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RADIO CONSTRAINTS ON THE IDENTIFICATIONS AND REDSHIFTS OF SUBMM GALAXIES

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ABSTRACT

We present deep radio maps from the Very Large Array (VLA) for 16 sources detected in a sub-millimeter (submm) survey of the distant Universe. Our deep VLA 1.4-GHz maps allow us to identify radio counterparts or place stringent limits ($\lesssim 20\mu$Jy in the source plane) on the radio flux of the submm sources. We compare the spectral indices of our sources between 850 μm and 1.4 GHz to empirical and theoretical models for distant starburst galaxies and active galactic nuclei (AGN) as a function of redshift. In this way we can derive redshift limits for the submm sources, even in the absence of an optical or near-infrared counterpart. We conclude that the submm population brighter than ~ 1 mJy has a median redshift of *at least* $<z>\sim 2$, more probably $<z>\sim$ 2.5–3, with almost all galaxies at $z \gg 1$. This estimate is a strong lower limit as both misidentification of the radio counterparts and non-thermal emission from an AGN will bias our redshift estimates to lower values. The high median redshift means that the submm population, if predominately powered by starbursts, contributes a substantial fraction of the total star formation density at high redshifts. A comparison of the spectral index limits with spectroscopic redshifts for proposed optical counterparts to individual submm galaxies suggests that half of the submm sources remain unidentified and thus their counterparts must be fainter than $I \gtrsim 24$.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — infrared: galaxies — radio: galaxies

1. INTRODUCTION

Faint submm sources are likely to be highly obscured starburst galaxies and AGN, where optical/UV radiation from massive stars or an active nucleus is absorbed by dust and reradiated in the far-infrared. The dust emission peaks at $\lambda \sim 100\mu$m and so long-wavelength observations of distant dusty galaxies can benefit as this peak is redshifted into their window. At 850 μm, this increase balances the geometrical dimming at higher redshifts, resulting in a constant flux density out to $z \sim$ 5–10 and the opportunity to select very high redshift galaxies.

A number of deep submm surveys have been published (Smail, Ivison & Blain 1997; Barger et al. 1998, 1999b; Hughes et al. 1998; Blain et al. 1999a; Eales et al. 1999) providing counts which are in good agreement at 850-μm flux densities above 2 mJy (the confusion limit of the blank-field surveys). The surface density of submm galaxies reaches ~ 2 per sq. arcmin by 1 mJy (Blain et al. 1999a). If these galaxies lie at $z \gtrsim 1$, then they have bolometric luminosities of $\gtrsim 10^{12}L_{\odot}$ and they are the distant analogs of the local ultraluminous infrared galaxy (ULIRG) population. However, the observed surface density of submm galaxies is several orders of magnitude greater than that expected from the local ULIRG population (Smail et al. 1997) indicating very substantial evolution of these systems in the distant Universe. The integrated emission from this population can account for the bulk of the extragalactic background detected at 850 μm by *COBE* (e.g. Fixsen et al. 1998), and so confirms these galaxies as an important source of radiation in the Universe (Blain et al. 1999a, 1999b).

To identify the era of obscured emission in the Universe, whether from AGN or starbursts, we have to measure the redshifts of a complete sample of submm galaxies. Several groups have attempted this (Hughes et al. 1998; Barger et al. 1999a; Lilly et al. 1999). Hughes et al. (1998) concluded that the bulk of the population is at $z \sim$ 2–4, based on photometric redshift limits for the probable counterparts of five submm sources in the *Hubble Deep Field* (HDF, c.f. Richards 1999 and Downes et al. 1999). Barger et al. (1999a) undertook a spectroscopic survey of the same submm sample analysed here and concluded that the median redshift was $<z>\sim$ 1.5–2, with the bulk of the population having $z \sim$ 1–3. Finally, Lilly et al. (1999) used archival spectroscopy and broad-band photometry of submm sources from the Eales et al. (1999) survey to claim that the population spans z = 0.1–3, with a third at $z < 1$. The differences between these studies are significant and important for our understanding of the nature of submm galaxies.

