Continuum Observations of the High-Redshift Universe at Sub-millimetre Wavelengths

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Abstract. New bolometer arrays operating on the world’s largest sub-millimetre and millimetre telescopes offer a unique view of the high-redshift universe with unprecedented sensitivity. Recent sub-millimetre continuum studies show that the host galaxies of many luminous high-redshift active galactic nuclei (radio galaxies and radio-quiet quasars) radiate strongly at rest-frame far-infrared wavelengths and thus contain substantial quantities of dust. In the majority of these high-redshift AGN-hosts, the inferred star formation is proceeding at a rate comparable to that found in local, interacting ultra-luminous far-infrared galaxies. This level of activity is an order of magnitude greater than the more modest star-formation rates apparently displayed by the recently-discovered Lyman-limit galaxies at z ~ 3, which have been argued to represent the era of spheroid formation (although the degree to which the effects of reddening by dust grains may have biased the interpretation of these optical/UV studies of high-z galaxies has yet to be properly determined). However, it is too early to say whether such bright far-infrared emission is a feature of all massive galaxies at z > 3, or whether it is in fact confined to the hosts of the most luminous AGN.

In this paper we review the current status of cosmological observations at sub-millimetre and millimetre wavelengths, highlighting our own recent SCUBA observations of high-redshift radio galaxies. We also explain how observations over the next few years should allow the true level of star-formation activity in the high-redshift universe to be properly quantified, and we provide example predictions for the first deep sub-millimetre survey (of the Hubble Deep Field), which we and our colleagues are currently undertaking with SCUBA at the JCMT.

1. Introduction

Sub-millimetre (sub-mm) cosmology is still in its infancy. Despite significant efforts with single-element bolometers over the last 5 years, only a handful of unlensed objects have been unambiguously detected (- for a summary, see Hughes,

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Dunlop & Rawlings 1997). However, the recent advent of sensitive sub-mm/mm bolometer arrays seems set to revolutionize the field. Studies of statistically significant samples of known high-redshift sources are now feasible, as are the first meaningful sub-mm blank-field surveys. The key logical steps in our own approach to this burgeoning field can be summarized as follows:

- Make pointed observations of known high-redshift objects spanning a wide range in redshift. We have concentrated on high-redshift steep-spectrum radio galaxies primarily because they can be reasonably expected to be the progenitors of at least a subset of present-day massive ellipticals, but also because, being selected on the basis of extended emission, their sub-mm properties are unlikely to be biased by gravitational lensing.

- Use sub-mm/far-infrared (FIR) data to first identify the emission mechanism that dominates the production of the rest-frame sub-mm/FIR luminosity. Then, if this emission is proven to be optically-thin thermal re-radiation from dust grains, use these same data to constrain the dust temperature, and hence calculate a reddening-free measure of the dust mass and infer the total mass of molecular gas in the galaxy. Assuming the dust grains are heated by young, massive stars, and not by an AGN, then estimate the ‘current’ star-formation rate (SFR).

- Compare the gas masses available for further star formation in the host galaxies of high-redshift active galactic nuclei (AGN), with the the final stellar masses of their expected low-redshift counterparts. Hence infer the evolutionary status of the galaxies that host high-redshift AGN.

- Building on the results of such pointed observations, design and undertake a series of complementary sub-mm surveys reaching different depths over different areas. Use the measured source counts and redshift distributions to determine the true level and history of star-formation activity at high redshift, and to determine the form of the cosmological evolution of the dust-enshrouded starburst population.

