The redshifts of bright sub-mm sources

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Abstract

One of the key goals in observational cosmology over the next few years will be to establish the redshift distribution of the recently-discovered sub-mm source population. In this brief review I discuss and summarize the redshift information which has been gleaned to date for the $\simeq 50$ bright sub-mm sources which have been uncovered via the six main classes of survey performed with SCUBA on the JCMT over the last 2-3 years. Despite the biases inherent in some of these surveys, and the crudeness of the redshift information available in others, I conclude that all current information suggests that only $10 - 15\%$ of luminous sub-mm sources lie at $z < 2$, and that the median redshift of this population is $z \simeq 3$. I suggest that such a high median redshift is arguably not unexpected given current theories designed to explain the correlation between black-hole mass and spheroid mass found at low redshift. In such scenarios, peak AGN emission is expected to correspond to, or even to cause termination of major star-formation activity in the host spheroid. In contrast, maximum dust emission is expected to occur roughly half-way through the star-formation process. Given that optical emission from bright quasars peaks at $z \simeq 2.5$, dust-emission from massive ellipticals might be reasonably expected to peak at some point in the preceding $\simeq 1$ Gyr, at $z \simeq 3$. Confirmation or refutation of this picture requires significantly-improved redshift information on bright samples of SCUBA sources.

Key words: cosmology:observations, galaxies:formation, galaxies:starburst, infrared:galaxies, ISM:dust

1 Introduction

The importance of understanding the nature of the recently-discovered sub-mm galaxy population has been discussed in detail by many authors (e.g. Hughes et al. 1998; Blain et al. 1999). Most importantly, constraining the redshift distribution of this population is a requirement for obtaining an unbiased view of the star-formation history of the universe, and potentially holds the key to understanding the formation and evolution of massive elliptical galaxies.
In this review I therefore concentrate on what we have learned to date about the redshift distribution of the sub-mm population from the six main classes of survey which researchers have undertaken in the last 2-3 years with the SCUBA camera on the JCMT.

First I consider current results from three different types of surveys aimed at determining the sub-mm luminosities of objects which have already been discovered at other wavelengths. These are i) radio galaxies, ii) optically selected quasars, and iii) micro-Jy radio sources. Such studies have the practical advantage of accurate source positions, and (at least in the first 2 cases) pre-existing redshift information. By focussing on specific sub-classes of object they are inevitably biased to some extent, but the extent of this bias may not necessarily be severe.

Second, I consider current results from surveys which have been designed to discover new sources at sub-mm wavelengths. Again, I have divided these into three distinct classes, namely i) surveys which aim to take advantage of the gravitational lensing effects of intervening rich clusters, ii) imaging surveys of the fields around known high-redshift objects, and iii) genuinely unbiased, blank-field surveys of non-descript regions of sky.

For the sake of clarity and comparability I have produced summary statistics for each survey considering only sources which have been detected in the sub-mm at significance levels > 4σ, and which have intrinsic sub-mm flux densities $S_{850} > 4mJy$.

Before proceeding with this census, it is important to note that, apart from the radio galaxies and quasars for which spectroscopic redshifts already exist, almost all of the redshift estimates discussed and summarized in what follows are based on the observed far-infrared→radio spectral energy distributions (SEDs) of the sources. This serves to emphasize the importance of understanding such SEDs, and legitimizes the inclusion of this review in this particular conference! However it does of course mean that many of the current redshift constraints are inevitably rather crude and uncertain.