It is very difficult to achieve high completeness in optical spectroscopic surveys of submm galaxies (e.g. Barger et al. 1999a) due to the very different behaviour of the K corrections for distant galaxies between submm and optical passbands. However, even a crude estimate of the median redshift of a *complete* sample of submm galaxies would provide a powerful insight into the relative dominance of obscured and unobscured emission at different epochs (Blain et al. 1999b).

In a recent paper, Carilli & Yun (1999, CY) demonstrated that using the spectral index between the submm (850 μm) and radio (1.4 GHz) wavebands, $\alpha^{850}_{1.4} = 0.42\log_{10}(S_{850}/S_{1.4})$, it was possible to obtain crude redshift limits for distant dusty galaxies, irrespective of the nature of the emission mechanism, AGN

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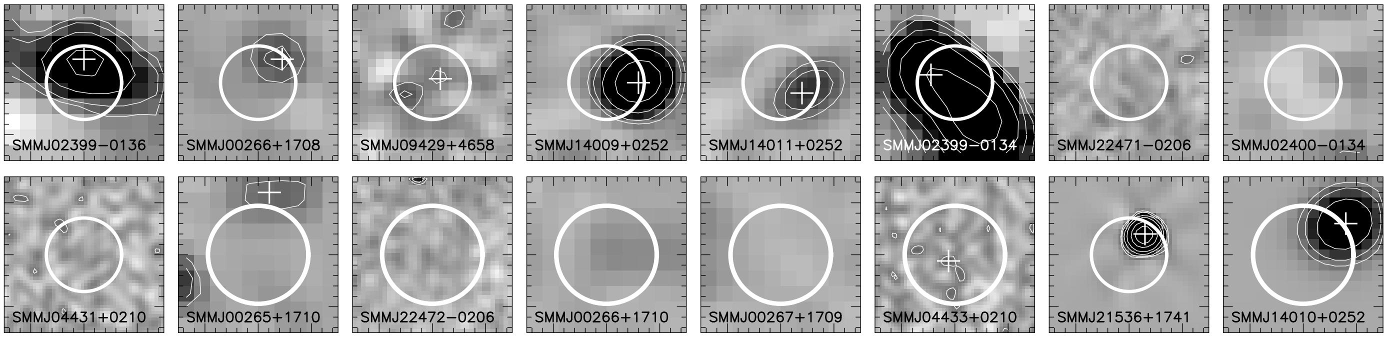

Fig. 1. 15×15 arcsec VLA maps of the 16 submm sources for which we have radio observations. These are ordered as in Table 1 and the maps span a range in sensitivity and resolutions (§2.1). The panels are centered on the nominal submm position in each case and we show the typical error boxes for the sources. We mark the radio counterpart by a + where they are identified. The panels have north top and east left and correspond to $\gtrsim 100h_{50}^{-1}$ kpc at $z > 1$. The contour levels are at apparent 1.4-GHz flux densities of 3, 5, 10, 20, 50, 100× the map noise listed in §2.1 (except for SMM J21536+1741 and SMM J14010+0252 where they are 100× these values).

or starburst. CY employed a number of theoretical and empirical spectral energy distributions (SEDs) to investigate the range in $\alpha_{1.4}^{850}$ for different assumed SEDs and showed that these models adequately described the small sample of high-redshift galaxies for which both radio and submm observations were available. As pointed out by Blain (1999, B99), if we adopt lower dust temperatures for the submm population than are seen in the local sources used in CY's models, then the allowed range of redshifts is slightly lower for a given value of $\alpha_{1.4}^{850}$. Nevertheless, the modest scatter between the models in CY suggests that this technique can provide useful limits on the redshifts of submm galaxies in the absence of an optical counterpart.

