A robust sample of submillimetre galaxies: constraints on the prevalence of dusty, high-redshift starbursts

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ABSTRACT
The modest significance of most sources detected in current (sub)millimetre [(sub)mm] surveys can potentially compromise some analyses due to the inclusion of spurious sources in catalogues typically selected at \( \geq 3.0–3.5\sigma \). Here, we develop and apply a dual-survey extraction technique to Submillimetre Common-User Bolometer Array (SCUBA) and Max-Planck Millimetre Bolometer (MAMBO) images of the Lockman Hole. Cut above 5\( \sigma \), our catalogue of submillimetre galaxies (SMGs) is more robust than previous samples, with a reduced likelihood of real, but faint SMGs (beneath and around the confusion limit) entering via superposition with noise. Our selection technique yields 19 SMGs in an effective area of 165 arcmin\(^2\), of which we expect at most two to be due to chance superposition of SCUBA and MAMBO noise peaks. The effective flux limit of the survey (\( \sim 4\) mJy at \( \sim 1\) mm) is well matched to our deep 1.4-GHz image (\( \sigma = 4.6\) \(\mu\)Jy beam\(^{-1}\)). The former is sensitive to luminous, dusty galaxies at extreme redshifts whilst the latter probes the \( z \lesssim 3\) regime. A high fraction of our robust SMGs (\( \sim 80\) per cent) have radio counterparts which, given the \( \sim 10\) per cent contamination by spurious sources, suggests that very distant SMGs (\( z \gg 3\)) are unlikely to make up more than \( \sim 10\) per cent of the bright SMG population. This implies that almost all of the \( S_{1\text{mm}} \gtrsim 4\) mJy SMG population is amenable to study via the deepest current radio imaging. We use these radio counterparts to provide an empirical calibration of the positional uncertainty in SMG catalogues. We then go on to outline the acquisition of redshifts for radio-identified SMGs, from sample selection in the submm, to counterpart selection in the radio and optical/infrared, to slit placement on spectrograph masks. We determine a median of \( z = 2.05 \pm 0.41\) from a sample of six secure redshifts for unambiguous radio-identified submm sources and \( z = 2.14 \pm 0.27\) when we include submm sources with multiple radio counterparts and/or less reliable redshifts. These figures are consistent with previous estimates, suggesting that our knowledge of the median redshift of bright SMG population has not been biased by the low significance of the source catalogues employed.

Key words: galaxies: formation – galaxies: starburst – cosmology: observations – early Universe.

1 INTRODUCTION
Surveys with bolometer arrays at millimetre (mm) and submillimetre (submm) wavelengths are potentially sensitive to dusty objects at extreme redshifts, galaxies that drop out of surveys at shorter and longer wavelengths due to obscuration and unfavourable K corrections. The first cosmological surveys using Submillimetre Common-User Bolometer Array (SCUBA) (Holland et al. 1999) and MAMBO (Kreysa et al. 1998) quickly and radically changed the accepted picture of galaxy formation and evolution, moving away from the

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optocentric view of the last century. The discovery of so-called
‘SCUBA galaxies’ (Smail, Ivison & Blain 1997) was greeted with
surprise due to the remarkable evolution in the dusty, starburst
galaxy population implied by such a large source density at the flux
levels accessible to the first generation of bolometer arrays (Blain
et al. 1999). Success was replaced by pessimism with the first
efforts to study submillimetre galaxies (SMGs) at optical and in-
frared (IR) wavelengths: early reports, backed up with a study in
the Hubble Deep Field-North by Hughes et al. (1998), suggested
that the majority of the submm population had no plausible optical
counterparts. Attention was diverted to various redshift engines
and broad-band photometric techniques (e.g. Townsend et al. 2001;
Aretxaga et al. 2003; Wiklind 2003). As a result, only a handful
of detailed studies were attempted, often for extreme and possibly
unrepresentative galaxies (e.g. Knudsen et al. 2003).

Recent progress has largely been the result of radio imaging of
submm survey fields. Early radio follow-up detected roughly half
of the submm sources observed (Smail et al. 2000; Ivison et al.
2002, hereafter I02), with an astrometric precision of ∼0.3 arcsec
and, combined with the submm flux density, provide a rough es-
timate of redshift (Carilli & Yun 1999). Radio data also enabled
some refinement of submm samples (I02), increasing the detection
fraction to two-thirds of SMGs at 0.85-mm flux density levels in
excess of ∼5 mJy. With positions in hand, these bright SMGs were
found to be a diverse population – some quasar-like, with broad
lines and X-ray detections (e.g. Ivison et al. 1998), some morpho-
logically complex (e.g. Ivison et al. 2000; cf. Downes & Solomon
2003; Smill, Smith & Ivison 2005), some extremely red (e.g. Smail
et al. 1999; Gear et al. 2000; I02; Webb et al. 2003b; Dunlop et al.
2004), some with the unmistakable signatures of obscured active
nuclei and/or superwinds (e.g. Smail et al. 2003).

Spectroscopic redshifts have been difficult to determine. The first
survey based on a submm/radio sample was undertaken by Chap-
man et al. (2003, 2005, hereafter C03, C05): the median redshift
was found to be ∼2.2 for S_{0.85 \text{ mm}} > 5-mJy galaxies selected us-
ing SCUBA and pinpointed at 1.4 GHz. The accurate redshifts re-
ported by C03 and C05 facilitated the first systematic measurements
of molecular gas mass for SMGs (∼10^{11} \text{ M}_\odot) via observations
of CO (Neri et al. 2003; Greve et al. 2005), as well as constraints on
gas-reservoir size and dynamical mass (Tacconi et al. 2005). The
data suggest SMGs are massive systems and provide some of the
strongest tests of galaxy formation models to date (Greve et al.
2005).

In spite of this progress, a detailed understanding of SMGs re-
 mains a distant goal. Confusion currently limits our investigations
to the brightest SMGs (although surveys through lensing clusters
have provided a handful of sources more typical of the faint pop-
ulation that dominates the cosmic background – Smail et al. 2002;
Borys et al. 2004; Kneib et al. 2004). We must also recall that selec-
tion biases have potentially skewed our understanding: around half
of all known SMGs remain undetected in the radio (due simply to
the lack of sufficiently deep radio data, which do not benefit from
the same K correction as submm data) and the radio-undetected
fraction remains largely unaffected by existing spectroscopic cam-
paigns. This is also only limited coverage of red and IR wavelengths
in spectroscopic surveys.

Here, we present a robust sample of bright SMGs selected using
SCUBA and MAMBO in one of the ‘8-mJy Survey’ regions: the
Lockman Hole (see Fox et al. 2002; I02; Scott et al. 2002; Greve et al.
2004; Mortier et al. 2005). Our goal is to provide a bright sample
which we would expect to detect in well-matched radio imaging
(σ_{0.85 \text{ mm}}/σ_{1.4 \text{ GHz}} ∼ 500) whilst minimizing, so far as is practicable,
the possibility that sources are spurious or anomalously bright. We
may thus determine the true fraction of radio drop-outs amongst
SMGs (potentially lying at very high redshift, z \gg 3), as well as
practical information such as the intrinsic positional uncertainty for
SMGs in the absence of radio/IR counterparts.

Throughout we adopt a cosmology, with Ω_m = 0.3, Ω_A = 0.7
and \text{H}_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}.

2 SAMPLE SELECTION

2.1 Strategy

Existing surveys have typically employed a signal-to-noise ratio
(S/N) threshold of 3.0–3.5. At these S/Ns, false detections are dom-
inated by ‘flux boosting’ (Section 2.2), possibly at the 10–40 per cent
level (Scott et al. 2002; Laurent et al. 2005). Our goal is to provide
a highly reliable submm source catalogue, free from concerns about
contamination by spurious or artificially bright sources. This issue
has limited our ability to address the true recovery fraction in the
radio, and hence the corrections that must be made to the redshift
distributions that are used to determine star formation histories and
galaxy formation models.

