galaxies at the present epoch and so should be larger than the velocity dispersion of

any less evolved large-scale structures at high redshifts. Furthermore, it is greater than the random offset velocity expected from emission generated in randomly oriented outflowing galactic winds at high redshifts (Erb et al. 2003). Most of the associations are pairs, but there is a group of three SMGs at $z = 3.1$ in the highest overdensity in the survey of LBGs in the SA22 field (Steidel et al. 2000), and a group of five SMGs at $z = 2$ in the Hubble Deep Field (HDF; Fig. 2). SMGs are often found to have disturbed and probably interacting morphologies (e.g., Ivison et al. 1998; Chapman et al. 2003b). Note that the associations are not close interacting pairs of SMGs (such as, e.g., SMM J09431+4700; Neri et al. 2003; see also Swinbank et al. 2004) but are separated on much larger scales, up to several Mpc. Their spatial separation is comparable both to the extent of the survey fields (Fig. 2) and to the scale of the local galaxy correlation length. It is possible that the successors of the SMGs may finally reside in the densest clusters, but at the observed epoch the SMGs with associated redshifts are much more widely spread, presumably lying throughout infalling, pre-virialized filaments and walls in the large-scale structures of galaxies.

In parallel to measuring the SMG redshifts, Chapman et al. (2004b) have found redshifts for a comparable number of optically faint radio galaxies (OFRGs) that are not detected at submillimeter wavelengths. Their optical spectra are similar to the SMGs, and it is very plausible that these submillimeter-faint OFRGs are comparably luminous to the SMGs but have dust temperatures too high to be detected at submillimeter wavelengths (Blain et al. 2004). The submillimeter-faint OFRGs display a similar abundance of systems with associated redshifts to the SMGs, both within the submillimeter-faint OFRG population itself (in the 03 hr, Lockman, SA13 and SA22 fields) and when cross-correlated with the SMG population (in the five-member HDF association and in the very overdense $z = 3.1$ structure in the SA22 field). Once *Spitzer Space Telescope* observations reveal whether these galaxies are truly as luminous as the SMGs, they offer to approximately double the density of the

sampling of large-scale structure provided by very luminous dusty galaxies.

3. THE CORRELATION LENGTH OF SMG CLUSTERING

To interpret our sparse data, we cannot use regular methods to determine clustering strength (Adelberger et al. 1998; Wilson 2001) but must make use of the limited information as best we can. We compare the number of pairs of galaxies found in each field with velocity separations less than 1200 km s^{-1} (Table 1) with the number of pairs expected assuming a comoving correlation length that is fixed throughout the redshift range of the SMG sample. We further assume that the redshift distribution of the population is known accurately, and determine the space density of SMGs in each field that is required to match the observed number. This allows us to estimate the number of pairs expected in each field in the absence of clustering, as listed in Table 1 (N'_{pair}). To evaluate the number of pairs expected with a particular correlation function ξ, which is assumed to be constant in redshift, we carry out a double integral over volume for the product of the space density of SMGs N at two positions separated by a three-dimensional distance r, and the two-point correlation function ξ:

$$
N_{\mathrm{pair}} =
\frac{1}{2} \int_{\theta,\phi} \int_{\theta',\phi'} \int_{z_{\min}}^{z_{\max}} \int_{-\Delta v}^{\Delta v} N(z,\theta,\phi) N(z',\theta',\phi')[1+\xi(r)]\, dV\, dV'.
$$

(1)

The factor of $\frac{1}{2}$ corrects for double counting. One radial variable is limited by the redshift range of the SMGs (values of $z_{\min} = 1.8$ and $z_{\max} = 4.0$ were used, but note that the effects of changing $z_{\min}$ to zero are less than 1%: the peaked distribution of N sets the size of N_{pair}), and the other the distance corresponding to relative velocity in the Hubble flow, with a limit Δv set to the limiting velocity that defines a pair. This is usually 1200 km s^{-1}. Note that we integrate over the velocity range, since we cannot be sure of the relative spatial distribution of galaxies along the line of sight because of peculiar velocities, and so all galaxies that lie within Δv of each other are counted. The solid angle of the survey in each rectangular field sets the limits on θ and ϕ. N is assumed to have the Gaussian redshift distribution discussed above, normalized to match the number of detections N_{gal} in each field (Table 1).

