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Correlations between bright submillimetre sources and low-redshift galaxies

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ABSTRACT

We present evidence for a positive angular correlation between bright submillimetre (sub-mm) sources and low-redshift galaxies. The study was conducted using 39 sources selected from three contiguous, flux-limited SCUBA surveys, cross-correlated with optical field galaxies with magnitudes $R < 23$ (with a median redshift of $z \simeq 0.5$). We find that the angular distribution of sub-mm sources is skewed towards overdensities in the galaxy population, consistent with 25 ± 12 per cent being associated with dense, low-redshift structure. The signal appears to be dominated by the brightest sources with a flux density $S_{850\,\mu\mathrm{m}} > 10$ mJy. We conduct Monte Carlo simulations of clustered sub-mm populations, and find that the probability of obtaining these correlations by chance is less than 0.4 per cent. The results may suggest that a larger than expected fraction of sub-mm sources lies at $z \simeq 0.5$. Alternatively, we argue that this signal is most likely caused by gravitational lensing bias, which may be entirely expected given the steep sub-mm source counts. Implications for future sub-mm surveys are discussed.

Key words: galaxies: evolution – galaxies: formation – galaxies: starburst – cosmology: observations – infrared: galaxies.

1 INTRODUCTION

The advent of the SCUBA array at the James Clerk Maxwell Telescope led to the discovery of a high surface density of apparently high-redshift, dust-enshrouded galaxies (e.g. Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999). Progress beyond these original discoveries has been limited, however, not least because of the optical faintness of many of these sources. Combined with the relatively large 10–15 arcsec SCUBA beam, this makes unambiguous identification extremely difficult (e.g. Smail et al. 2002). This deadlock has recently been partially overcome with deep radio observations at the VLA, which have yielded precise locations for significant samples of submillimetre (sub-mm) galaxies for the first time. Follow-up spectroscopy has produced the first reliable $N(z)$ estimate for the population of SCUBA galaxies (Chapman et al. 2003), showing a median redshift of $z = 2.4$ with only a small fraction (a few per cent) of galaxies at $z < 1$.

There have been suggestions that many sub-mm sources could be powered by active galactic nuclei (AGN) (e.g. Almaini, Lawrence & Boyle 1999), but the failure to detect significant numbers as luminous X-ray sources suggests that the AGN-dominated fraction is likely to be small (Fabian et al. 2000; Severgnini et al. 2000; Almaini et al. 2003; Waskett et al. 2003). Nevertheless, a large fraction (probably >40 per cent) appear to host moderate-luminosity AGN activity (Alexander et al. 2003). The suggestion that some fraction could be very local cold clouds within the Milky Way (Lawrence 2001) has not been entirely ruled out, but it now seems likely that the majority are high-redshift, dust-enshrouded galaxies with the observed sub-mm emission dominated by the re-radiation of absorbed stellar light by dust.

As the true nature of these sources emerges, the next step is to make use of this population to constrain both the history of obscured star formation and theories for the formation of massive galaxies. A crucial step will be to measure the clustering of the sub-mm galaxies, which will directly test the hypothesis that these are the progenitors of massive elliptical galaxies (Percival et al. 2003). There are preliminary indications that the SCUBA sources are clustered (Scott et al. 2002), but surveys containing hundreds of sub-mm sources will be required to determine the strength of clustering to the required precision. There is also intriguing evidence that sub-mm sources are clustered with Lyman-break galaxies (Webb et al. 2003) and

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X-ray emitting AGN (Almaini et al. 2003). The first result can naturally be explained in terms of large-scale structure at $z \sim 3$, but the correlation with X-ray sources is more puzzling. Recent determinations of the redshift distribution of *Chandra*-selected X-ray sources (Hornschemeier et al. 2001; Gilli et al. 2003) show the majority seem to lie at $z < 1$. This may indicate that many sub-mm sources lie at lower redshift than previously assumed. An alternative possibility (motivated by the very steep sub-mm number counts, e.g. Scott et al. 2002) is that these correlations are an artefact of gravitational lensing. It is now emerging that hard X-ray sources are excellent tracers of peaks in the density field at $z < 1$ (Elbaz & Cesarsky 2003; Gilli et al. 2003). Could these structures lead to a substantial gravitational lensing bias for distant sub-mm populations? There are already indications that a few SCUBA sources are falsely associated with low-redshift galaxies because of strong gravitational lensing (Chapman et al. 2002; Dunlop et al. 2004). Combined with the more subtle effects of weak gravitational lensing, models predict that approximately 30 per cent of the sources selected at $S_{850\,\mu\rm m} >$ 10 mJy could be gravitationally lensed (Perrotta et al. 2003; see also Blain, Moller & Maller 1999), although the precise fraction depends critically on the slope of the (intrinsic) sub-mm source counts.

To explore these issues further, in this paper we examine the possibility that a significant fraction of the sub-mm population is correlated (in 2D) with low-redshift large-scale structure, as traced by optically selected galaxies. Section 2 outlines the optical and sub-mm data used for this analysis. Section 3 compares the distribution of these populations for individual and combined fields. Section 4 examines the effects of an intrinsically clustered sub-mm population using Monte Carlo simulations. In Section 5 we discuss the predictions of gravitational lensing bias, while Section 6 discusses the effects of cosmic variance between our fields. Section 7 presents the summary and conclusions.