In this paper we apply the CY analysis to deep radio observations of a complete sample of submm galaxies selected from the SCUBA Cluster Lens Survey (Smail et al. 1998). Our aim is to constrain the redshift distribution of this population and in the process test the optical identifications and spectroscopic redshifts from Smail et al. (1998) and Barger et al. (1999a). We present the observations and their analysis in §2, discuss our results in §3 and give our main conclusions in §4.

2. OBSERVATIONS, REDUCTION AND ANALYSIS

The 850-μm maps on which our survey is based were obtained using the long-wavelength array of the Sub-millimeter Common-User Bolometer Array (SCUBA, Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT)[8]. The details of the observations, their reduction and analysis are given in Smail et al. (1997, 1998) and Ivison et al. (1998). Each field covers an area of 5.2 arcmin^2 with a typical 1σ sensitivity of $\sim$1.7 mJy, giving a total survey area of 0.01 deg^2. The median amplification by the cluster lenses for background sources detected in our fields is expected to be $2.5^{+5.0}_{-1.5}$ (Blain et al. 1999a; Barger et al. 1999a), and so we have effectively surveyed an area of about 15 arcmin^2 in the source plane to an equivalent 1σ sensitivity of 0.7 mJy. The follow-up of these submm sources also benefits from the achromatic amplification, which boosts the apparent brightness of counterparts in all other wavebands.

2.1. *Radio Observations*

All the radio maps used in this work were obtained with the VLA[9] at 1.4 GHz in A or B configuration, giving effective resolutions of 1.5″ and 5″, respectively. More details of the reduction and analysis of these maps are given in the following references (we list the VLA configuration and 1σ map noise for each cluster): Morrison et al. (1999) for Cl 0024+16 (B/15 μJy), A 370 (B/10 μJy) and Cl 0939+47 (B/9 μJy); Ivison et al. (1999) for A 1835 (B/16 μJy) and Ivison et al. (2000) for MS 0440+02 (A/15 μJy) and Cl 2244–02 (A/17 μJy). No deep radio map is available for A 2390, although shallower observations were used to study the submm/radio spectral index of the central cluster galaxy (Edge et al. 1999).

Radio counterparts were searched for around the nominal positions of the submm sources based on the SCUBA astrometry and 2σ error-boxes of 6″ or 8″ diameter depending upon whether the submm source was respectively a 4σ or 3σ detection (Fig. 1). The size of these error-boxes includes both the systematic and random errors in the source positions and they have been confirmed as realistic using two sources with CO interferometric observations (Frayer et al. 1998, 1999). To assign radio fluxes to the individual submm sources we have adopted the conservative approach of identifying the radio counterpart as the brightest radio source within the submm error-box (Fig. 1). The behaviour of the radio-submm spectral index is such that a brighter radio counterpart leads to a lower redshift estimate. Thus by selecting the brightest available radio source, we should obtain a lower bound on the redshift of the submm source. Apparent radio fluxes or 3σ limits are listed in Table 1. Note that a faint radio source lies just outside the error-box of SMM J00265+1710, and so we adopt the radio flux of that source as a lower limit in this case. For SMM J02399–0134, the radio counterpart is confused due to emission from a nearby bright cluster elliptical (Fig. 1), and so we only quote an approximate 1.4-GHz flux for this galaxy.

2.2. *Radio-Submm Spectral Indices*

The 850-μm and 1.4-GHz fluxes or limits for 16 of the sources in Smail et al. (1998), for which we have radio observations, are listed in Table 1 in order of their apparent submm fluxes, along with their proposed spectroscopic redshifts, z_{spec}, from Barger et al. (1999a). Where a radio counterpart is identified the spectroscopic redshift of the closest optical candidate is listed in the table. The errors on $\alpha_{1.4}^{850}$ are calculated assuming the 1σ flux uncertainties in each band (§2.1 and Smail et al. 1998). For non-detections at 1.4 GHz we use the 3σ flux limit of the relevant radio map. Using the $\alpha_{1.4}^{850}$ values, the redshift ranges, z_α, are derived from the extremes of the predictions