To achieve this we have combined independent submm and mm
maps of the Lockman Hole, constructing a single, reliable catalogue
that is several times larger than would have been realised by simply
adopting a high S/N threshold in the individual submm and mm
maps. Greve et al. (2004) argued that several maps with low S/N
of the same region, with only marginal differences in frequency,
produce several visualizations of essentially the same sky, tracing
the same population of luminous, dust-enshrouded galaxies and we
have adopted the same philosophy in the present work.

2.2 Practicalities

Our maps came from the survey of Greve et al. (2004) who presented
a 1.2-mm map of the Lockman Hole region (as well as data on the
ELAIS N2 region), centred on the coordinates mapped at 0.85 mm
by SCUBA in the ‘8-mJy Survey’ (Scott et al. 2002; Scott 2004).
Mortier et al. (2005) have recently presented a refined analysis of
SCUBA data which lies within the Lockman Hole MAMBO map;
we began with a 2σ MAMBO catalogue, extracted as described by
Greve et al. (2004), and looked for 0.85-mm sources within 14 arcsec
(roughly the area of five beams) in the Mortier et al. (2005) sample,
applying a correction for separation and checking for a combined
significance above our initial threshold, 4.5σ. We included sources
that exceed 4.5σ in either data set, as long as there is a valid reason
why the source is not seen in the other images. SMGs from Scott et al.
(2002) were substituted where blends were evident in the Mortier
et al. (2005) catalogue.

The noise properties of submm images are not Gaussian due to the
myriad of real, faint sources near the confusion limit. The most im-
portant effect of increasing the S/N threshold should be to drastically
reduce the false detections due to faint SMGs that have been boosted
above the detection threshold by noise – flux boosting, see Scott
et al. (2002) and Greve et al. (2004). However, with so many \gtrsim 2σ
sources in our catalogues, it was important to investigate how many
SMGs may have contaminated our combined sample due to random
coincidence of faint MAMBO and SCUBA peaks. To this end, we
performed simulations, offsetting the MAMBO sample by \pm 30 and
\pm 45 arcsec [in right ascension (RA) and declination (Dec.)]. Each
simulation typically yielded 10 SMGs – far too many to hope that
a statistically robust catalogue would emerge from the process. The
Ar obust sample of submillimetre galaxies

MonteCarlo sampl e
No offsets applied

Figure 1. Left-hand panels: positional offsets between SCUBA and MAMBO peaks for spurious (top) and real (bottom) catalogues with a combined significance above 4.5σ. Larger symbols represent a higher combined S/N. Spurious sources were generated by offsetting MAMBO catalogue positions by ±30 and ±45 arcsec (in RA and Dec.). Histograms show the radial offset (r = \sqrt{(\Delta \alpha^2 + \Delta \delta^2)}) between SCUBA and MAMBO peaks for spurious (top, normalized to one simulation) and real (bottom) catalogues. Right-hand panels: the same plots, after application of the selection filters described in Section 2.2.

results of these simulations are illustrated in Fig. 1. The simulated catalogues clearly yield a very different distribution of offsets from the position-matched data, closer to the form expected for randomly scattered peaks (n ∝ r²), and without the expected concentration of high-S/N pairs at low r.

Using the information in these plots we took a number of approaches to minimize the number of spurious SMGs in our sample. We found that raising the minimum catalogue threshold to ⩾2.5σ reduced the number of false detections whilst having no effect on the real catalogue. Lowering the search radius to 11 arcsec reduced the number of false positives in line with the ratio of the respective search areas, removing only one source from the real catalogue. Insisting that the higher of the two peaks was ⩾3.5σ removed a further quarter of the simulated SMGs, whilst reducing the real catalogue by half that amount. Finally, we increased the combined threshold to ⩾5σ. The effects of this approach on the SCUBA–MAMBO positional offsets are shown in the right-hand set of panels of Fig. 1. We were left with a catalogue of 19 SMGs, of which we expect at most two to be the result of chance superposition of SCUBA and MAMBO noise peaks. This compares well with the sample of seven that would have resulted from adopting a ⩾5σ threshold in any one image. We list the resulting 19 sources in Table 1.

We note that all four of the SCUBA sources detected individually above 5σ are also found in the MAMBO image with a S/N of at least 2.0, although one is below 2.5σ and has thus been excised from our final sample. Of the six ⩾5σ MAMBO sources, all those that fall within the original 8-mJy Survey region were detected by SCUBA at ⩾2.5σ. LH 1200.004, which lies off the 8-mJy Survey SCUBA map, to the east, was subsequently detected by the SCUBA Half-Degree Extragalactic Survey (SHADES) survey (Dunlop 2005; http://www.roe.ac.uk/ifa/shades).

3 IDENTIFICATION OF THE SUBMILLIMETRE GALAXIES IN THE RADIO

The process of identifying counterparts to SMGs has been refined in a series of studies (Ivison et al. 1998, 2000, 2002, 2004; Smail et al. 1999, 2000; Webb et al. 2003a,b; Borys et al. 2004; Clements et al. 2004; Pope et al. 2005). The most effective methods employ radio, optical, near-IR and mid-IR imaging, either individually or in combination. These techniques rely upon identifying the red rest-frame optical light expected of a dust-enshrouded galaxy and the synchrotron emission expected of a starburst or radio-loud active galaxy. Radio sources, extremely red objects (EROs) and 24-µm sources are sufficiently rare that finding either within an SMG error circle can be viewed as a robust identification in most cases. However, finding an ERO or mid-IR counterpart does not imply that it is responsible for the submm emission, merely that it is likely to be associated with the SMG in some way; for radio counterparts, a more physical link between the radio and submm emission exists.

Fig. 2 shows how the flux density of a luminous, dusty starburst varies with redshift at both 1 mm and 1.4 GHz, adopting the starburst spectral energy distribution (SED) of Carilli & Yun (1999). To identify a z ≤ 3 5-mJy SMG (the average of the 0.85- and 1.2-mm flux densities) in a 1.4-GHz image, it is clear that the radio data must achieve a sensitivity of at least 5 µJy beam⁻¹.

Even at this radio sensitivity, the lack of a robust radio identification could have at least five origins.

(i) The SMG could be entirely spurious;
(ii) the SMG could be real, but flux boosted significantly;
(iii) the radio/far-IR emission could be significantly larger than the 1.4-GHz synthesized beam (I02; Chapman et al. 2004a);
spectral index of Arp 220 (α \nu) radio surveys lose sensitivity to these galaxies at ∼z > 0.7. By contrast, dusty starbursts out to extreme redshifts (∼z > 3) produce a more gentle decline in radio flux density with redshift than would be expected for starbursts with a more typical spectral index (α ∼ −0.7).

Table 1. Combined sample of MAMBO/SCUBA sources in the Lockman Hole.