2 THE OBSERVATIONAL DATA

2.1 The sub-mm surveys

To examine any associations between sub-mm sources and low-redshift galaxies in an unbiased manner we must select our sub-mm catalogue from complete, flux-limited surveys. To this end we select 39 sub-mm sources detected above a signal-to-noise (S/N) limit of 3.5σ from three separate contiguous surveys. Two are from the 8-mJy SCUBA survey of Scott et al. (2002), which covers 260 arcmin^2 over two fields (ELAIS-N2 and the Lockman Hole East) using a jiggle-mapping technique to an rms noise level of ∼2.5 mJy per beam at 850 μm. The third is from the shallower SCUBA map of the *Hubble Deep Field* (HDF) conducted by Borys et al. (2002), which covered 125 arcmin^2 in scan-map mode to an rms noise level of approximately 3.5 mJy.

To minimize spurious sources, we follow Ivison et al. (2002) and exclude the sources from the 8-mJy survey which lie in regions where the noise is in excess of 3 mJy per beam. This removes five sources from the Lockman Hole and one source from ELAIS-N2. We also remove any sources from the sample of Borys et al. (2002) which were not subsequently confirmed (above 3.5σ) in the 'supermap' paper of Borys et al. (2003). We also exclude source SMMJ 123608+621246. This source was not confirmed in deeper observations by Wang et al. (2004) or in a re-analysis of the same data by Borys (private communication).

The final sample therefore contains 16 sources from ELAIS-N2, 17 sources from the Lockman Hole and six sources from the HDF.

2.2 The optical galaxy catalogue

Our aim is to determine whether the SCUBA sources are associated with low-redshift large-scale structure, particularly structure which could cause gravitational lensing for an intrinsically high-redshift population.

For a background source at $z > 2$, the optimal redshift for gravitational lensing occurs for a foreground lens at $z \simeq 0.5$ (Clowe et al. 2000), assuming the currently favoured lambda-dominated cosmology. In the absence of redshifts for the majority of field galaxies in the survey regions described above we choose to cross-correlate the SCUBA catalogues with galaxies selected from optical photometry.

To estimate the redshift distribution of our optical galaxies we use the photometric redshift surveys of the COMBO-17 consortium (Wolf et al. 2003). Based on these data, we select galaxies with Vega magnitudes $R < 23$. Galaxies selected in this manner show a median redshift of $z = 0.53$ (Wolf, private communication) with only a small tail of a few per cent at $z > 1$, and as such are ideal probes of low-redshift large-scale structure.

An R-band image of ELAIS-N2 was obtained with the Prime Focus Camera (PFC) on the William Herschel Telescope (WHT) during 1999 May, primarily for the purpose of identifying X-ray sources from the ELAIS Deep X-ray Survey (Manners et al. 2003; Willott et al. 2003). This uses detectors with a pixel scale of 0.236 arcsec, covering a field of view of approximately 16 × 16 arcmin^2. In measured seeing of 0.7 arcsec, a 5σ limiting magnitude of $R = 25.0$ in a 4-arcsec aperture is obtained. Galaxy catalogues to a limit $R <$ 23.0 are then extracted using the SEXTRACTOR package. Candidate stellar sources with a CLASS_STAR parameter >0.8 are removed from the analysis.

We have no access to deep R-band imaging for the Lockman region, so we use an I-band image also obtained using the WHT PFC during 2000 November. In measured seeing of 0.8 arcsec this reaches a 5σ limiting magnitude of $I = 23.9$. Based on the I-band catalogues from the COMBO-17 survey, we find that a limiting magnitude of $I = 22.5$ provides a catalogue of galaxies with a near-identical $N(z)$ distribution to a sample selected with $R < 23$, removing candidate stars as above.

In the HDF region we use the catalogue of Capak et al. (2004), obtained using the Suprimecam camera at the Subaru telescope in 2001 February and March. This reaches a 5σ limiting magnitude of approximately $R_{AB} = 26.6$. A galaxy catalogue to a depth of $R_{\rm Vega} <$ 23 was then extracted using star/galaxy separation flags provided by Capak (private communication).

Finally, the regions surrounding the brightest stars (typically those with $R < 16$) are excluded from the analysis described below to avoid incompleteness in these regions.

3 CORRELATIONS BETWEEN OPTICAL AND SUB-mm GALAXIES

3.1 Individual fields

Figs 1 and 2 show the distribution of SCUBA sub-mm galaxies compared to the low-z galaxy catalogues described above. By eye, the ELAIS-N2 field shows a strong correlation between these populations.[1] In the Lockman and HDF fields any correlations are visually

[1] Interestingly this same general structure is seen in the *Chandra* X-ray population in this field (Almaini et al. 2003), strengthening recent suggestions that hard X-ray sources are strong tracers of peaks in the large-scale structure at $z < 1$ (Elbaz & Cesarsky 2003; Gilli et al. 2003).