We then change the correlation length r_0 included in $\xi(r)$, keeping $\gamma = -1.8$, until the number of pairs predicted by equation (1) matches the observed number of pairs N_{pair} (Table 1), either field by field or in a combination of fields, as listed in Table 1. The uncertainties on the derived values of r_0 are determined by the range of r_0 values that match the Poisson errors on N_{gal} and N_{pair} in each field. N'_{pair} in Table 1 is derived for $r_0 = 0$ Mpc. Note that the overall result is presented with and without the SA22 field included, as the overdensity in that field was known prior to substantial submillimeter observations, although the radio-pinpointed submillimeter observations were carried out before any redshifts were determined.

We now illustrate the robustness of this pair-counting procedure in an LBG survey field with a more richly sampled redshift distribution. The largest and best-populated LBG survey field, the $850'' \times 850''$ Westphal field,[2] contains 192

galaxies with redshifts, and 912 galaxy pairs using our definition. As the LBG redshift distribution is approximately a Gaussian with $\bar{z} = 3.0$ and $\sigma_z = 0.28$, 594 pairs would be expected with no clustering. This corresponds to an excess of pairs over random by a factor of 1.55, which requires a correlation length of $r_0 = (5.8 \pm 0.3)\ h^{-1}$ Mpc using our method of integrating over the two-point correlation function. By comparison, we obtain a correlation length $r_0 = (6 \pm 0.3)\ h^{-1}$ Mpc in this field if we evaluate the two-point ACF against a mock catalog of random galaxy positions with the same redshift distribution (Landy & Szalay 1993) and then compare the results with the ACF obtained from an assumed three-dimensional correlation function using Limber's equation (e.g., Wilson 2003). Although this is a single relatively small field and fluctuations in the correlation amplitude are certainly expected, the result from the pair-counting method used to analyze our small SMG sample is in accordance with that expected from more established methods. Note that the strength of clustering in this field appears to be greater than for the LBG sample as a whole.

Over all seven fields we find a correlation length $r_0 = (6.9 \pm 2.1)\ h^{-1}$ Mpc for the SMG sample. Only in the best-sampled HDF field is a significant result obtained in an individual field, $r_0 = (9.5 \pm 3.3)\ h^{-1}$ Mpc; the other fields all include too few galaxies and pairs. Note that varying the choice of field area or Δv makes relatively little difference to the result. If the size of the HDF field is doubled, then the calculated correlation length is reduced to $r_0 = (7.5 \pm 3.2)\ h^{-1}$ Mpc, consistent with the value above. If Δv is reduced to 600 km s^{-1}, then only two pairs of galaxies are lost from the 18 in the sample. The calculated correlation length is then increased by 24%. If the value of Δv is increased to 1800 km s^{-1}, then an additional three pairs are counted and the correlation length is reduced by 8%. Hence, within the uncertainties the results are robust to changes in the assumptions made.

The correlation length for SA22 is greater, but note that SA22 includes a known strong overdensity at the redshift of the association of SMGs (Steidel et al. 2000), and so it is possible that the value for SA22 does not give a fair representation of the clustering of SMGs in a typical field.

Using the larger spectroscopic catalogs of LBGs, we conducted several additional tests of the results. We again verified that the predicted and measured counts of pairs are not very sensitive to reasonable changes in the chosen velocity range Δv away from 1200 km s^{-1}. The results depend more strongly on the shape and size of the field, with smaller fields yielding a larger boost in the expected number of pairs for a certain correlation length, as the correlation function ξ is larger when sampled on smaller scales. We also randomized the redshifts of the LBG catalog and, as expected, found that the measured excess of pairs vanished. The pair-counting method is thus sensitive to real three-dimensional structure in the galaxy distribution. We also examined the effects of randomly dropping a redshift-independent fraction of the LBGs from the catalog, to simulate the effects of incompleteness in sampling a galaxy population with a well-known and independent correlation length measurement. The results do not change significantly, even if the sample becomes 50% incomplete. As we know that the catalogs of redshifts for radio-selected SMGs are probably complete at the 70% level (Chapman et al. 2004a) and that no redshifts in the range $1.8 < z < 4$ are preferentially excluded from our redshift sample, we can be confident in the accuracy of our results.