<table>
<thead>
<tr>
<th>Name</th>
<th>Position at 1.2 mm αJ2000 h m s</th>
<th>δJ2000 m</th>
<th>S1.2 mm (mJy)</th>
<th>S/N</th>
<th>Position at 0.85 mm αJ2000 h m s</th>
<th>δJ2000 m</th>
<th>S0.85 mm (mJy)</th>
<th>S/N</th>
<th>Separation (arcsec)</th>
<th>Final S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH 1200.004 = Lock850.02d</td>
<td>10:52:38.3 +57:24:37 4.8 ± 0.6</td>
<td>57</td>
<td>8.0</td>
<td>10:52:38.6 +57:24:38 10.9 ± 2.1</td>
<td>57</td>
<td>5.1</td>
<td>2.1 &gt;8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.014 = Lock850.01</td>
<td>10:52:38.3 +57:25:15 4.1 ± 0.6</td>
<td>57</td>
<td>6.8</td>
<td>10:52:38.6 +57:23:39 5.2 ± 2.0</td>
<td>57</td>
<td>2.6</td>
<td>3.6 &gt;7.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.017 = Lock850.10</td>
<td>10:52:04.1 +57:26:57 3.6 ± 0.6</td>
<td>57</td>
<td>6.0</td>
<td>10:52:04.2 +57:27:01 10.5 ± 2.0</td>
<td>57</td>
<td>5.2</td>
<td>3.4 &gt;8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.018</td>
<td>10:52:03.9 +57:27:10 1.3 ± 0.6</td>
<td>57</td>
<td>2.2</td>
<td>10:52:03.9 +57:27:10 1.3 ± 0.6</td>
<td>57</td>
<td>2.2</td>
<td>1.8 &gt;5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.019</td>
<td>10:52:03.9 +57:28:17 1.0 ± 0.6</td>
<td>57</td>
<td>2.2</td>
<td>10:52:03.9 +57:28:17 1.0 ± 0.6</td>
<td>57</td>
<td>2.2</td>
<td>1.8 &gt;5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.020</td>
<td>10:52:03.9 +57:29:26 0.8 ± 0.6</td>
<td>57</td>
<td>1.6</td>
<td>10:52:03.9 +57:29:26 0.8 ± 0.6</td>
<td>57</td>
<td>1.6</td>
<td>1.2 &gt;5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.021</td>
<td>10:52:03.9 +57:30:35 0.6 ± 0.6</td>
<td>57</td>
<td>1.2</td>
<td>10:52:03.9 +57:30:35 0.6 ± 0.6</td>
<td>57</td>
<td>1.2</td>
<td>0.8 &gt;5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.022</td>
<td>10:52:03.9 +57:31:44 0.4 ± 0.6</td>
<td>57</td>
<td>0.8</td>
<td>10:52:03.9 +57:31:44 0.4 ± 0.6</td>
<td>57</td>
<td>0.8</td>
<td>0.5 &gt;5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figs 3 and 4 show postage stamps around the positions given in Table 2 for the SMGs in our sample.

1 NRAO is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation (NSF).
to only the integrated flux, were also catalogued. In the Lockman Hole, the surface density of all radio sources above this threshold is $1.9 \pm 0.1$ arcmin$^{-2}$.

For each SMG we have searched for a potential radio (1.4-GHz) counterpart out to a radius of 8 arcsec from the mid-point of the 0.85- and 1.2-mm emission. This relatively large search area (201 arcsec$^2$ around each source) represents a 2.6σ positional confidence region (see later) and should ensure that few (<1 per cent) real associations are missed. As demonstrated by I02, this search radius can be tolerated without compromising the statistical significance of genuine associations. Even at the extreme depths reached by the radio imaging reported here, the cumulative surface density of radio sources yields only 0.1 source per search area.

The flux densities and positions of all candidate radio counterparts are listed in Table 2, along with the search positions. To quantify the formal significance of each of the potential (sub)mm/radio associations we have used the method of Downes et al. (1986) to correct the raw Poisson probability, $P$, that a radio source of the observed flux density could lie at the observed distance from the SMG for the number of ways that such an apparently significant association could have been uncovered by chance.

Of the four sources which have more than one potential radio counterpart, we find that the correct identification is never statistically obvious. The formal probability of the second candidate association occurring by chance is low, $P \leq 0.05$. The obvious interpretations of such multiple statistical associations are either gravitational lensing (implausible in most of the cases here, unless the lenses are as obscured as the lensed galaxies) or arise from true physical associations due to clustering of star-forming objects/active galactic nuclei (AGNs) at the source redshift (likely, and already proven in several cases – e.g. Ledlow et al. 2002). Another possibility is that sources with multiple radio counterparts are boosted into bright submm catalogues by virtue of comprising multiple, faint, physically unrelated SMGs, that is, by confusion.

In total, this calculation has yielded statistically robust radio counterparts for 15 of the 19 SMGs. The plausibility of this figure can be checked by noting that the ratio of areas inside and outside the circles in Fig. 3 is 4.5:1. In total, 10 random ‘field’ radio sources are detected robustly in the outer areas. We thus expect only a handful (at most 2–3) of the counterparts to be spurious, particularly given that μJy radio sources are expected to be overdense around SMGs as a result of mergers and/or clustering (Blain et al. 2004).

Figure 3. Postage stamps (30 arcsec × 30 arcsec) of the fields surrounding the >5σ SMGs in the Lockman Hole. Optical (R) data are shown as a grey-scale upon which 1.4-GHz contours are plotted at $-3, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40$ and $50 \times \sigma_{1.4}$, where $\sigma_{1.4}$ has been measured locally and is indicated in the bottom-left corner of each stamp in units of µJy. Open and solid crosses mark the nominal centroids of SCUBA and MAMBO galaxies, respectively; 8-arcsec radius circles (∼99.9 per cent positional confidence – see Section 3.3) mark the average positions; dashed red lines represent the position of slits on LRIS masks of C05, marked with the mask number; solid green lines represent slits on the GMOS masks, marked with the mask and object identification number (format: M–NN); solid brown lines mark NIRSPEC slit positions; blue squares mark radio counterparts with $P < 0.05$, solid squares being the most probable in each case (see Section 3.2). North (N) is up; East (E) is to the left. We have excluded LH 1200.104 as a bright diffraction spike from a nearby star obliterates any useful information in that region.

We find that two SMGs are completely blank in the radio, while a further two lack robust radio counterparts. Based on the \( P \) values given in Table 2, the most likely candidates for spurious associations are LH 1200.007 and .019. LH 1200.019 and .022 also lack robust Spitzer identifications (E. Egami, private communication), although the radio source \( (P \sim 0.1) \) North of LH 1200.019 is well detected at 24 \( \mu \text{m} \); LH 1200.007 has no clear-cut Spitzer identification, but two faint 24-\( \mu \text{m} \) sources are detected to the north-west and south-east. Finally, LH 1200.104 has a clear identification in the Spitzer imaging described by Ivison et al. (in preparation). LH 1200.022 is thus the least secure SMG in the sample.

We show in Fig. 5 the distribution of flux ratios for the SMGs in our robust sample. These demonstrate a real dispersion in 0.85-/1.2-mm and 1.2-mm/1.4-GHz flux ratios, indicative of a broad underlying distribution of observed SEDs. We can identify regions of the plot where high- and low-redshift sources would reside. However, the degeneracy between characteristic dust temperature and redshift means that variations in dust temperature within the population may mask any redshift variations. On this basis, it appears that LH 1200.042 and .096 may be either particularly hot or particularly low-redshift SMGs, while LH1200.007 has either unusually cold dust or lies at a high redshift.

The mean radio flux density observed for our sample is 89 ± 73 \( \mu \text{Jy} \), taking only the detections and summing flux densities for those with multiple counterparts. The trend in the most common spectral index, \( S_{850 \mu \text{m}} / S_{1.4 \text{GHz}} \), determined by C05, 11.1 ± 35.2z, suggests that the mean redshift of our radio-detected SMG sample, with \( S_{850 \mu \text{m}} = 7.4 \pm 2.7 \text{mJy} \), is \( z \sim 2.2 \). The high dispersion in Fig. 5 echoes the findings of C05, who saw an rms scatter in \( S_{850 \mu \text{m}} / S_{1.4 \text{GHz}} \) of \( \sim 40 \) for their \( z = 1-4 \) SMG sample. In fact, the large scatter provides a plausible explanation for the handful of radio non-detections amongst our SMGs: we would expect at least...
Ar robust sample of submillimetre galaxies

Figure 4. Postage stamps (20 arcsec × 20 arcsec) of the fields surrounding LH 1200.001, .005, .007, .009, .010, .011, .014 and .096. Near-IR (K) data are shown as a grey-scale upon which 1.4-GHz contours are plotted at −3, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40 and 50 × σ. Open crosses mark SCUBA galaxies; solid crosses mark MAMBO galaxies; 8-arcsec radius circles mark the average positions; squares mark objects discussed in the text. N is up; E is to the left.