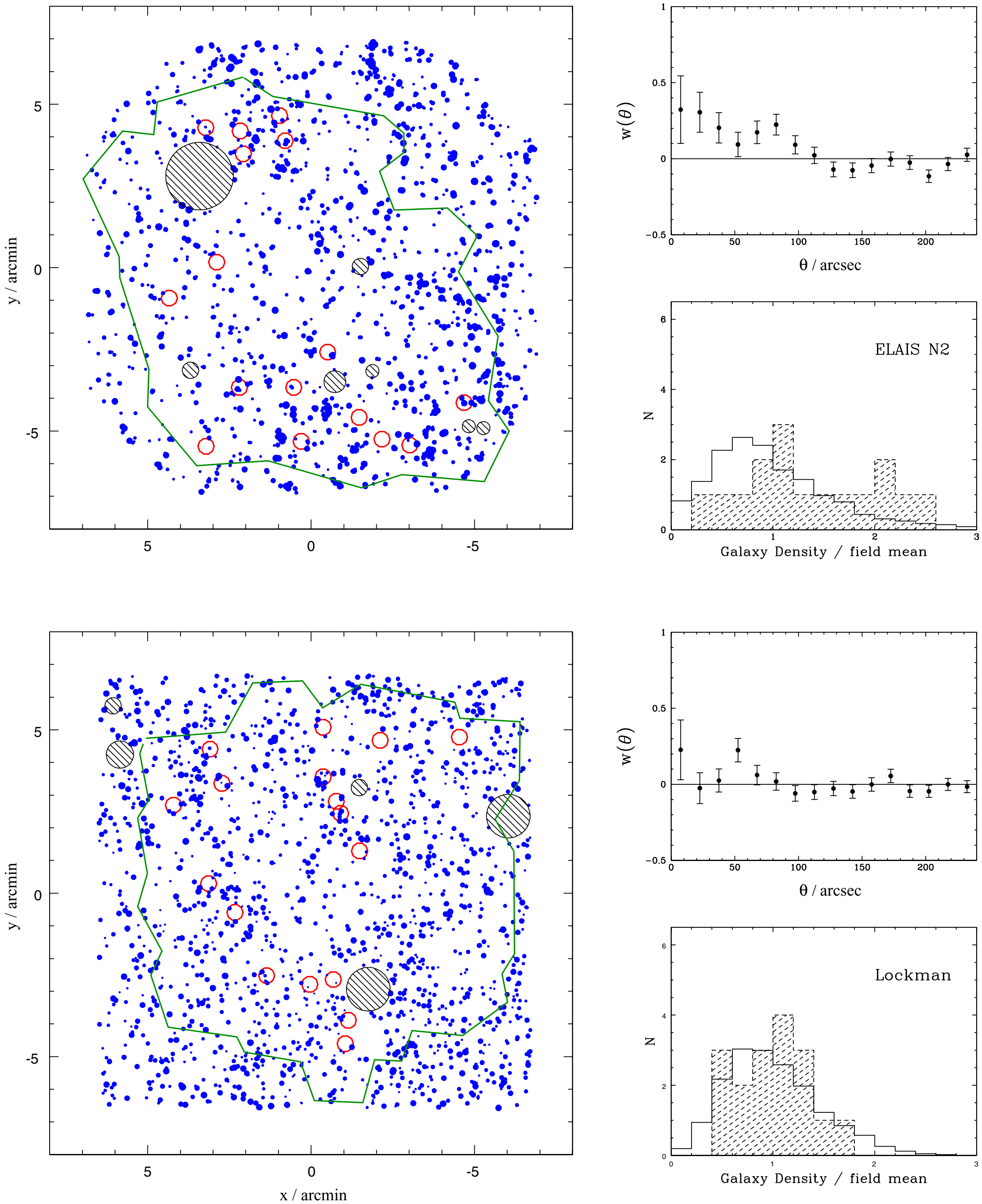

Figure 1. Left column: The distribution of SCUBA sub-mm sources (open circles) and galaxies (filled points) to a limit of $R < 23$ in the ELAIS-N2 field (top) and $I < 22.5$ in the Lockman Hole (bottom). The size of the galaxy points reflects their optical brightness. Hatched areas denote regions removed from the optical catalogue due to the presence of bright stars. The boundaries of the SCUBA maps are shown by the solid line. Right column: This shows the SCUBA/galaxy cross-correlation function $w(\theta)$ and a histogram of the galaxy densities within a 30-arcsec radius of each SCUBA source (dashed histogram) compared to the expected distribution from 100 000 randomly placed apertures (solid histogram).

less striking, but again there is evidence for a number of SCUBA sources lying in the vicinity of overdense structure.

To quantify this visual impression we perform a two-point angular cross-correlation, using the same basic estimator defined in Almaini et al. (2003). As expected, this reveals a clear excess of low-z galaxies around SCUBA sources in the ELAIS-N2 field (3–4σ significance within 1 arcmin) with weaker evidence for an excess in the Lockman and HDF fields ($\sim 2\sigma$ significance within 1 arcmin). A problem with the cross-correlation estimator, however, is that it effectively averages out the correlations over all sub-mm sources. In