Of greatest current importance is the use of the sub-mm:radio flux-density ratio $S_{850\mu m} : S_{1.4GHz}$ which is a relatively sensitive function of redshift for a starburst galaxy, initially rising $\propto (1 + z)^{4.5}$ before flattening towards higher redshift in a manner which depends on the form of the assumed template spectrum. This ratio was first used by Hughes et al. (1998) to set redshift constraints on the sub-mm sources detected in the Hubble Deep Field, and has since been explored in detail by Carilli & Yun (1999), Carrilli & Yun (2000), Dunne et al. (2000), Barger et al. (2000), and Blain (2001). There is now general agreement that adopting M82 as a template SED (e.g. Carilli & Yun 1999) is probably not appropriate for the luminous sub-mm population and is
The mm-submm spectral energy distributions of the $z \simeq 4$ radio galaxies 4C41.17 ($z = 3.8$) and 8C1435+635 ($z = 4.25$) as determined from a combination of observations made with the JCMT (Dunlop et al. 1994; Ivison et al. 1998), the IRAM 30-m telescope (Ivison 1995), and the Caltech Submm Observatory (Benford et al. 1999). Both sources show very similar levels of sub-mm emission $S_{850} \simeq 10\text{mJy}$, and it is clear from these SEDs that this emission arises from dust radiating at a (rest-frame) temperature of $T \simeq 40\text{K}$. In both cases the inferred dust mass is $M > 10^8\text{M}_\odot$ and the inferred star-formation rate is $> 1000\text{M}_\odot\text{yr}^{-1}$.

likely to lead to excessive redshift estimates. Instead, most authors now adopt Arp220 as the most appropriate low-redshift template ULIRG. Alternatively, Dunne et al. (2000) have chosen to derive a mean-SED from their SCUBA survey of low-redshift IRAS galaxies. There is some continuing controversy over the precise form of the best relation to use. Dunne et al. (2000) argue convincingly that their relation is most robustly calibrated at low redshift. On the other hand the revised relation presented by Carilli & Yun (2000) appears to do a better job of reproducing the redshifts of the handful of objects with known CO redshifts at $z > 2$. However, the level of this disagreement is now comparable to the uncertainties in these relations, and the key point in what follows is that essentially all authors in this field would appear to agree that a flux-density ratio $S_{850} : S_{1.4\text{GHz}} > 100$ (or equivalently a spectral index $\alpha_{850}^{1.4} > 0.84$) implies $z > 2$. Finally, when utilising this redshift-estimation technique, it is always worth remembering that over-optimistic radio-submm associations, or failure to recognize an AGN contribution to radio flux-density, will always result in an under-estimate of the true redshift of the source. Over-estimation of redshift is less likely to occur.

2 Redshifts of known sources now detected in the sub-mm

2.1 Radio galaxies

The first radio galaxies to be detected at sub-mm/mm wavelengths were also the most distant and powerful radio galaxies known at the time - 4C41.17 at $z = 3.8$ (Dunlop et al. 1994) and 8C1435+635 at $z = 4.2$ (Ivison et al. 1998).
Even before SCUBA it was clear that these $z \simeq 4$ detections were telling us something important because attempts to detect other well-known radio galaxies at lower redshift were much less successful (Hughes et al. 1997). However, it was only with the advent of SCUBA that it became possible to observe sufficiently large samples of radio galaxies to determine if the large dust masses found in 4C41.17 and 8C1435+635 (Figure 1) are primarily a consequence of their extreme redshifts or their extreme radio luminosities.

My colleagues and I have now completed the first such major sub-mm survey of radio galaxies, using SCUBA in photometry mode to undertake sensitive 850-micron observations (rms noise < 1 mJy) of $\simeq 50$ powerful radio galaxies spanning the redshift range $1 < z < 5$ (Archibald et al. 2000). As shown in Figure 2, this study has confirmed the increased sub-mm detectability of radio galaxies with increasing redshift (15% success rate at $z < 2.5$, 75% success rate at $z > 2.5$). Moreover, we have been able to break the degeneracy between radio luminosity and redshift, and find that the primary dependence of sub-mm luminosity is with redshift - specifically we find that average sub-mm luminosity increases approximately $\propto (1+z)^3$ out to $z \simeq 4$. The median redshift of the sub-mm detected radio galaxies in this sample is $z_{med} = 3.1$. It is important to stress that this is not simply a reflection of the redshift distribution of the parent sample, as this has $z_{med} = 2$ (see Figure 2). Interestingly, all but one of the radio galaxies with $S_{850} > 5\text{mJy}$ lie at $z > 3$, and the median redshift for this subset is $z_{med} = 3.5$.