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[2] Data from the Westphal field are available from Caltech at ftp://ftp.astro.caltech.edu/pub/ccs/lbgsurvey/westphal.

A correlation length of ~7 h^{-1} Mpc for the SMGs is close to that predicted by Shu et al. (2001), assuming that star formation activity in massive halos follows a Schmidt Law with gas surface density; this is a very uncertain assumption given the apparent large masses and complex dynamical structure in these galaxies (Frayer et al. 1998, 1999; Neri et al. 2003; T. R. Greve et al. 2004, in preparation).

We can also compare and contrast the correlation length result for the SMGs with the results for rarer, more sparsely sampled populations of galaxies. The sample of QSOs with a surface density of ~30 deg^{-2} and $z \simeq 1.6 \pm 0.65$ from the Two-Degree Field (2dF) survey overlaps in redshift with the lower end of the SMG redshift distribution. The correlation function of the 2dF QSOs is smaller than that for the SMGs, ~5 h^{-1} Mpc (Croom et al. 2002). The 2dF correlation function is evaluated over a very much larger area (~730 deg^2) and so is not prone to field-to-field variations. The correlation length for other samples of high-redshift galaxies, including very deep near-IR selected populations (Daddi et al. 2003) and bright radio galaxies (Röttgering et al. 2003), have also been evaluated at similar redshifts to our SMG samples. For the former, the survey areas are small in extent and have relatively incomplete redshift distributions, while for the latter the survey volumes are sparsely sampled. It is hence difficult to compare the correlation functions of these samples directly with SMGs at present.

We are targeting a statistically reliable subset of our SMGs with known redshifts to detect CO emission lines using millimeter-wave interferometry and rest-frame optical nebular line emission using near-infrared spectrographs. The CO line width can be used to provide a dynamically determined estimate of the mass within ~10 kpc (Frayer et al. 1998; Neri et al. 2003; Genzel et al. 2003; T. R. Greve et al. 2004, in preparation); a more accurate mass can be obtained if the emission can be resolved spatially. Initial indications are that SMGs have velocity dispersions that are greater by a factor of 2 and thus have dynamical masses greater by a factor of ~4 as compared with the dynamical masses of LBGs at $z \simeq 2$ (4×10^{10} $M_\odot$; Erb et al. 2003). The half-light radii of SMGs appear to be larger than those of SMGs (Chapman et al. 2003b), which would lead to a further increase in the relative mass of SMGs as compared with LBGs by a factor of 2. At $z \simeq 2$, near-IR observations of resolved nebular line emission are easier, although published samples of $z \simeq 3$ LBGs are larger. LBGs appear to be typically twice as massive at $z = 2$ as at $z \simeq 3$. None of these direct dynamical measures indicate, however, that SMGs are as massive as the several 10^{13} $M_\odot$ halos their clustering properties would suggest (Fig. 2). Their central dynamical masses derived on 10 kpc length scales are likely to be a factor of only 3–4 times less than the mass of the dark matter halo, extended to on the order of 200 kpc, given the steep r^{-3} decline in the expected profile of dark matter halos outside of the visible galaxy (Navarro et al. 1997). Recent near-IR and CO observations of SMGs (Genzel et al. 2003; Tecza et al. 2004; T. R. Greve et al. 2004, in preparation; Swinbank et al. 2004) tend to support the greater masses of SMGs as compared with LBGs. It is interesting to note that the masses of the dark matter halos surrounding the large, well-studied sample of LBGs at $z \simeq 3$ inferred from their clustering properties ($\sim 8 \times 10^{11}$ $M_\odot$; Adelberger et al. 1998; Fig. 1) also exceed the central dynamical masses inferred from spatially structured asymmetric line profiles and velocity dispersions but by a smaller factor than for the SMGs. If in fact SMGs can only form in the most massive halos, then in

a hierarchical picture of galaxy formation this could account for their apparent typical moderate redshifts (Chapman et al. 2003a, 2004a).