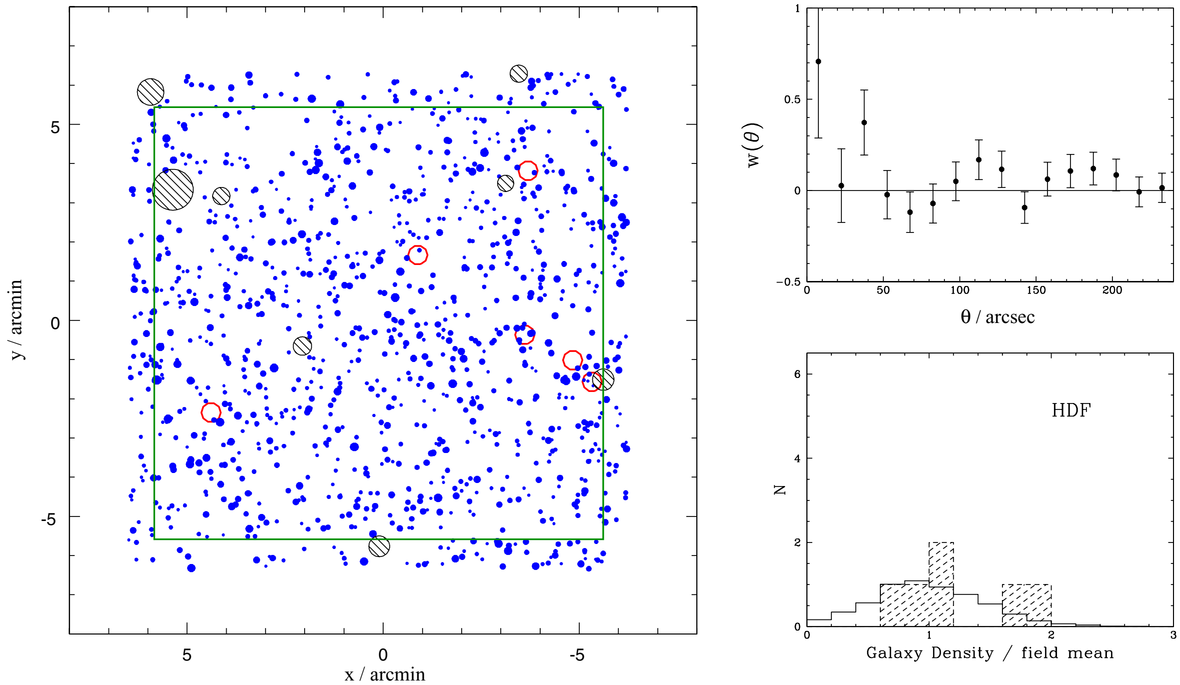

Figure 2. As Fig. 1, but using the sub-mm sources from the scan map of the HDF region (Borys et al. 2002) relative to galaxies selected to a limit of $R < 23$.

order to estimate the fraction of sub-mm sources lying in overdense regions we henceforth consider the *distribution* of galaxy environments traced by the sub-mm sources. We select a 30-arcsec radius (a priori) around each SCUBA source and measure the density of galaxies observed compared to the field mean. The resulting distributions are shown as histograms in Figs 1 and 2. We compare with the distribution expected from 100 000 randomly placed apertures distributed within the SCUBA map regions.

For the ELAIS-N2 field in particular, the sub-mm sources appear to be skewed towards regions of high galaxy density. A Kolmogorov–Smirnov (KS) test (on the unbinned distributions) gives a probability of >99 per cent that the SCUBA sources are not drawn from the same parent population as the randomly placed apertures. For both the Lockman Hole and HDF regions the sub-mm sources also appear slightly skewed towards high-density regions, although at much lower statistical significance (formally rejecting the null hypothesis at only the 85 per cent level in each case).

3.2 The combined data

In Fig. 3 we show a histogram of galaxy densities from the three fields combined, formed by simply adding the distributions from the individual fields. We note that the peak in the expected density distribution occurs at $\rho/\bar{\rho} < 1$, reflecting the fact that the optical galaxies are clustered. A typical 30-arcsec aperture will therefore sample slightly below-average density compared to the overall field mean.

The combined data show clear evidence that the SCUBA sources are skewed towards higher density regions in the galaxy distribution. Formally a KS test rejects the hypothesis that these are drawn from the same underlying population as the random apertures at >99 per cent significance.

The maximum deviation in the KS test occurs at a density $\rho/\bar{\rho} = 0.85$ (midway between the peaks in the two distributions shown in Fig. 3). To estimate the *fraction* of 'excess' SCUBA sources producing this signal, we consider the number observed in regions above this density value. From a total of 39 SCUBA galaxies we observe 30 with $\rho/\bar{\rho} > 0.85$ compared to 20.3 expected. This corresponds to an estimated 'excess' of 9.7 SCUBA galaxies, or 24.9 ± 11.6 per cent of the total (assuming Poisson statistics).

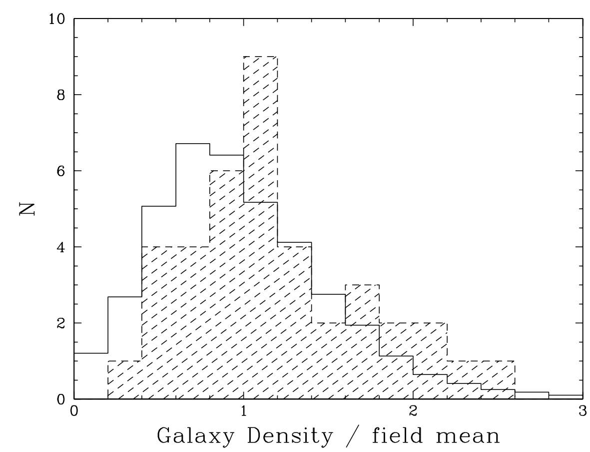

Figure 3. Histograms of the optical galaxy densities within a 30-arcsec radius of the 39 SCUBA sources from three fields combined (shaded region) compared to the expectation from randomly placed apertures (solid line).

A more conservative estimate can be obtained by considering the fraction lying in the densest regions with $\rho/\bar{\rho} > 1$. In these regions we observe 24 SCUBA galaxies compared with 16.3 expected, corresponding to an excess of 19.7 ± 10.3 per cent. The statistical significance of these results is investigated further in Section 4.