Table 2. Radio properties of MAMBO/SCUBA sources in the Lockman Hole.

<table>
<thead>
<tr>
<th>Name</th>
<th>Average (sub)mm position</th>
<th>Radio position</th>
<th>S_{1.4GHz}</th>
<th>Radio–submm offset</th>
<th>P</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α_{J2000} h m s</td>
<td>δ_{J2000} ° ′ ″</td>
<td>α_{J2000} h m s</td>
<td>δ_{J2000} ° ′ ″</td>
<td>(µJy)</td>
<td>(arcsec)</td>
</tr>
<tr>
<td>LH 1200.001</td>
<td>10:52:38.46 +57:24:37.4</td>
<td>10:52:38.30 +57:24:35.8</td>
<td>29 ± 11</td>
<td>2.1</td>
<td>0.0237</td>
<td>To SSW</td>
</tr>
<tr>
<td>LH 1200.002</td>
<td>10:52:38.69 +57:23:19.9</td>
<td>10:52:38.39 +57:23:19.6</td>
<td>45 ± 20</td>
<td>2.2</td>
<td>0.0309</td>
<td>To NNW</td>
</tr>
<tr>
<td>LH 1200.003</td>
<td>10:52:04.15 +57:26:59.1</td>
<td>10:52:04.22 +57:26:55.4</td>
<td>72 ± 12</td>
<td>3.7</td>
<td>0.0213</td>
<td>To S</td>
</tr>
<tr>
<td>LH 1200.004</td>
<td>10:52:57.00 +57:21:07.0</td>
<td>10:52:57.09 +57:21:02.8</td>
<td>44 ± 11</td>
<td>4.3</td>
<td>0.0437</td>
<td>To S</td>
</tr>
<tr>
<td>LH 1200.005</td>
<td>10:52:01.37 +57:24:45.6</td>
<td>10:52:01.25 +57:24:45.7</td>
<td>73 ± 10</td>
<td>1.0</td>
<td>0.0025</td>
<td>Central</td>
</tr>
<tr>
<td>LH 1200.006</td>
<td>10:52:27.50 +57:25:16.0</td>
<td>10:52:27.58 +57:25:12.4</td>
<td>47 ± 10</td>
<td>3.7</td>
<td>0.0332</td>
<td>To SSE</td>
</tr>
<tr>
<td>LH 1200.007</td>
<td>10:52:04.08 +57:18:12.1</td>
<td>10:52:04.58 +57:18:05.9</td>
<td>18 ± 7</td>
<td>7.4</td>
<td>0.1304</td>
<td>Central; Central</td>
</tr>
<tr>
<td>LH 1200.008</td>
<td>10:51:51.31 +57:19:52.0</td>
<td>10:51:41.43 +57:19:51.9</td>
<td>315 ± 12</td>
<td>1.0</td>
<td>0.0004</td>
<td>Central; just resolved</td>
</tr>
<tr>
<td>LH 1200.009</td>
<td>10:52:27.84 +57:22:18.5</td>
<td>10:52:27.77 +57:22:18.2</td>
<td>29 ± 9</td>
<td>0.6</td>
<td>0.0031</td>
<td>Central</td>
</tr>
<tr>
<td>LH 1200.010</td>
<td>10:52:30.15 +57:22:09.1</td>
<td>10:52:30.73 +57:22:09.5</td>
<td>54 ± 14</td>
<td>4.7</td>
<td>0.0406</td>
<td>To E, resolved</td>
</tr>
<tr>
<td>LH 1200.011</td>
<td>10:51:58.23 +57:17:56.6</td>
<td>10:51:58.02 +57:18:00.2</td>
<td>98 ± 12</td>
<td>4.0</td>
<td>0.0172</td>
<td>To NNW</td>
</tr>
<tr>
<td>LH 1200.012</td>
<td>10:51:55.66 +57:23:11.6</td>
<td>10:51:55.47 +57:23:12.7</td>
<td>47 ± 10</td>
<td>1.9</td>
<td>0.0120</td>
<td>38 ± 1.9 µJy at 4.9 GHz</td>
</tr>
<tr>
<td>LH 1200.014</td>
<td>10:51:59.80 +57:24:23.1</td>
<td>10:52:00.26 +57:24:21.7</td>
<td>58 ± 12</td>
<td>4.0</td>
<td>0.0300</td>
<td>To ESE</td>
</tr>
<tr>
<td>LH 1200.017</td>
<td>10:51:21.93 +57:18:41.0</td>
<td>10:51:22.20 +57:18:39.9</td>
<td>92 ± 12</td>
<td>2.4</td>
<td>0.0082</td>
<td>To ESE</td>
</tr>
<tr>
<td>LH 1200.019</td>
<td>10:51:28.03 +57:19:47.0</td>
<td>10:51:28.03 +57:19:57.7</td>
<td>58 ± 12</td>
<td>10.7</td>
<td>0.1020</td>
<td>To N, outside search area</td>
</tr>
<tr>
<td>LH 1200.022</td>
<td>10:52:03.15 +57:15:41.6</td>
<td>5σ &lt; 25</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.042</td>
<td>10:52:16.11 +57:25:05.6</td>
<td>10:52:15.63 +57:25:04.2</td>
<td>53 ± 12</td>
<td>4.1</td>
<td>0.0341</td>
<td>To WSW</td>
</tr>
<tr>
<td>LH 1200.096</td>
<td>10:51:51.42 +57:26:39.1</td>
<td>10:51:51.69 +57:26:36.0</td>
<td>135 ± 13</td>
<td>3.8</td>
<td>0.0112</td>
<td>To SE, just resolved</td>
</tr>
<tr>
<td>LH 1200.104</td>
<td>10:51:53.82 +57:18:38.6</td>
<td>5σ &lt; 25</td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The noise level is around 4.6 µJy beam^{−1}; however, flux density uncertainties are larger unless one assumes the source to be unresolved.

10 per cent to be scattered below the radio flux density threshold of our survey.

Is there anything which distinguishes the non-radio SMGs from the rest of the population? Three of the four were detected at <4σ in the MAMBO survey (LH 1200.019, .022 and .104). This is interesting since we would expect the 1.2-mm MAMBO data to be more sensitive than SCUBA to the most distant starbursts (Fig. 5), and hence to yield more radio non-detections – a possible hint that LH 1200.104, at least, is warm rather than cold and/or distant. Two of the radio non-detections, LH 1200.007 and .022, have the largest mm–submm separations in the sample and may thus consist of blended, faint sources.

3.3 Implications for submm positional uncertainty

Fig. 6 shows a histogram of positional offsets in RA and Dec. between the average of the 0.85- and 1.2-mm positions and the most likely radio counterparts. A Gaussian fit to the distribution yields...
a FWHM of $5.2 \pm 1.2$ arcsec, which translates into a $1\sigma$ separation of $2.2$ arcsec between our (sub)mm and radio positions. The sample can thus be employed to re-calibrate the rule-of-thumb relationship between positional accuracy, beam size and S/N (typically, S/N $\sim 6$ here). We must acknowledge a mild circularity to the logic, given that positional offsets have been used to calculate $P$, although this may be offset by the lack of correction for radio sources in the field.