[8]The JCMT is operated by the Joint Astronomy Centre on behalf of the United Kingdom Particle Physics and Astronomy Research Council, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

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TABLE 1
Spectral Properties of the Submm Sample

Submm Source	S_{850} (mJy)	$S_{1.4}$ (μJy)	$\alpha^{850}_{1.4}$	z_α	$z^d_{\rm spec}$ Reliable	$z^d_{\rm spec}$ Uncertain	Comments
4σ Detections							
SMM J02399–0136	25.4	526	0.70 ± 0.02	1.1–2.9	2.80	···	L1/L2 – Seyfert 2 merger[a]
SMM J00266+1708	18.6	100	0.95 ± 0.04	2.0–4.5	···	0.44	M8 – 1″ away from radio source
SMM J09429+4658	17.2	32	1.14 ± 0.07	>3.9	···	···	H5 – ERO[b]
SMM J14009+0252	14.5	529	0.60 ± 0.03	0.7–2.3	···	···	J5[c] – no spectroscopic observation
SMM J14011+0252	12.3	115	0.85 ± 0.05	1.7–3.8	2.55	···	J1/J2 – starburst merger[c]
SMM J02399–0134	11.0	∼500	0.55 ± 0.04	0.6–2.1	1.06	···	L3 – Seyfert 1.5/2 ring galaxy[e]
SMM J22471–0206	9.2	<65	$> 0.90 \pm 0.08$	>1.8	···	1.16	P4 – weak AGN?
SMM J02400–0134	7.6	<33	$> 0.99 \pm 0.11$	>2.4	···	···	Optical blank field[f]
SMM J04431+0210	7.2	<70	$> 0.84 \pm 0.10$	>1.6	···	···	N4 – ERO[b]
3σ Detections							
SMM J21536+1742	6.7	···	···	···	···	1.60?	No deep radio map
SMM J00265+1710	6.1	≤110	$\geq 0.73 \pm 0.07$	>1.2	···	0.21	M6/M10 – radio ID outside error-box
SMM J22472–0206	6.1	<50	$> 0.87 \pm 0.12$	>1.7	···	2.11?	P2
SMM J00266+1710	5.9	<33	$> 0.93 \pm 0.12$	>2.9	···	0.94	M3 – faint radio source at map limit?
SMM J00267+1709	5.0	<30	$> 0.92 \pm 0.13$	>1.9	···	···	Optical blank field[f]
SMM J04433+0210	4.5	70	0.75 ± 0.12	1.3–3.2	···	···	No spectroscopic observation
Cluster Galaxies							
SMM J21536+1741	9.1	226×10^3	-0.58 ± 0.05	···	0.23	···	cD – central galaxy in A 2390[g]
SMM J14010+0252	5.4	28.6×10^3	-0.30 ± 0.06	···	0.25	···	cD – central galaxy in A 1835[g]

REFERENCES.— *a*) Ivison et al. (1998) – *b*) Smail et al. (1999) – *c*) Ivison et al. (1999) – *d*) Barger et al. (1999a) – *e*) Soucail et al. (1999) – *f*) Smail et al. (1998) — *g*) Edge et al. (1999).

from the four CY models and a further model from B99, with a dust temperature of 30 K to illustrate the minimum possible redshift assuming a very low T_d. The two central cluster galaxies in our sample are not included in our analysis.

There are three caveats to bear in mind when using $\alpha^{850}_{1.4}$ to estimate redshifts for distant galaxies. First, most of the distant galaxies which CY used to compare with their model predictions show some signs of AGN activity. If these AGN also contribute to the 1.4-GHz non-thermal emission of the galaxy they will lower the observed $\alpha^{850}_{1.4}$ values (as some obviously do in Fig. 1a of CY). This will mean that any radio-quiet submm sources could lie at the high end of the predicted $\alpha^{850}_{1.4}$ range at each epoch. Secondly, the CY and B99 models we use assume effective dust temperatures for the galaxies, $T_{\rm d} \gtrsim 30$ K. If the dust in distant dusty galaxies is much cooler then this, it will again shift the predicted redshifts systematically lower (see B99). Finally, as mentioned in CY99, the effects of inverse Compton scattering of radio photons off the microwave background may reduce the radio luminosities of star-forming galaxies at $z \gtrsim 3$ and hence increase $\alpha^{850}_{1.4}$ for the most distant galaxies. Nevertheless, the relatively good agreement shown in CY of the spectral indices of distant galaxies with the models is an important confirmation that $\alpha^{850}_{1.4}$ indices can be used to derive robust lower limits to the redshifts of submm sources without reliable spectroscopic identifications.