3.3 Bright and faint SCUBA galaxies

A prediction of gravitational lensing models (e.g. Perrotta et al. 2003) is that brighter sub-mm sources are more likely to be

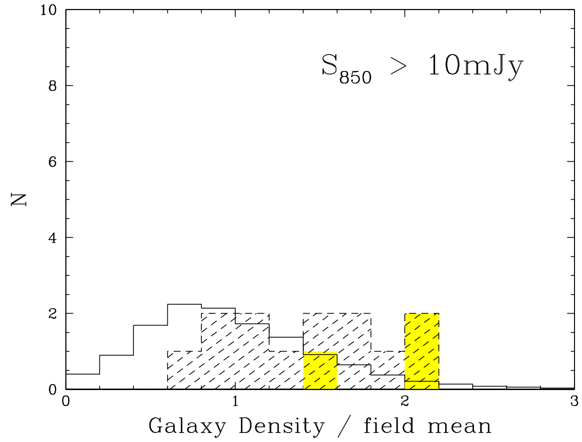

Figure 4. As Fig. 3, but using only the 13 brightest SCUBA sources detected above a flux limit of $S_{850\,\mu\mathrm{m}} > 10$ mJy. The shaded subhistogram highlights the three sources from the ELAIS-N2 field.

gravitationally lensed. This will be expected if the slope of the (unlensed) source counts steepens, which may reflect a turn-over in the underlying sub-mm luminosity function. Adopting the galaxy formation models of Granato et al. (2001), Perotta et al. (2003) predict a sharp increase in the lensed fraction for $S_{850\,\mu\mathrm{m}} > 10$mJy.

To test this prediction we split the sample into the 13 brightest SCUBA galaxies with $S_{850\,\mu\mathrm{m}} > 10$ mJy (Fig. 4) and 26 fainter systems below this flux density (Fig. 5). The brighter galaxies show a notably more skewed distribution. Formally a KS test rejects the hypothesis that these are drawn from the same underlying population at the random apertures at >99 per cent significance. In contrast, a KS test on the fainter galaxies only rejects the null hypothesis at >85 per cent significance.

We note that while the ELAIS-N2 field gave the strongest correlations in Section 3.1, only three of these sources are brighter than 10 mJy and these do not appear to dominate the signal (see shaded histogram in Fig. 4). Excluding these sources, the significance of the KS test drops, but the null hypothesis is still rejected at >95 per cent significance.

We conclude that there is strong evidence for a correlation between low-z structure and bright SCUBA galaxies. Determining the precise relationship as a function of sub-mm flux density, however, will clearly require a larger sample.

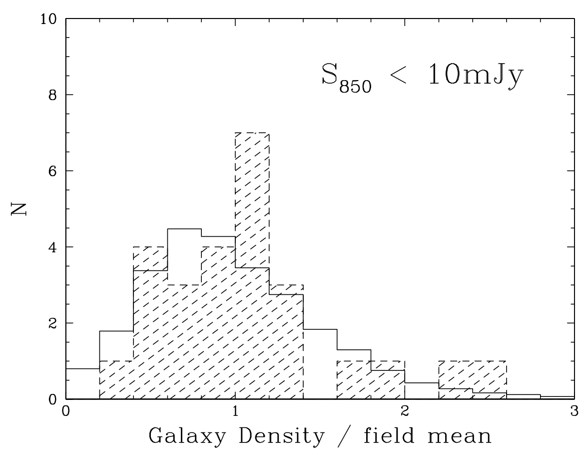

Figure 5. As Fig. 3, but using only the 26 fainter SCUBA sources with $S_{850\,\mu\mathrm{m}} < 10$ mJy.

For the SCUBA galaxies with $S_{850\,\mu\mathrm{m}} > 10$ mJy we can estimate the fractional 'excess' which is associated with the low-z galaxies. In high-density regions ($\rho/\bar{\rho} > 1$) we find 10 SCUBA galaxies, compared to only 5.4 expected from a random distribution. Although these are small-number statistics, from the total of 13 sub-mm sources this corresponds to an estimated excess of 35 ± 18.

3.4 The choice of aperture size

Throughout the density analysis we have used a 30-arcsec radius aperture. This corresponds to a comoving radius of 270 kpc at $z = 0.5$, which is similar to the size of a dark matter halo for a small group or a large galaxy (Fischer et al. 2000). For completeness we repeated the analyses with a range of aperture sizes from 20 to 60 arcsec, but found that this had no major influence on any of the results presented here. Formally the 20-arcsec aperture gave marginally more significant correlations and a 60-arcsec aperture gave the least. The differences were small, however, so we will not comment further. Hereafter we therefore stick to our a priori choice of 30-arcsec radius apertures.

4 SIMULATIONS OF CLUSTERED SUB-mm SOURCES

An implicit assumption in the density analysis presented above is that the SCUBA sources are intrinsically randomly distributed. Although a definitive measurement of sub-mm source clustering has yet to be made (Scott et al. 2002) in this section we explore the implications of a sub-mm population which is intrinsically highly clustered. If the SCUBA sources are strongly clustered one would expect a higher probability of finding a large number clustered around low-redshift overdensities (or voids) purely by chance.

Appendix A describes a technique for producing mock 2D catalogues of clustered populations. We generated three sets of catalogues with differing clustering strengths. The first is a 'highly clustered' model, in which SCUBA sources cluster as strongly as the extremely red object (ERO) population. These galaxies have the strongest $w(\theta)$ of any known population at $z > 1$ and as such represent a realistic upper bound to the strength of clustering expected from the SCUBA sources (particularly since the SCUBA sources are believed to have a much broader $n(z)$ distribution, which should dilute the angular signal). We simulate a population with a standard two-point angular correlation function: $w(\theta) = (\theta/\theta_0)^{-0.8}$, where the clustering strength for EROs is given by $\theta_0 = 1.5 \times 10^{-2}$ deg (Daddi et al. 2000; Roche et al. 2002). The 'least-clustered' model has an amplitude $\theta_0 = 0$, equivalent to a random Poisson distribution. We also simulate a population with an 'intermediate' level of clustering, with $\theta_0 = 7.5 \times 10^{-3}$ deg.