Following Ivison et al. (in preparation), the conventional positional uncertainty, $\sigma$, occurs where the distribution of radial offsets peaks; this is the same as the $1\sigma$ separation deduced earlier. Within this radius we expect to find 39.3 per cent of the population, with 86.5 and 98.9 per cent within $2\sigma$ and $3\sigma$, (from $1-e^{-2}\sigma$). In the absence of radio counterparts, it would seem from our analysis that around 39 per cent of SMGs can be located within a radial distance of $\sim \theta/(\text{signal-to-noiseratio})$, where $\theta$ is the FWHM beam size, in arcsec). Thus the positional uncertainty ($\sigma$) for $3-3.5\sigma$ SCUBA-selected SMGs is $4-5$ arcsec, cf. the rule of thumb quoted by Hughes et al. (1998).

4 OPTICAL/INFRARED OBSERVATIONS

Divining robust counterparts and redshifts for SMGs is a challenging process, with fewer than 10 published redshifts prior to 2002. Ideally, the process follows the pattern outlined below.

(i) Definition of submm sample (e.g. Scott et al. 2002; Greve et al. 2004);
(ii) determination of robust counterparts, using sensible priors and data of sufficient quality in the radio and optical/IR (e.g. I02; Borys et al. 2004);
(iii) spectroscopy, preferably with an instrument sensitive from the blue atmospheric cut-off ($\sim 310$ nm) to $\sim 1$ $\mu$m.

For the particularly retentive, when the spectroscopic identification is not for a radio-identified galaxy these should be augmented with:
(iv) confirmation of redshift in IR via H$\alpha$ or another nebular line (Ivison et al. 2000; Simpson et al. 2004; Swinbank et al. 2004);
(v) detection of molecular gas at that redshift via CO (e.g. Neri et al. 2003; Greve et al. 2005).

We have endeavoured to follow this process, although only the last two of the seven Keck runs described by C05 preceded the arrival of the MAMBO catalogue, so steps (iii) and (iv) have largely preceded (i) and (ii). This should not have introduced any strong bias but it has inevitably reduced the number of robust identifications with successful redshift determinations.

4.1 Imaging with Subaru and Gemini

To illustrate the precise coverage of our spectroscopic observations, we exploit $R$-band archival imaging taken with the 8-m Subaru Telescope using SuprimeCam ($3\sigma$ limit $\sim 27.4$, 1.5-arcsec radius aperture). Postage stamps of these data are shown in Fig. 3, with the radio counterparts highlighted – those with $P < 0.05$ from Section 3.2. For the purposes of cross-identification of radio/optical counterparts – that is, to match the radio astrometry – the optical image required a shift of $\Delta \alpha = -0.5$ arcsec and $\Delta \delta = -0.4$ arcsec. We report the $R$-band photometry of potential counterparts in Table 3.

New near-IR (K) imaging (Fig. 4) of eight of the SMGs is also exploited here, obtained in photometric conditions with seeing $<0.6$ arcsec at the 8-m Gemini Observatory, Mauna Kea, using the Near-infrared Imager (NIRI) (GN/01A/11) with a total

Figure 5. 0.85-/1.2-mm flux ratio versus the 1.2-mm/1.4-GHz flux ratio, for our robust SMG sample. The plot shows a large dispersion in both the flux ratios, broader than the estimated errors, indicating a true dispersion in their properties. As we discuss later, these two flux ratios provide a crude indication of redshift or the characteristic dust temperature. SMGs in the upper left-hand region of the plot are expected to be at low redshift or have a higher characteristic dust temperature; those SMGs in the lower right-hand region may be at high redshift or have cooler dust. The absence of SMGs in the upper right-hand region of the plot arises due to the lack of very hot, high-redshift sources with spectra which are consistently steep from 0.85 mm, through 1.2 mm, and out to 1.4 GHz. To provide the most conservative limits we have added the radio flux densities where multiple counterparts exist.

Figure 6. Histogram of positional offsets in RA and Dec. between the average of the 0.85- and 1.2-mm positions and that of the most likely radio counterpart, negative values corresponding to radio sources SE of a SW–NE line through the (sub)mm position. A Gaussian fit to the distribution yields a FWHM of $5.2 \pm 1.2$ arcsec, which translates into a $1\sigma$ uncertainty of 2.2 arcsec for our (sub)mm positions.
integration time of 5.4 ks per source. The resulting 3σ limit in $K$ is 20.9 for a 1.5-arcsec radius aperture. As we have only partial coverage of our fields in $K$, we only include it in our qualitative discussion of the properties of potential counterparts in these regions in Appendix A.

### 4.2 Spectroscopy with Keck

C05 describe spectroscopy of faint radio galaxies and SMGs with the Low-resolution Imaging Spectrograph (LRIS) spectrograph (Oke et al. 1995) on the 10-m Keck-I telescope during seven runs between 2002 March and 2004 February. Positions for the 1.2 arcsec $\lesssim 1$ arcsec. We obtained 2.4-ks $H$ and $K$ spectra of LH 1200.001 during 2005 March 16 and 17 UT, using identical procedures to those described by Swinbank et al. (2004), although in poorer seeing ($\sim$1 arcsec).

### 4.3 Spectroscopy with Gemini

To augment the spectroscopic data from Keck, we have obtained spectra from the Gemini$^3$ Multi-Object Spectrograph (GMOS) on the 8.1-m Gemini III telescope during four runs in 2003–04. These spectra utilized a 42 arcsec $\times$ 0.76-arcsec slit (marked in Fig. 3), yielding a resolution of $\sim$1500 across the $K$ band. We obtained 2.4-ks $H$ and $K$ spectra of LH 1200.001 during 2005 March 16 and 17 UT, using identical procedures to those described by Swinbank et al. (2004), although in poorer seeing ($\sim$1 arcsec).