Differences between the inferred dynamical and dark matter masses of high-redshift galaxies provide a direct hint that more complex astrophysics in SMGs could break a simple link between clustering amplitude and mass (see Shu et al. 2001). For example, the time dependence of merging has been claimed to both boost (from infall; Scannapieco & Thacker 2003) and leave unaffected (Percival et al. 2003) the clustering properties of galaxies. Intuitively, very luminous SMGs that are only briefly visible in overdense regions might be expected to have a weaker clustering signal as compared with a quiescent population that has the same spatial distribution; however, the strength of clustering could be increased if the luminous SMG phase is triggered preferentially in overdense regions. Further observations to investigate the relationship between the luminous SMGs and their underlying dark matter distribution are necessary to account for the effects of time evolution. Note that there is also certain to be strong field-to-field variation in the density of structures of associated redshifts for SMGs (Fig. 2).

We stress that accurate spectroscopic redshifts are essential in order to reveal clustering properties of the SMGs. The same information cannot be derived from two-dimensional data. The expected ACFs for $z \simeq 1$ extremely red objects (EROs), $z \sim 3$ LBGs, and SMGs assuming the correlation lengths discussed above are shown in Figure 1. The relatively narrow redshift range for the EROs leads to a large expected signal, while the LBGs and SMGs have a much weaker ACF, due in part to the greater distance to both samples and mainly to their broader redshift distributions, especially for the SMGs. The inferred correlation length for the SMGs is similar to the projected extent of the SMG survey fields, so the relative spatial positions of the members of each association reveal little information on the maximum extent and strength of the clustering present. We await much larger square degree–scale fields in order to sample the clustering properties of SMGs in a representative region of the high-redshift universe.

4. CONSEQUENCES OF STRONG SMG CLUSTERING

There are two immediate consequences of the presence of a strong clustering signal in the SMG survey. These concern both the nature of the SMGs themselves and the galaxies that result when the SMG activity is completed. First, since the correlation length of SMGs appears to be somewhat larger than for both LBG and QSO surveys at comparable redshifts, it seems unlikely that the SMGs form a simple evolutionary sequence with either population. It is attractive to link together these different samples of high-redshift galaxies, but they are likely to be substantially distinct populations. If they are distinct, then the large luminosities of the SMGs would not represent a shorter-lived, more luminous phase during the active lifetime of more typical, less deeply dust-enshrouded star-forming galaxies, and few powerful active galactic nuclei (AGNs) would burn out of the dust cocoons of SMGs to appear as optically visible QSOs. Second, if there are no complex biases at work, then the correlation length inferred for the SMGs is consistent with a form of evolution that subsequently matches the large comoving correlation length typical of evolved EROs at $z \simeq 1$ and of clusters of galaxies at the present epoch (Fig. 3). If this picture is correct, then the descendants of SMGs would be rare
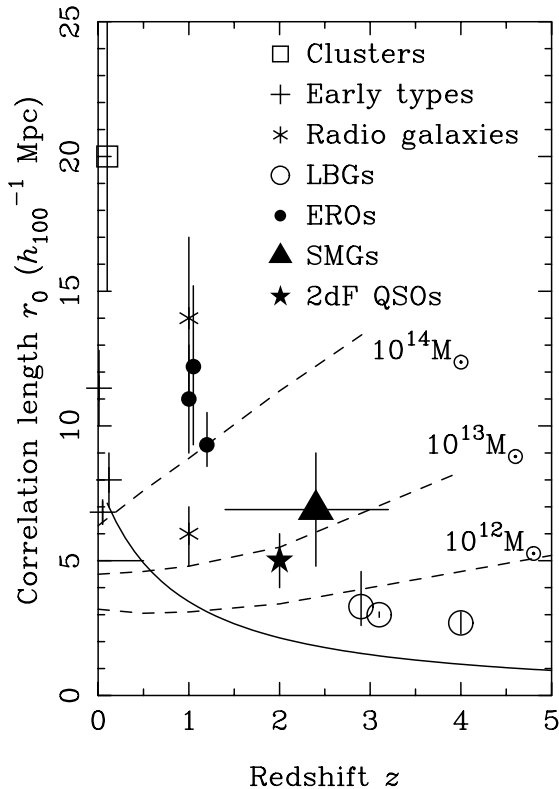
Fig. 3.—Comoving correlation length of the SMGs inferred from our survey in contrast to other populations of low- and high-redshift galaxies (see the summary in Overzier et al. 2003). The horizontal error bar on the SMG point spans the range of redshifts over which SMG associations are found (Table 1). The solid line shows a representative model for the evolution of a certain overdensity. The dashed lines show the expected correlation length of dark matter halos as a function of mass and redshift.