Large mock catalogues covering several thousand square degrees were generated. Tests confirmed that the mock catalogue generation successfully reproduces a distribution with the desired $w(\theta)$. Independent regions were then selected and overlaid over the galaxy distributions in the real fields. The density histogram analysis was then repeated for each set of mock data. The fraction of sources lying in regions of above-average galaxy density ($\rho > \bar{\rho}$) is then calculated. Normalizing these results to the actual number of SCUBA sources in each field, we can then predict the likelihood function for N sources (from a total of 39) to lie in regions of above-average density. The results for the three fields combined are shown in Fig. 6, based on 10 000 simulations for each value of θ_0. We note that the expectation value ($\simeq$16) differs from $39/2 = 19.5$, reflecting the fact that the galaxy population itself is clustered. The typical density

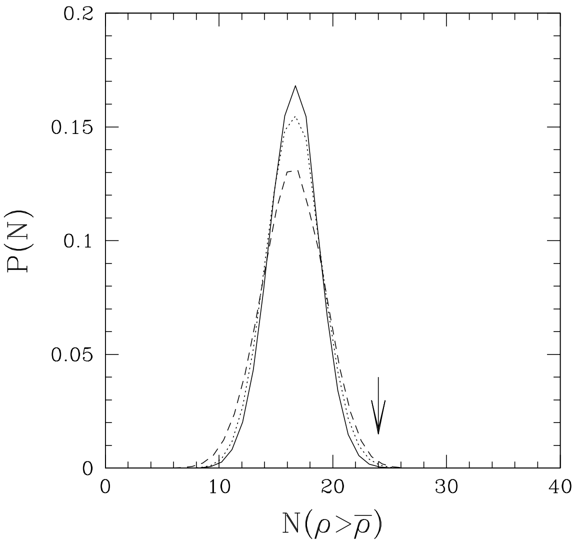

Figure 6. Likelihood functions for the number of sub-mm sources (from a total of 39) expected to lie in overdense galaxy regions. Three models are used to simulate the distribution of sub-mm sources. The solid line assumes a Poisson distribution, the dotted line represents a model with moderate angular clustering while the dashed line is based on simulations of strongly clustered sources (see Section 4). The arrow shows the observed number ($N = 24$) found for the combined data in the three fields.

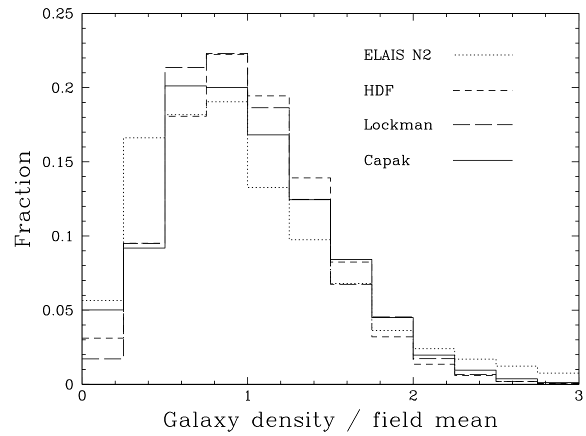

Figure 7. Histogram of galaxy densities in the three sub-mm fields to the optical depths described in Section 2.2, compared with those from a larger 0.2 deg^2 region from Capak et al. (2004). Histograms are based on 100 000 randomly placed apertures of 30-arcsec radius.

sampled by a small aperture should be slightly below the average field density.

As expected, the simulations with clustered sub-mm sources give a broader likelihood distribution for N. A simulation with strong clustering is more likely to place a large number of sub-mm sources together in an overdense region, or in a void. Nevertheless, the probability of observing $N \geqslant 24$ is still very small, regardless of the clustering strength. For a Poisson distribution $P(N \geqslant 24) = 0.08$ per cent. For the intermediate clustering model $P(N \geqslant 24) = 0.19$ per cent, rising to $P(N \geqslant 24) = 0.31$ per cent in the case of strong clustering. In conclusion, the probability of these results being produced by chance correlations is <0.4 per cent *even if sub-mm sources cluster as strongly as EROs*.

We can also use the distribution in Fig. 6 to estimate a lower limit on the number of sub-mm sources associated with low-z structure. We estimate this by removing sources in overdense regions until the probability of a chance alignment rises above 5 per cent. In the case of Poisson clustering, this occurs for $N < 20$ (four sources removed) while in the strong clustering model this occurs at $N < 21$ (three sources removed). Thus a conservative lower limit to the number of 'excess' SCUBA sources associated with low-z structure is 3/39 (8 per cent) at the 95 per cent confidence level.

5 GRAVITATIONAL LENSING BIAS

We have presented evidence for a significant angular correlation between SCUBA sub-mm sources and overdensities of optical galaxies at low redshift. In this section we argue that gravitational lensing bias provides a natural explanation for these effects, motivated by the particularly steep sub-mm source counts.

In a small solid angle, where the lensing magnification is given by μ, one can readily demonstrate that a population with cumulative number counts given by a power law of index β will be modified as follows:

$$N'(>S) = \mu^{\beta-1} N(>S). \qquad (1)$$

Observed sub-mm number counts have a slope with $\beta \simeq 2.5$, possibly steepening at $S_{850\,\mu m} > 8$ mJy (Scott et al. 2002). Foreground large-scale structure (e.g. galaxy groups and overdensities) can readily lead to a magnification of $\mu \simeq 1.1$–1.3 (Hamana, Martel & Futamase 2000). Thus in the vicinity of such structure one would *expect* an enhancement in number counts of 15–50 per cent. Calculating the full effects of lensing bias would require integrating over the full range of flux magnifications, allowing for the relative positions of sources and lenses, so we refer the reader to existing detailed models. These models predict that between a few per cent (Blain et al. 1999) and 30 per cent (Perotta et al. 2003) of sub-mm sources at $S_{850\,\mu m} > 10$ mJy will only be seen because of lensing bias, with the precise fraction depending strongly on the bright-end slope of the sub-mm luminosity function. These predictions are consistent with our findings.