#### Table 3. Redshifts and $R$ magnitudes of MAMBO/SCUBA sources.

<table>
<thead>
<tr>
<th>Name$^a$</th>
<th>$R$ magnitude$^b$</th>
<th>Magnitude-related notes</th>
<th>$z^c$</th>
<th>Spectrometer</th>
<th>Redshift-related notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH 1200.001</td>
<td>25.67 ± 0.08</td>
<td>NNW radio id</td>
<td>2.94</td>
<td>GMOS</td>
<td>Optical galaxy to NW: Lyα, N v, Si II</td>
</tr>
<tr>
<td>24.34 ± 0.05</td>
<td>SSW radio id</td>
<td>3.04?</td>
<td>LRIS</td>
<td>Lyα, N v?, AGN?</td>
<td></td>
</tr>
<tr>
<td>LH 1200.002</td>
<td>24.83 ± 0.04</td>
<td>Tentative radio id</td>
<td></td>
<td>GMOS</td>
<td>$z = 0.47$ for nearby optical galaxy</td>
</tr>
<tr>
<td>LH 1200.003</td>
<td>24.04 ± 0.03</td>
<td>Central radio id</td>
<td>0.53</td>
<td>LRIS</td>
<td></td>
</tr>
<tr>
<td>25.40 ± 0.12</td>
<td>S radio id</td>
<td>1.48</td>
<td>LRIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.004</td>
<td>26.14 ± 0.18</td>
<td>Central radio id</td>
<td>LRIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.22 ± 0.07</td>
<td>S radio id</td>
<td>Line at 558 nm?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.005</td>
<td>25.79 ± 0.14</td>
<td>Central radio id; ERO</td>
<td>2.15?</td>
<td>LRIS, NIRSPEC</td>
<td>ERO, 3 arcsec to W to radio source, Hα?</td>
</tr>
<tr>
<td>LH 1200.006</td>
<td>25.00 ± 0.06</td>
<td>SSE radio id</td>
<td>2.14?</td>
<td>LRIS, NIRSPEC</td>
<td>IS abs, starburst</td>
</tr>
<tr>
<td>LH 1200.007</td>
<td>3σ $&gt; 27.4$</td>
<td>X-ray source, 21.76 ± 0.01</td>
<td>LRIS</td>
<td>$z = 0.715$ for X-ray source</td>
<td></td>
</tr>
<tr>
<td>LH 1200.008</td>
<td>22.01 ± 0.01</td>
<td>Central radio id</td>
<td>1.21</td>
<td>LRIS</td>
<td>IS abs; starburst</td>
</tr>
<tr>
<td>LH 1200.009</td>
<td>3σ $&gt; 27.4$</td>
<td>Central radio id</td>
<td>1.96?</td>
<td>LRIS</td>
<td>Lyα, C IV; starburst (opt gal 4 arcsec SWW of radio)</td>
</tr>
<tr>
<td>LH 1200.010</td>
<td>22.78 ± 0.02</td>
<td>Confused region</td>
<td>2.61</td>
<td>LRIS, GMOS, NIRSPEC</td>
<td>Lyα, N v, Si II, Hα; starburst</td>
</tr>
<tr>
<td>LH 1200.011</td>
<td>23.68 ± 0.03</td>
<td>NNW radio id</td>
<td>2.24</td>
<td>LRIS, NIRSPEC</td>
<td>Lyα abs, C IV abs, Hα; starburst</td>
</tr>
<tr>
<td>LH 1200.012</td>
<td>2.24 ± 0.03</td>
<td>Confused region</td>
<td>2.66</td>
<td>LRIS, NIRSPEC</td>
<td>Hor; see Section 5</td>
</tr>
<tr>
<td>LH 1200.014</td>
<td>23.05 ± 0.02</td>
<td>Confused region</td>
<td>0.69</td>
<td>LRIS</td>
<td>[O II], Ca HK (2 arcsec SWW of brightest radio id)</td>
</tr>
<tr>
<td>LH 1200.107</td>
<td>23.86 ± 0.02</td>
<td>N radio id</td>
<td>2.24</td>
<td>GMOS</td>
<td></td>
</tr>
<tr>
<td>LH 1200.109</td>
<td>3σ $&gt; 27.4$</td>
<td>Brightest object 24.50 ± 0.05</td>
<td>LRIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.022</td>
<td>3σ $&gt; 27.4$</td>
<td>Brightest object 21.20 ± 0.01</td>
<td>LRIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.042</td>
<td>25.17 ± 0.07</td>
<td>WSW radio id</td>
<td>1.85</td>
<td>LRIS</td>
<td>IS abs</td>
</tr>
<tr>
<td>LH 1200.096</td>
<td>24.90 ± 0.07</td>
<td>SE radio id</td>
<td>1.15</td>
<td>LRIS</td>
<td>Starburst</td>
</tr>
<tr>
<td>LH 1200.104</td>
<td>–</td>
<td>Diffraction spike</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LH 1200.109</td>
<td>3σ $&gt; 27.4$</td>
<td>Brightest object 24.50 ± 0.05</td>
<td>LRIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH 1200.012</td>
<td>2.24 ± 0.03</td>
<td>Confused region</td>
<td>2.66</td>
<td>LRIS, NIRSPEC</td>
<td>Hor; see Section 5</td>
</tr>
</tbody>
</table>

---

$^a$Sources in parentheses lack robust radio identifications. $^b$Values in bold are for sources identified in the radio ($P < 0.05$). $^c$Values in bold are for redshifts that we consider to be most robust.

---

$^2$The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

$^3$The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the NSF (United States), the Particle Physics and Astronomy Research Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNP (Brazil) and CONICET (Argentina).
BEST magnitudes of our sample in $R$ broadly agree, with median Clements et al. (2004) and Pope et al. (2005). The various surveys compared with those from the surveys by I02, Smail et al. (2002), I02 = 22–26, with a faint tail. The median magnitude is $R = 25.0$, comparable to the sample analysed by C05, $R = 25.2$, and $\sim 0.6$ mag fainter than the spectroscopically identified sample of C05. As expected, a similar bias in the spectroscopically identified subset exists within our own sample, which is $\sim 0.9$ mag brighter than our complete catalogue.

5 DISCUSSION

5.1 The distribution of optical magnitudes

Table 3 lists the $R_{\text{mag}}$ magnitudes of our sample in $R$, measured using SExtractor. Fig. 7 shows a histogram of $R$ magnitudes compared with those from the surveys by I02, Smail et al. (2002), Clements et al. (2004) and Pope et al. (2005). The various surveys broadly agree, with median $R$-band magnitudes ranging between $R \sim 24–26$ and a wide range in magnitude within each sample. The

![Figure 7. Histogram of optical ($R$) magnitudes for radio-identified SMGs in our sample, compared with those from the surveys by Smail et al. (2002), I02, Clements et al. (2004) and Pope et al. (2005). Magnitudes have been converted to a uniform scale (Vega), and the SCUBA Lens Survey data have been corrected for magnification (Smail et al. 2002). We find a broad agreement between the magnitude distributions with median $R$-band magnitudes of $R = 24.0–26.2$, although our new robust sample shows a smaller dispersion than many of the other published catalogues. Where only 1 or $i_{775}$ magnitudes are available, the average ($R - I$) colour (0.75) for 19 radio-identified SMGs with $R$ and $I$ data has been assumed, somewhat redder than the $R - I = 0.4$ measured for field galaxies (Smail et al. 1995). Arrows represent an SMG for which only a lower limit in $R$ is available.](http://mnras.oxfordjournals.org/issue)

Clements et al. (2004) sample has a bright tail which is less evident in the other surveys. Our sample appears to show the smallest dispersion, although the presence of upper-limits in all five samples makes this statement hard to quantify.

Nevertheless, from this comparison we can state that the bright, radio-identified SMG population, spanning barely a magnitude in submm flux density, covers over 10 orders of magnitude in rest-frame ultraviolet (UV) flux. The optical magnitudes of the radio-identified SMGs discussed in this paper span around $R = 22–26$, with a faint tail. The median magnitude is $R = 25.0$, comparable to the sample analysed by C05, $R = 25.2$, and $\sim 0.6$ mag fainter than the spectroscopically identified sample of C05. As expected, a similar bias in the spectroscopically identified subset exists within our own sample, which is $\sim 0.9$ mag brighter than our complete catalogue.

5.2 The distribution of spectroscopic redshifts

The redshift distribution determined here inevitably suffers from spectroscopic incompleteness, but our sample should be otherwise unbiased. Concentrating on cases where our spectroscopy failed to secure a robust redshift the failures tend to coincide with the faintest optical counterparts, $R > 25$, as one might expect. Looking at the long-wavelength flux ratios (Fig. 5) for those targets where we failed to obtain identifications or redshifts, for example, LH1200.002 or 0.04, we see no indication that their (sub)mm/radio photometric properties differ from those of the sample as a whole. It seems unlikely therefore that they lie at substantially higher redshifts than the subset of SMGs for which we have obtained redshifts. The exceptions are LH1200.022, and especially LH1200.007, which have relatively low 0.85-/1.2-mm flux density ratios and fairly high 1.2-mm/1.4-GHz flux density ratios. This suggests they may lie at high redshift, or be particularly cold. However, as discussed in Section 3.2, these two sources are not particularly secure (although that may simply reflect their general faintness in all bands due to their high redshifts). Reliable identification of these two sources is therefore only achievable through higher-resolution (interferometric) (sub)mm observations (e.g. Lutz et al. 2001).