3. RESULTS AND DISCUSSION

We show in Fig. 2 three cumulative redshift distributions for the population representing extreme interpretations of the z_α limits from the spectral index models. We see that even making the most conservative assumptions about the likely redshifts from the $\alpha^{850}_{1.4}$ indices we still predict a *median* redshift for the submm population above an intrinsic 850-μm flux of 1 mJy of $< z > \sim 2$, and probably closer to $z \sim 2.5$–3.

Comparing the cumulative redshift distribution to that derived from the (incomplete) spectroscopic study of this sample (Barger et al. 1999a) we see broad similarities. However, comparison of redshifts for individual sources from the two studies (Table 1), while showing good agreement for those submm sources with reliable identifications (e.g. Ivison et al. 1998, 1999) also indicates that the majority of the uncertain spectroscopic IDs are likely to be incorrect. Barger et al. (1999a) obtained spectroscopy of most of the possible counterparts within each submm error-box. We can therefore state that the true submm sources must be fainter than the faintest spectroscopic target. Including the two optical blank-field sources already known (Smail et al. 1998), we conclude that approximately half of the submm population are therefore currently unidentified. These submm sources have no radio counterparts and are too faint for optical spectroscopy, $I \gtrsim 24$, their identification will thus be very difficult.

Our median redshift is compatible with the results of Hughes et al. (1998) and CY for the five submm sources in the HDF based on analyses of their SEDs and radio-submm indices. Compared to the only other submm survey for which spectroscopic redshift information has been published — for the Eales et al. (1999) sample by Lilly et al. (1999) — we again see a median redshift, $< z > \sim 2$, similar to that determined here. However, Lilly et al. (1999) claim that a third of the submm population lies at $z < 1$; in contrast, we find no galaxies in our field sample at $z < 1$. This apparent contradication may result simply from the small sizes of the current samples or might indicate that foreground bright optical galaxies maybe lensing the distant submm sources detected in the field surveys (see Blain, Möller & Maller 1999; Hughes et al. 1998).

The detection rate of radio counterparts to the submm sources is higher for the intrinsically brighter sources. All the submm sources with observed fluxes above ~ 10 mJy (intrinsic fluxes of $\gtrsim 4$ mJy) have radio counterparts, while the majority of the fainter sources do not (this is consistent with CY's results in the HDF). The detections and astrometry of the fainter sources are sufficiently reliable that this result is not due to spurious detections (see Ivison et al. 1999).