**Redshift Summary:** Median $z \simeq 3.1$. 1/9 $4\sigma$ $S_{850} > 4\text{mJy}$ sources at $z < 2$.

**Bias:** Potentially unbiassed if radio galaxies are representative of massive galaxies in general.

### 2.2 Quasars

A substantial number of high-redshift ($z \simeq 4$) optically-selected quasars have now been detected at sub-mm (McMahon et al. 1999) and mm (Carilli et al. 2000) wavelengths. However, to date such observations have been deliberately concentrated on very high-redshift quasars, and no study has yet been completed of the sub-mm luminosity of QSOs of comparable optical luminosity over a wide range in redshift, analogous to that described above for radio galaxies. As a result it is not yet possible to quantify the redshift dependence of dust mass in quasars. However, McMahon et al. (1999) have explored whether, at high redshift, there is any evidence that sub-mm luminosity depends on optical luminosity and do not find any support for such a luminosity dependence.

**Redshift Summary:** Median $z \simeq 4.4$. 0/9 sources at $z < 2$.

**Bias:** Biassed - bias potentially severe and not yet quantified.
Fig. 2. The cumulative redshift distribution of the radio-galaxy sample observed by Archibald et al. (2000). The green/dotted line is the entire sample, while the black line is only for galaxies detected at 850$\mu m$. The median redshift of the parent sample is $z_{med} = 2$. For objects detected at 850-$\mu m$ the median redshift is $z_{med} = 3.1$.

2.3 Weak radio sources

Barger et al. (2000) have found that a substantial fraction ($\simeq 1/3$) of optically-faint micro-Jy radio sources can be detected by SCUBA at flux densities $S_{850} > 6$mJy. This is an important, albeit not entirely unexpected, result as both synchrotron emission from Type II supernovae and thermal emission from warm dust are symptomatic of very recent ($< 10^8$yr) massive star-formation activity. Barger et al. conclude that $\simeq 70\%$ of the bright sub-mm population can be located via micro-Jy radio maps, and that the entire sub-mm population lies in the redshift band $1 < z < 3$. However, a closer examination of their data suggests that this conclusion may be premature. In fact, of the 4 sub-mm sources they have discovered with $S_{850} > 8$mJy, only two are $\mu$Jy radio sources, and the listed radio-submm SED-based redshift estimates for these 4 sources are $z = 1.5$, $z = 2.5$, $z > 3.5$ and $z > 5$. This ‘survey’ thus arguably supports a mean/median redshift of $z \simeq 3$ for the bright sub-mm population, albeit with very large errors. In fact, even at somewhat lower sub-mm flux densities, examination of their figure 2 suggests that $\mu$Jy radio-source selection can only identify $\simeq 50\%$ of the SCUBA population, especially when one factors in the inevitable bias introduced by imaging only sub areas which contain the majority of faint radio sources. Furthermore, the $\simeq 50\%$ of the SCUBA population which can be detected by this approach must, inevitably, be the lower-redshift half. Wide area blank-field surveys, such as the 8-mJy survey described below, offer the only way to properly quantify this bias.

**Redshift Summary:** Median $z > 2.9$ 1/4 sources at $z < 2$.

**Bias:** Biased to lower-$z$ sources, but extent of bias not yet properly quantified.
3 Redshifts of sub-mm selected sources

I now consider our current information on the redshifts of sources which have been discovered through sub-mm imaging. Such sources have been uncovered via three different classes of sub-mm survey, namely i) surveys designed to take advantage of the gravitational lensing provided by rich galaxy clusters, ii) surveys of the fields around known high-redshift AGN, and iii) unbiased blank-field surveys, generally conducted in regions of sky which have already been well-studied at other wavelengths. Below I give a summary of the main results from each class of survey. I have deliberately focussed attention on the brightest sources, because it is generally only for these sources that solid, unconfused sub-mm/mm positional information has been obtained so far.