For the six SMGs where we have a single radio identification (and hence an unambiguous counterpart) and for which we have measured robust redshifts (Table 3), we determine a median of $z = 2.05 \pm 0.41$ (where the scatter is estimated from bootstrap re-sampling). This rises slightly to $z = 2.14 \pm 0.27$ if we include the four sources with robust redshifts for at least one radio counterpart and the five SMGs where we have less secure redshifts. These figures are slightly lower than, but entirely consistent with, the spectroscopic redshift distribution determined by C05 ($z = 2.2$). This suggests that the statistical properties of the C05 sample have not been strongly biased by the modest significance ($> 3\sigma$) of some of the submm data used in their analysis.

The median redshift we derive is in reasonable agreement with that predicted by the GALFORM semi-analytic model (Baugh et al. 2005), which gives a median redshift of $z = 2.1$ at our flux limit, with a quartile range of $\pm 0.9$ and only 10–20 per cent of the population at $z \geq 3$. This again suggests that much of the activity in the bright SMG population is amenable to study via the precise positions derived from their radio counterparts. This provides a much-needed route to identify the true far-IR luminous source within these frequently morphologically complex and crowded fields.

We illustrate in Fig. 8 the distribution of 1.2-mm/1.4-GHz and 0.85-/1.2-mm flux ratios for our sample versus our spectroscopic redshifts. The former show a trend to higher flux ratios at
higher redshifts, in line with predictions from SED modelling (e.g. Carilli & Yun 1999), although with a large scatter; the latter flux ratio, however, is essentially a scatter plot. We conclude that significant more reliable flux measurements (in terms of both absolute calibration and overall S/N) will be needed to use the 0.85-/1.2-mm flux ratio for astrophysical analysis.

Figure 8. The distribution of flux ratios versus redshift for our robust (circles) and plausible (squares) redshift identifications. The upper panel shows the flux ratio between 1.2 mm and 1.4 GHz versus redshift, with a clear trend for higher ratios at higher redshifts as expected from SED modelling (see Carilli & Yun 1999; Greve et al. 2004). The lower panel shows the ratio of 0.85-mm fluxes to those measured at 1.2 mm, again against redshift. The scatter in this panel shows that much more precise (sub)mm flux density measurements will be needed before this ratio can be used to investigate the redshifts of submm wavebands are insufficiently precise for typical SMGs to allow them to be used as a reliable redshift indicator, particularly, when some data do not comprise fully sampled images. The disagreement may have been compounded by the lower significance of the Eales et al. (2003) targets, and the dual-wavelength extraction performed here could exclude the most distant starbursts (though we note that the radio-detection of a substantial number of the Eales et al. (2003) targets is hard to reconcile with the high median redshift claimed for that sample; indeed, the radio-based estimates given in Eales et al. (2003), with \( \bar{z} = 2.35 \), are more consistent with the spectroscopic results).

6 CONCLUSIONS

We have developed and applied a dual-survey extraction technique to SCUBA and MAMBO images of the Lockman Hole, resulting in a robust sample of 19 SMGs. Of these, 15 are detected securely by our deep radio imaging. Those undetected at 1.4 GHz can be explained by a combination of contamination by spurious sources (10 per cent) and the large observed scatter in radio flux densities, which is probably due to a significant range in dust temperature.

We determine 15 spectroscopic redshifts, of which we consider 10 to be secure. The resulting redshift distribution (\( \bar{z} = 2.14 \) for the full spectroscopic sample) is consistent with that determined for a much larger sample by CO5 (\( \bar{z} = 2.2 \)). Our results thus support the conclusions of CO5, who modelled their incompleteness and estimated only a small shift (\( \Delta z = +0.1 \)) in the median redshift as a result. Those galaxies for which our spectroscopy failed to determine redshifts are usually optically faint, \( R > 25 \), where the sample ranges from \( R = 22 \) to greater than 26 with a median of 25.0.

From the radio detections, and the spectroscopy, it seems unlikely that a significant fraction of bright SMGs lie at very high redshift (\( \bar{z} > 3 \)) and we conclude that the bright SMG population is readily amenable to study via radio-selected samples, down to a 850-\( \mu \)m flux density limit of \( \sim 7 \) mJy. We note, however, that the dual-wavelength extraction performed here could potentially bias our sample against very high-redshift sources which would only be detected at 1.2 mm.

An analysis of separations between SMGs and their radio counterparts has allowed us to re-calibrate the rule-of-thumb relationship between positional accuracy, beam size and significance. The most secure SMGs, at \( \sim 10 \) arcsec, representative of those expected in upcoming, confusion-limited, wide-field (tens of square degrees) 0.85-mm surveys using SCUBA-2 (Audley et al. 2004), with lower significance, simultaneous detections at 0.45 mm, will be located with an uncertainty of \( \sigma_r \sim 1 \) arcsec, at which level the precision of the telescope pointing and SCUBA-2 flat-field may become important contributors to the positional error budget. Assuming these sources of uncertainty can be minimized, the current requirement for deep radio coverage to identify counterparts and enable follow-up spectroscopy may not be as urgent, particularly if 3 arcsec \( \times \) 3 arcsec.
deployable integral-field units are employed for spectroscopic follow-up (e.g. KMOS — Sharples et al. 2003, 2004).

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APPENDIX A

Following are the notes on our spectroscopic observations of the individual sources, referring to the slit positions shown in Fig. 3.

(i) $LH_{1200.001}$. A complex field. LRIS slits on several masks had been placed on a faint $R$-band source coincident with the most probable radio counterpart ($P = 0.024$). Its spectrum, shown in Fig. A1, is consistent with a redshift of 3.036, with Lyman $\alpha$ (Lyr) and hints of weak $N\alpha$ and several other lines. We searched for $[O\alpha]$ and $[O\alpha]$ using NIRSPEC (Section 4.1), yet we were not able to confirm or rule out $z = 3.036$ with confidence. A search for CO(3–2) using the Plateau de Bure Interferometer was unsuccessful (Greve et al. 2005), though this could have been due to insufficient velocity coverage. The second radio counterpart, 4 arcsec to the north and also with $P < 0.05$, is associated with an ERO (Fig. 4). The NIRSPEC long slit was positioned to cover this galaxy; no lines were evident. Its closest neighbour was observed with GMOS (Fig. A2; [2–8]) and found to have emission lines (Lyr, possibly $N\lambda$ and Si$n$) consistent with $z = 2.943$ (the apparent continuum bluward of Lyr is merely an artefact of the reduction process). At the edge of the same slit, near the northern radio position, there is tentative evidence for line emission from Lyr, $N\lambda$ and possibly C$\lambda$ at $z = 2.88$. The optically bright radio source 11 arcsec SE of the SMG centroid (Fig. A2; [2–6]) is an AGN, with broad $C\lambda$ and $Mg\lambda$ emission lines, this time at $z = 1.11$. The optical galaxy 8 arcsec SSE of the SMG (Fig. A2; [2–7]) has $[O\alpha]$ at $z = 0.56$. A further ERO, overlooked by I02, and detected at 3.5$\sigma$ in our smoothed radio image, lies 7.5 arcsec NNE of the SMG centroid (Fig. 4). We conclude that the submm emission likely originates from the two central radio components, which most probably lie at $z \sim 3$.

(ii) $LH_{1200.002}$. Two galaxies in this field were targeted spectroscopically with GMOS. One target, slit [2–5], lies close to the faint radio emission near the SMG centroid, but we were unable to...
Figure A1. Rest-frame UV/optical LRIS spectra of the counterparts discussed in the text with rest-frame and observed wavelength scales below and above, respectively, and line identifications are shown.
identify its redshift. The other target – probably unassociated with
the SMG – has a faint emission line which, if \([\text{O II}]\), indicates \(z = 0.469\) (Fig. A2; [2–4]).