6 IS ELAIS N2 AN UNUSUAL FIELD?

The ELAIS N2 field shows the most dramatic correlation between sub-mm sources and low-redshift galaxies. In this section we investigate the possibility that this may be an unusual field.

In Fig. 7 we compare the density histograms in the three fields, along with the distribution obtained from a much larger 0.2 deg^2 region from the Capak et al. (2004) HDF Subaru catalogue (see Section 2.2). This shows that the ELAIS N2 field does have a broader distribution of galaxy densities, consistent with a more strongly clustered population. An investigation of the galaxy–galaxy autocorrelation function confirms that this is the most strongly clustered field, with an autocorrelation amplitude approximately 40 per cent higher than an average blank field at $R < 23$ on 1-arcmin scales (Roche et al. 1996). From the compilation of clustering measurements given in Roche et al. (1996) we estimate that approximately 5–10 per cent of blank fields of this size would show galaxy clustering comparable to (or stronger than) ELAIS-N2 at $R < 23$. The galaxy number counts appear broadly normal, although they are approximately 2σ higher than average around $R = 20$–21.

In summary, the ELAIS-N2 field does not appear to be particularly unusual, but it does contain denser low-z structure than an average field (and the Lockman/HDF regions). We note that in the lensing model one would expect a stronger biasing signal in high-density regions, and our results are certainly consistent with such an interpretation. In turn, this could also explain the puzzling cross-correlation of sub-mm and X-ray sources in this field (Almaini et al. 2003). The hard X-ray sources are strong tracers of peaks in the density field at $z < 1$ (Elbaz & Cesarsky 2003; Gilli et al. 2003), and could therefore be tracing the foreground lensing structure.

On balance, however, we urge caution in over-interpreting these data, particularly given the relatively small number of sub-mm sources per field. An investigation using independent data over a much larger area is clearly required to overcome sample variance and investigate further. This may soon be possible with the SHADES survey (http://www.roe.ac.uk/ifa/shades/) or the future generation of surveys with SCUBA2 (Holland et al. 2003).

7 CONCLUSIONS

From an analysis of three bright, flux-limited surveys we find evidence for a significant angular correlation between SCUBA sub-mm sources and low-redshift galaxies. In particular, the distribution of sub-mm sources appears to be skewed towards overdense regions in the $R < 23$ galaxy population, consistent with 20–25 per cent of the sub-mm population being apparently associated with low-redshift structure, although there are strong field-to-field variations. In contrast, recent determinations of the $n(z)$ distribution for bright sub-mm sources suggest that at most only 5 per cent are found at $z < 1$ (Chapman et al. 2003). We note that the sub-mm sources used in our analysis span a similar range in flux density to the work of Chapman et al. (with strongly overlapping samples) so survey depth is unlikely to explain the difference.

Simulations suggest that the significance of these findings does not depend strongly on the intrinsic clustering strength of the sub-mm populations. Even for a population with an angular correlation function as strong as extremely red objects (EROs), the probability of obtaining these correlations by chance is less than 0.4 per cent. The simulations also provide a conservative lower bound of 8 per cent on the 'excess' fraction of sub-mm sources associated with low-z structure (at the 95 per cent significance level).

Interestingly, the signal appears to be dominated by the brightest sources with a flux density $S_{850\,\mu m} > 10$ mJy, although a larger sample will be required to investigate the precise relationship as a function of sub-mm flux.

We argue that these findings are consistent with the expectations of gravitational lensing bias, which is particularly strong in the bright sub-mm regime due to the unusually steep source number counts. These effects will have consequences for attempts to measure the intrinsic clustering of sub-mm sources, since the correlation function $w(\theta)$ will be enhanced by excess pairs in the vicinity of low-redshift structure (Moessner & Jain 1998). Large sub-mm surveys now underway, such at the SHADES survey, may be able to disentangle these effects by simply excluding sources which lie in the vicinity of low-z structure. Such techniques might also be used to estimate the true (unlensed) source number counts, which may be much steeper than presently accepted if the lensing bias is substantial. This could reflect a sharp turn-over in the underlying luminosity sub-mm function, and hence in the mass function of galaxies at high-redshift (Benson et al. 2003).