3.1 Lensing surveys

The ultimate goal of spectroscopic redshifts, confirmed by CO detections, has been achieved for three of the sources detected via SCUBA imaging of the fields of rich clusters – SMMJ02399−0136 at $z = 2.80$, SMMJ14011+0252 at $z = 2.55$, and SMMJ02399−0134 at $z = 1.06$ (Smail et al. 2000). However, while it is obviously nice to have some concrete numbers, it is unclear how representative these sources are, given that their redshift determination was assisted by their unusually bright optical counterparts and, in the latter two cases, by the presence of an AGN. For the sample as a whole one has to resort to the radio-submm redshift estimator discussed above. Based on the fact that only $\approx 1/2$ of the sample has proved detectable at 1.4GHz, Smail et al. (2000) argue that the median redshift is most likely $\approx 3$. This result provides direct support for the argument advanced above (in section 2.3) that targeted sub-mm observations of known micro-Jy radio sources are likely to reveal only the low-redshift half of the sub-mm galaxy population. It also means that the median redshift of the lensing-survey sources is in excellent accord with the median redshift of sub-mm detected radio galaxies discussed in section 2.1.

**Redshift Summary:** Median $z = 3$. 2/7 sources at $z < 2$.

**Bias:** Unbiased.

3.2 AGN companions

Sub-mm surveys of the fields around known high-redshift objects are, by definition, inevitably biased to some extent. However, given the probability that galaxy formation at high redshift is itself biased towards regions of high density, such targeted imaging surveys are a potentially important complement
Fig. 3. SCUBA image of the field around the $z = 3.8$ radio galaxy 4C41.17, revealing 3 bright sub-mm sources in addition to the radio galaxy itself (Ivison et al. 2000).

to genuinely unbiased blank-field surveys. Indeed the first few deep SCUBA images of the fields around high-redshift radio galaxies have proved remarkably successful at uncovering bright sub-mm sources, as illustrated in Figure 3. Deep radio imaging in the vicinity of such powerful radio sources is obviously challenging, but is underway at the time of writing. However, existing 450:850 ratios, and the faintness of possible optical/IR identifications already support the statistically-probable conclusion that these sources lie at the same redshift as the central AGN. Moreover, direct confirmation of this has recently been obtained for one source via CO imaging (Ivison 2001). The best estimate of the yield of this work to date is 8 sources with $S_{850} > 6\text{mJy}$ - 3 at $z = 3.8$, 2 at $z = 4.4$ and 3 at $z = 3.5$.

**Redshift Summary:** Median $z = 3.8$. 0/8 sources at $z < 2$.
**Bias:** Biased - imaging largely confined to objects at $z > 3$.

### 3.3 Blank-field surveys

#### 3.3.1 The Hubble Deep Field

At the time of writing none of the sub-mm sources in the Hubble Deep Field reported by Hughes et al. (1998) has a reliable redshift. Given the wealth of supporting data this serves to demonstrate how hard it will be to obtain complete redshift information on sub-mm selected samples. Interesting constraints can, however, be placed on the redshift of the brightest source HDF850.1 ($S_{850} = 7\text{mJy}$), following its detection with the IRAM PdB interferometer at 1.3mm (Downes et al. 1999). While the accurate position provided by the interferometric detection has not in fact yielded an unambiguous optical identification, it has enabled a robust upper limit to be placed on the 1.4GHz:850$\mu$m flux-density ratio of $> 200$. This, along with the 450:850 and
Fig. 4. Observed 450/850 µm and 850/1350 µm flux-density ratios for HDF850.1 compared with what might be expected as a function of redshift. The curves show the extreme range of colours for SEDs that represent dust enshrouded starburst galaxies and AGN - Arp220 (solid), M82 (dashed) and Mkn231 (dot-dashed). The solid horizontal line in the left-hand panel shows the existing upper limit to the 450/850 µm flux ratio for HDF850.1. The horizontal lines in the RH panel show the measured 850/1350 µm flux ratio for HDF850.1 (solid line), and the ±1σ errors on this ratio (dot-dashed lines).

850:1300 ratios all point to a redshift in the range 3 < z < 5 (see Figures 4 and 5), in which case it is certainly possible that its optical/IR counterpart is too faint to be detected by existing optical/IR imaging. Radio-submm SED constraints suggest z ≃ 2 for the second-brightest source in the HDF.