(iii) \(\text{LH 1200.003}\). Another complex field. LH 1200.003 may be
a blend of 2–3 SMGs, with MAMBO resolving the source into two,
and the VLA resolving three faint radio sources (one marginally
outside our radio search region). Slits had been placed on all
likely counterparts. The radio source to the SE, targeted by slits
on five LRIS masks at various position angles (PAs), is a star-
burst at \(z = 1.482\). The most probable (central) radio identifi-
cation is associated with a galaxy at \(z = 0.526\) (Fig. A1). The
galaxy to the NNW – possibly associated with faint mm emission,
LH 1200.213 in Greve et al. (2004) – was targeted spectroscopically
using LRIS and GMOS and is an AGN at \(z = 2.43\), with broad C\(\text{IV}\)
emission, as well as narrower Ly\(\alpha\), He\(\text{II}\), N\(\text{IV}\) and N\(\text{V}\) (Fig. A2;
[1–5]).

(iv) \(\text{LH 1200.004}\). From two possibilities, an LRIS slit had been
placed on the galaxy with the marginally higher \(P\) value (0.044
versus 0.033). The galaxy has a weak line in its spectrum at 558 nm,
possibly Ly\(\alpha\), but we were unable to determine the redshift reliably.

(v) \(\text{LH 1200.005}\). LRIS slits were placed on a faint optical galaxy
\(\sim 3\) arcsec west of the obvious radio counterpart. The galaxy is
estimated to lie at \(z = 2.148\) from absorption lines in its optical
spectrum (C05), a value tentatively confirmed via H\(\alpha\) in the \(K\)
band, although NIRSPEC slit-rotation problems mean the line cannot be
recovered in the final spectrum or image. Although optically faint
(Fig. 3, \(R = 25.78 \pm 0.14\)), the ERO described by Lutz et al. (2001),
seen in Fig. 4 at the radio position, was targeted using LRIS and
GMOS. No redshift was forthcoming. The likelihood of finding a
\(z \sim 2\) galaxy so close to the SMG centroid is slim, so the two may
well be associated, but we regard the redshift as tentative until H\(\alpha\)
is detected unambiguously.
(vi) **LH 1200.006.** LRIS slits had been placed on by far the most probable radio counterpart in the region (\(P = 0.033\)). Its optical spectrum was identified by C\(\text{O}_5\) as that of a starburst at \(z = 2.142\) (Fig. A1). This position was also observed by Swinbank et al. (2004) using NIRSPEC, although only [N\(\text{ii}\)] would have been accessible. Since the one-dimensional optical spectrum is not wholly convincing, this redshift cannot be relied upon absolutely. The optically bright object to the NW was targeted by GMOS: a foreground galaxy (\(z = 0.14\)) with H\(\beta\) and [O\(\text{iii}\)] emission lines evident (Fig. A2; [2–20]).

(vii) **LH 1200.007.** There is no secure radio counterpart. An LRIS slit was placed on a nearby XMM–Newton X-ray source, which is marginally detected in our smoothed radio image. It lies at \(z = 0.715\) (Fig. A1), and may contribute submm flux to what could well be a blended submm source. The faint, red galaxy to the north, barely seen in a noisy part of our \(K\) image (Fig. 4), was not targeted spectroscopically.

(viii) **LH 1200.008.** An LRIS slit had been placed on by far the most probable radio counterpart in the region (\(P = 0.0004\)), an \(R = 22.0\) galaxy amongst a dense ensemble of fainter objects (Fig. 3), with absorption lines in its spectrum corresponding to \(z = 1.212\) (Fig. A1), with C\(\text{iii}\) and H\(\text{ii}\) weakly in emission.

(ix) **LH 1200.009.** GMOS slits were placed on the radio counterpart and on an optically bright galaxy to the NNW. An unambiguous redshift could not be determined for either, although the NNW galaxy may show faint [O\(\text{ii}\)] at \(z = 0.489\) (Fig. A2; [2–31]). LRIS slits had been placed on a faint \(R\)-band galaxy \(~6\) arcsec SSW of the obvious radio counterpart. This was due to a positional offset in an earlier version of the Greve et al. (2004) MAMBO catalogue. The galaxy 3 arcsec NW of the slit centre, 4 arcsec SSW of the radio source, appears to be a Ly\(\alpha\) emitter at \(z = 1.956\) (Fig. A1), though no other lines are seen. As with LH 1200.005, the likelihood of finding a \(z \sim 2\) galaxy so close to the submm centroid is low, so it may be associated with the radio source and the SMG. The position of the radio source is blank to \(K > 22\) in our deep Gemini/NIRI imaging (Fig. 4). The Ly\(\alpha\) emitter is detected, barely, in \(K\). We note that at least one similarly faint SMG (SMJ141009+0252, \(K \sim 21\)) has been found at \(z \sim 2\) (Smith et al., in preparation).

(x) **LH 1200.010.** LRIS slits had been placed on both of the radio-identified galaxies in this region with one of them (and several other radio-quiet galaxies) targeted by GMOS. By far the most robust counterpart (\(P = 0.041\)), morphologically complex in \(R\) (Fig. 3) but relatively uncluttered in \(K\) (Fig. 4), has the spectrum of a starburst at \(z = 2.611\) (C\(\text{O}_5\), SMJ105230.73+572209.5), confirmed in H\(\alpha\) by Swinbank et al. (2005) and in \(\text{N}\ii\) by GMOS (Ly\(\alpha\) falling between chips – Fig. A2; [2–10]), although undetected in CO(3–2) at IRAM (Greve et al. 2004). The LRIS spectrum of the radio-bright disc-like galaxy 10 arcsec to the SW is also consistent with this redshift. Nothing was seen at the remaining GMOS slit positions, [2–11] and [2–12].

(xi) **LH 1200.011.** An LRIS slit had been placed on by far the most probable radio counterpart in the region (\(P = 0.017\)), a compact source with a 5-arcsec long tail visible in \(R\) and \(K\) (Figs 3 and 4). It has the spectrum of a starburst at \(z = 2.239\) (C\(\text{O}_5\), SMJ105158.02+571800.2), confirmed convincingly in H\(\alpha\) and [N\(\text{ii}\)] by Swinbank et al. (2005). The fainter radio source, 14 arcsec to the NEE, lies at \(z = 1.047\). Simpson et al. (2004) identified a \(J\)-band feature, presumably a noise spike, as [O\(\text{ii}\)] at \(z = 2.12\) (rest frame 359 nm for \(z = 2.34\), as well as a continuum break at 1.2 \(\mu\)m (consistent with the Balmer break at either redshift).
ERO (I02) visible out to 24 μm (Egami et al. 2004), ignoring several brighter optical galaxies. The LRIS spectrum was classified as a starburst at $z = 1.147$ by C05 (Fig. A1 – SMM J105151.69+572636.0); GMOS saw nothing at this position. This is the curious SMG discussed by I02, apparently associated with the steep-spectrum lobe of a radio galaxy, the flat-spectrum core of which lies to the west, with [O II] evident at $z = 0.586$ in its spectrum (Fig. A2, [1–20]). Is this system a jet-triggered burst, a galaxy projected onto an unrelated radio lobe, or a faint, dusty, ultrasteep-spectrum radio galaxy? Our picture of this system is muddled and contradictory. To confuse matters further, our NIRI $K$-band imaging (Fig. 4) reveals another ERO, WSW of the radio emission, visible out to 8 μm in the Spitzer imaging, and just missed by GMOS slit [1–19] on a nearby, bluer galaxy.

(xix) LH 1200.104. Despite the lack of radio detections in the vicinity, a bright Spitzer counterpart described by Ivison et al. (in preparation) suggests this SMG is not spurious. A diffraction spike from the nearby star makes identification impossible in our optical imaging.

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