comoving space density of bright radio-detected SMGs at $z \simeq 2.5$ is $\sim 2.7 \times 10^{-5}$ Mpc^{-3}. The corresponding density of EROs at $0.7 < z < 1.5$ is $(2.2 \pm 0.6) \times 10^{-4}$ Mpc^{-3} in a sample with spectroscopic completeness of $\sim 70\%$ (Cimatti et al. 2002). The density of EROs matches closely the comoving abundance of L^* elliptical galaxies at the present epoch, which is $\sim 2 \times 10^{-4}$ Mpc^{-3}. Hence, because the comoving abundance of SMGs is much less, even neglecting merging, the SMGs and EROs can only be part of a direct evolutionary sequence with the same density in space if the duty cycle of SMGs is short, less than 700 Myr, to generate enough evolved, long-lived EROs in the 6 Gyr prior to $z \simeq 1$. The resulting EROs could then evolve naturally into L^* elliptical galaxies at the present epoch with a very modest amount of merging. The unknown time profile of the luminosity of SMGs would certainly also have an effect on the results. Direct accurate determinations of the masses of SMGs are critically important to investigate these links. The first hints from systematic CO observations are that SMGs are massive enough to generate the stellar populations of L^* elliptical galaxies directly (Neri et al. 2003; T. R. Greve et al. 2004, in preparation).

The correlation function of SMGs appears to be consistent with their being associated with massive dark matter halos at high redshifts, halos more massive than those hosting LBGs and QSOs at comparable redshifts. The successors of SMGs could thus be associated with clusters of galaxies at the present epoch. A key test of the nature of the SMGs requires a larger sample of dynamical mass estimates for the population, and a direct comparison of their spatial distribution as compared with populations of more common optical/UV-selected galaxies in the same fields.

5. SUMMARY

The discovery of associated systems of high-redshift luminous SMGs, enabled by the measurement of a substantially complete redshift distribution ($z \simeq 2-3$), hints that they represent a strongly clustered population. We derive a correlation length of (6.9 ± 2.1) h^{-1} Mpc in our best-sampled field. Representative samples of high-redshift SMGs may thus be found in high-density environments that could evolve into rich clusters of galaxies at the present epoch. The large correlation length casts doubt on a simple evolutionary link with populations of high-redshift optical/UV-selected galaxies and QSOs, while offering the potential to use associations of SMG redshifts to signpost the densest regions of the high-redshift universe with only a modest requirement on spectroscopic observing time. A key goal is now to investigate and compare the masses of SMGs inferred from clustering measurements and the dynamical masses inferred from near-IR and millimeter-wave CO spectroscopy. This could help to determine the nature of the power source and lifetime of the SMGs themselves, and reveal the galaxies at the present epoch that evolve from the SMGs.

in the field, and found predominantly in rich cluster environments. However, this appears to be inconsistent with their space densities, since a progenitor of a rich cluster of galaxies is not expected to intersect every 100 arcmin^2 field sampled out to redshift $z \simeq 3$. The condition for this to occur is a comoving density of protoclusters on the order of 10^{-6} Mpc^{-3}, in contrast to the observed comoving density of clusters with masses $M > 8 \times 10^{14}$ $M_\odot$ at $z = 0$, which is $\sim 10^{-7}$ Mpc^{-3} (Bahcall et al. 2003). However, it is possible that SMGs in more extended unvirialized wall and filament large-scale structures with masses of several times 10^{13} $M_\odot$ at $z \simeq 2.5$ (Fig. 3) that subsequently drain, merge, and collapse into more massive clusters could provide a greater effective covering factor to reconcile these values. More likely, either the halo masses are less extreme than inferred from a picture of simple one-to-one halo biasing at a given mass, or some other astrophysical biasing effect must be at work. By considering the correlations between dark matter subhalos and a "halo occupancy distribution," it is possible to enhance clustering on a given halo mass scale (Berlind et al. 2003). Building a better observational view of the density of the environments of SMGs based on deep multiwaveband imaging and densely sampled spectroscopy should allow these ideas to be tested.

The suggestion of an evolutionary link between SMGs and passive EROs from their clustering strength may provide useful constraints on the lifetime of the SMG phase. The

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