Redshift Summary: Median z = 3. 0/2 sources at z < 2.
Bias: Unbiassed, but sample very small.

3.3.2 The Canada-UK Deep Sub-mm Survey

The recent completion of the 14-hr field of the Canada-UK SCUBA survey has yielded 7 sources with signal:noise > 4σ and \( S_{850} > 4 \) mJy (Eales et al. 2000). Of particular interest is the brightest source (CUDSS 14.1; \( S_{850} = 9 \) mJy) which, like HDF850.1 has now been detected with the the IRAM PdB interferometer at 1.3mm (Gear et al. 2000). Again radio-mm-submm SED constraints favour a high redshift in the range 2 < z < 4.5; Eales et al. choose an estimated redshift of z ≃ 2.2. Most of the other 4-σ sources in this sample have not been detected at 1.4GHz, but their relatively weak sub-mm fluxes means the resulting redshift constraint is generally simply z > 2.

Redshift Summary: Median z > 2.1. 1/7 sources at z < 2.
Bias: Unbiassed, but only 3 sources brighter than 5 mJy, so radio-submm redshift constraints are weak.
3.3.3 The 8-mJy survey

The ongoing SCUBA survey of the ELAISN2 and Lockman-E fields has now covered 150 sq. arcmin to even depth, and has currently yielded 12 sources with signal:noise > 4σ at flux densities \( S_{850} > 8 \text{ mJy} \) (Scott et al. 2001). Very deep radio data will not be available for these fields until early in 2001, and so at present it is not possible to place even crude constraints on the redshifts of most of these sources. However, the brightest source in the Lockman field has been detected by the IRAM PdB interferometer, and in this case identified with a faint red complex object via very-deep \( K \)-band imaging. As shown in Figure 5, both SED constraints and the properties of this infrared identification favour a redshift in the range \( 2 < z < 4.5 \) (Lutz et al. 2001; Dunlop 2001).

**Redshift Summary:** Median \( z \approx 3. \) \( 0/2 \) sources at \( z < 2. \)
**Bias:** Unbiased, but currently lacking in redshift information. Addition of deep radio data in early 2001 will transform this situation.
| Survey           | No. | No. at $z < 2$ | $z_{\text{median}}$ |
|------------------|-----|---------------|-------------------|
| Radio Galaxies   | 9   | 1             | 3.1               |
| Quasars          | 9   | 0             | 4.4               |
| $\mu$-Jy Radio  | 4   | 1             | $>2.9$            |
| Lensing Surveys  | 7   | 2             | 3                 |
| AGN fields       | 8   | 0             | 3.8               |
| HDF              | 2   | 0             | 3                 |
| CUDDS            | 7   | 1             | $>2.1$            |
| 8mJy             | 2   | 0             | 3                 |
| **Total**        | 48  | 5             |                   |

Table 1

Our current knowledge of the redshifts of sources with $S_{850} > 4\text{mJy}$ and S/N > 4.

4 Conclusion

The results discussed above are summarized in Table 1. Despite the biases inherent in several of these surveys, it is interesting that of the $\simeq 50$ significant extragalactic sources with $S_{850} > 4\text{mJy}$ uncovered by SCUBA during its first 2-3 years of operation, only $\simeq 10\%$ appear to lie at $z < 2$. Certainly, all of these studies can be reconciled with a median redshift of at least $z_{\text{med}} = 3$ for the luminous sub-mm galaxy population.

Such a high median redshift is arguably not unexpected given current theories designed to explain the correlation between black-hole mass and spheroid mass found at low redshift. In such scenarios, peak AGN emission is expected to correspond to, or even to cause termination of major star-formation activity in the host spheroid. In contrast, maximum dust emission is expected to occur approximately half-way through the star-formation process (Eales & Edmunds 1996; Archibald et al. 2001). Given that the optical emission from powerful quasars peaks at $z \simeq 2.5$, dust-emission from massive ellipticals might be expected to peak 0.5-1 Gyr earlier, at $z \simeq 3$. Confirmation or refutation of this appealingly-simple picture requires substantially-improved redshift information on bright samples of SCUBA sources, such as the 8mJy survey.

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