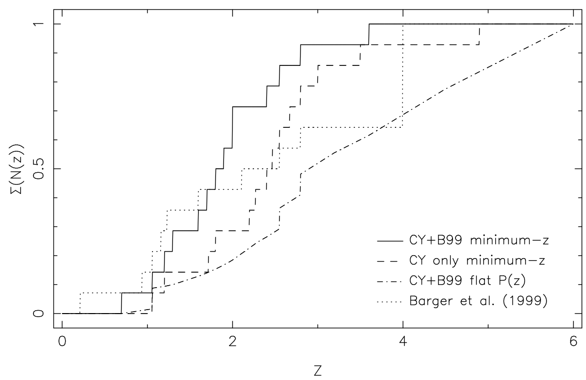

Fig. 2. The cumulative redshift distribution for the full submm sample. We have used the spectroscopic redshifts of those sources thought to be reliable (Table 1) and combined these with the probable redshift ranges of the remaining sources derived from their $\alpha^{850}_{1.4}$ indices or limits. The solid line shows the cumulative distribution if we assume the minimum redshift distribution which is obtained if *all* sources are assumed to lie at their lower z_α limit given in Table 1 (the dashed line is the equivalent analysis but restricted to just the CY models). The effect of non-thermal radio emission, which drives down the $\alpha^{850}_{1.4}$ indices, means that this is a very conservative assumption if some fraction of the population harbor radio-loud AGN. The dot-dashed line assumes a flat probability distribution for the sources within their z_α ranges and a maximum redshift of $z = 6$ for those sources where we only have a lower limit on $\alpha^{850}_{1.4}$. Finally, the dotted line is the cumulative redshift distribution from Barger et al. (1999a) with two of the source identifications corrected as in Smail et al. (1999) and all blank-field/ERO candidates placed at $z = 4$.

Making the conservative assumption of placing all of the non-detections at their lower bounds on $\alpha^{850}_{1.4}$, we find that this distribution is consistent with being drawn from the $\alpha^{850}_{1.4}$ distribution of the brighter sources with a probability of $P \sim 0.4$. However, simply comparing the $\alpha^{850}_{1.4}$ indices for the two subsamples we see that half of the radio-detected bright submm sources have $\alpha^{850}_{1.4}$ values lower than the lowest limit on the undetected sources, the likelihood that this occurs by chance is only $P \sim 3 \times 10^{-4}$ suggesting that there may be real differences between the $\alpha^{850}_{1.4}$ values for the two subsamples. Several factors could cause this difference, most simply the apparently fainter submm sources may be at higher redshifts (a correlation which could naturally exist in a low density Universe). Alternatively, intrinsic differences in the spectral indices of fainter sources would occur if they contain a lower fraction of radio-loud AGN or have typically cooler dust temperatures. Both effects are plausible given what we know about the correlations of AGN fractions and dust temperature with luminosity in local ULIRG samples (Sanders & Mirabel 1996). Further detailed observations of both distant and local ULIRGs are needed to distinguish between these possibilities.

The relatively high median redshift we find for the submm population, $<z> \sim 2$–3, indicates that their equivalent star formation density at these epochs is around $0.5\,M_\odot$ yr^{-1} Mpc^{-3} (Blain et al. 1999a), roughly three times that seen in UV-selected samples (Steidel et al. 1999). Emission from dust heated by obscured AGN will reduce this estimate, but it is hard not to conclude that the submm galaxies contain a substantial fraction of the star formation in the high redshift Universe. The absence of radio counterparts for the fainter submm sources means that searches for distant dusty starbursts using radio samples will give a very biased view of the population.

4. CONCLUSIONS

- We present radio maps of 16 galaxies selected in a deep submm survey. We combine submm and radio fluxes (or limits) to determine the radio-submm spectral indices of these galaxies and interpret these using model predictions to derive the redshifts for a complete sample of faint submm galaxies.
- We find a median redshift $<z> \sim 2$ for the submm population down to $S_{850} \sim 1$ mJy under conservative assumptions, and $<z> \sim 2.5$–3 for more reasonable assumptions. Median redshifts below $<z> \ll 2$ are only possible if the bulk of the emission is coming from dust at $\ll 30$ K (compared to the 40–50 K typically seen in well-studied, distant submm galaxies, or their low-redshift analogs: ULIRGs). As a result we find no evidence for a significant low-redshift, $z < 1$, tail in our distribution in contrast to Lilly et al. (1999).
- We compare the individual redshifts estimated from $\alpha^{850}_{1.4}$ with the spectroscopic observations of proposed optical counterparts of the submm sources. We find that the majority of the 'uncertain' spectroscopic identifications from Barger et al. (1999a) are likely to be incorrect. We conclude that the true counterparts lie at higher redshifts and are intrinsically very faint, $I \gtrsim 24$, making the prospects for a complete optical spectroscopic survey of the submm population bleak.

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