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REFERENCES

Alexander D. M. et al., 2003, AJ, 125, 383
Almaini O., Lawrence A., Boyle B. J., 1999, MNRAS, 305, L59
Almaini O. et al., 2003, MNRAS, 338, 303
Barger A. J., Cowie L. L., Sanders D. B., Fulton E., Taniguchi Y., Sato Y., Kawara K., Okuda H., 1998, Nat, 394, 248
Benson A. J., Bower R. G., Frenk C. S., Lacey C. G., Baugh C. M., Cole S., 2003, ApJ, 599, 38
Blain A. W., Moller O., Maller A. H., 1999, MNRAS, 303, 423
Borys C., Chapman S. C., Halpern M., Scott D., 2002, MNRAS, 330, 92
Borys C., Chapman S. C., Halpern M., Scott D., 2003, MNRAS, 344, 385
Capak P. et al., 2004, AJ, 127, 180
Chapman S. C., Smail I., Ivison R. J., Blain A. W., 2002, MNRAS, 335, L17
Chapman S. C., Blain A. W., Ivison R. J., Smail I., 2003, Nat, 422, 695
Clowe D., Luppino G. A., Kaiser N., Gioia I. M., 2000, ApJ, 539, 540
Daddi E., Cimatti A., Pozzetti L., Hoekstra H., Röttgering H. J. A., Renzini A., Zamorani G., Mannucci F., 2000, A&A, 361, 535
Dunlop J. S. et al., 2004, MNRAS, 350, 769
Eales S., Lilly S., Gear W., Dunne L., Bond J. R., Hammer F., Le Fèvre O., Crampton D., 1999, ApJ, 515, 518
Elbaz D., Cesarsky C. J., 2003, Sci, 300, 270
Fabian A. C. et al., 2000, MNRAS, 315, L8
Fischer P. et al., 2000, AJ, 120, 1198
Gilli R. et al., 2003, ApJ, 592, 721
Granato G. L., Silva L., Monaco P., Panuzzo P., Salucci P., De Zotti G., Danese L., 2001, MNRAS, 324, 757
Hamana T., Martel H., Futamase T., 2000, ApJ, 529, 56
Holland W. S., Duncan W., Kelly B. D., Irwin K. D., Walton A. J., Ade P. A. R., Robson E. I., 2003, SPIE, 4855, 1
Hornschemeier A. E. et al., 2001, ApJ, 554, 742
Hughes D. H. et al., 1998, Nat, 394, 241
Ivison R. J. et al., 2002, MNRAS, 337, 1
Lawrence A., 2001, MNRAS, 323, 147
Lilly S. J., Eales S. A., Gear W. K. P., Hammer F., Le Fèvre O., Crampton D., Bond J. R., Dunne L., 1999, ApJ, 518, 641
Magorrian J. et al., 1998, AJ, 115, 2285
Maiolino R., Salvati M., Bassani L., Dadina M., della Ceca R., Matt G., Risaliti G., Zamorani G., 1998, A&A, 338, 781
Manners J. C. et al., 2003, MNRAS, 343, 293
Moessner R., Jain B., 1998, MNRAS, 294, L18
Peacock J. A., Smith R. E., 2000, MNRAS, 318, 1144
Percival W. J., Scott D., Peacock J. A., Dunlop J. S., 2003, MNRAS, 338, L31
Perrotta F., Magliocchetti M., Baccigalupi C., Bartelmann M., De Zotti G., Granato G. L., Silva L., Danese L., 2003, MNRAS, 338, 623
Roche N., Shanks T., Metcalfe N., Fong R., 1996, MNRAS, 280, 397
Roche N. D., Almaini O., Dunlop J., Ivison R. J., Willott C. J., 2002, MNRAS, 337, 1282
Scott S. E. et al., 2002, MNRAS, 331, 817
Severgnini et al., 2000, A&A, 360, 457
Smail I., Ivison R. J., Blain A. W., 1997, ApJ, 490, L5.
Smail I., Ivison R. J., Blain A. W., Kneib J. P., 2002, MNRAS, 331, 495
Wang W. H., Cowie L. L., Barger A. J., 2004, ApJ, 613, 655
Waskett T. J. et al., 2003, MNRAS, 341, 1217
Webb T. M. et al., 2003, ApJ, 582, 6
Willott C. J. et al., 2003, MNRAS, 339, 397
Wolf C., Meisenheimer K., Rix H.-W., Borch A., Dye S., Kleinheinrich M., 2003, A&A, 401, 73

APPENDIX A: MONTE CARLO SIMULATIONS OF 2D CLUSTERED POPULATIONS

There are many ways to simulate a clustered galaxy population. We conduct our simulations using a modification of the halo model of Peacock & Smith (2000), adapting it to the two-dimensional regime. Specifically we wish to simulate a distribution of sources with an angular correlation function of the form:

$$w(\theta) = (\theta/\theta_0)^{-\gamma}. \quad \text{(A1)}$$

We assume that galaxies live in circularly symmetric haloes of angular radius $\phi_{\rm H}$ with radial density profiles of the form $\rho \propto r^{-\epsilon}$. By placing down halo centres at random it can be shown (see Peacock & Smith 2000) that the resulting population will have an angular correlation function with slope $\gamma = 2\epsilon - 2$. To reproduce the standard observed slope of angular clustering ($\gamma = 0.8$) we therefore require a halo density profile of the form

$$\rho \propto r^{-1.4}. \quad \text{(A2)}$$

The haloes are then populated with randomly placed galaxies according to this density distribution. Correlated pairs only occur within a given halo, so the amplitude of the correlation function will be diluted by the number of randomly placed haloes. It can be shown that a correlation function of the form given in equation (A1) can be produced if the number density of haloes is given by:

$$N = 0.2266\ \phi_{\rm H}^{-2}(\theta_0/\phi_{\rm H})^{-\gamma}. \quad \text{(A3)}$$

The number of galaxies per halo is then chosen to ensure the desired surface density for the full Monte Carlo simulation. The choice of halo radius ($\phi_{\rm H}$) is somewhat arbitrary, but to ensure that the two-point function has the correct form on the 30-arcsec scales probed by our analysis we choose values of $\phi_{\rm H}$ in the range $\phi_{\rm H} \sim 3$–$10\ \theta_0$, corresponding to 1–9 arcmin given the correlation lengths used in Section 4. Comparing these simulations we found that the precise choice of $\phi_{\rm H}$ made no difference to the output density histograms.

Finally we ensure that the simulated box is sufficiently padded, with halo centres placed up to a radius Φ_H outside the survey region to be simulated. Tests are then conducted to ensure that the mock catalogues generated by this procedure have the desired correlation function $w(\theta)$.

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