2. **Bright far-infrared emission from massive galaxies at high-redshift**

In the local universe, powerful active galactic nuclei are found to reside exclusively in extremely luminous host galaxies. Near-infrared images of the dominant stellar populations in the hosts of luminous low-redshift quasars and radio galaxies show that they have $K$-band luminosities $L_K \equiv 2 - 5L_K$ and that, morphologically, radio galaxies, the hosts of radio-loud quasars, and even the hosts of the more luminous radio-quiet quasars appear to be giant ellipticals (Taylor et al. 1996). It is therefore natural to assume that the hosts of luminous high-redshift radio sources are among the progenitors of the most massive present day ellipticals which have stellar masses $M_{stars} > 5 \times 10^{11}M_\odot$. Models for the photometric evolution of elliptical galaxies (e.g. Mazzei & de Zotti 1996) suggest that within the first few Gyr of their lifetimes a significant fraction ($\sim 30\%$) of their bolometric luminosity is radiated at rest-frame FIR wavelengths due to rapid massive star-formation proceeding at a rate $> 100M_\odot/yr$. At high redshifts, $z > 2$, this characteristic FIR ($60 - 200\mu m$) spectral peak is shifted into
the longer-wavelength sub-mm regime. It is the existence of this relatively brief luminous, starburst phase in the early evolution of massive galaxies that we aim to either confirm or refute.

Sub-mm observations may well be the only unbiased means of identifying the primary formation epoch of massive galaxies (assuming such a unique epoch exists) if the ISM of massive high-redshift galaxies is rapidly enriched to at least solar metallicity. In the local universe, star-formation within the most massive metal-rich galaxies produces the highest rest-frame UV-extinction (Heckman 1998) and naturally, given a suitable dust covering factor, the galaxy luminosity is dominated by re-radiated FIR emission ($L_{\text{FIR}}/L_{\text{UV}} \sim 10^{-100}$). Consequently one cannot necessarily expect optical studies of high-redshift galaxies (e.g. Steidel et al. 1996, Madau et al. 1996) to provide an accurate picture of the level of star-forming activity in the young universe without a more precise understanding of the impact of dust-obscuration on such rest-frame ultraviolet observations.

New bolometer arrays recently commissioned on the largest sub-mm/mm telescopes (JCMT, CSO and IRAM) now have the sensitivity necessary to mount meaningful searches for a dust-enshrouded population of high-redshift primæval galaxies, where we define primæval to mean the progenitors of low-redshift massive ellipticals which have gathered together the major fraction of their final baryonic mass and are caught early in the process of converting this material into stars.

In this review we concentrate on describing the opportunities to make sub-mm and millimeter continuum observations of high-redshift AGN with existing and future ground-based and space-borne instrumentation, summarise the new results from the recently commissioned bolometer array SCUBA (Gear & Cunningham 1995), operating on the 15-m James Clerk Maxwell Telescope, and highlight the uncertainties that affect their interpretation. We also briefly discuss the potential impact on models of galaxy formation/evolution of such pointed observations of known high-redshift sources, and of the first deep sub-mm surveys which are currently underway. Molecular emission and absorption line investigations are described elsewhere in these proceedings.

Throughout this paper we assume $q_0 = 0.5$ and $H_0 = 50\text{ km s}^{-1}\text{ Mpc}^{-1}$ unless stated otherwise and correct all previously published data to the same cosmology.

3. Observing dust emission at high redshift

Ground-based astronomy is provided with a few extremely dry, high-altitude, stable observing sites (e.g. Mauna Kea - Hawaii, Atacama Desert - Chile, South-Pole and Dome A - Antarctica) with sufficient atmospheric transmission that sensitive sub-mm and mm wavelength observations ($350 - 1300\mu m$) can be attempted with broad-band continuum receivers. There is a great determination to exploit such high-quality sites. New interferometric arrays (SMA, MMA, LMSA, LSA), large-single dish sub-mm (South Pole 10-m) and millimetre (LMT) telescopes, together with upgrades to the IRAM Plateau de Bure interferometer are all currently proposed, and receiver development continues apace. Future space-borne sub-mm/FIR telescopes (e.g. SIRTF, FIRST) will have the obvious advantage of complete coverage of the FIR–sub-mm regime, unhindered
Figure 1. The redshift dependence of flux density derived from the SED of the starburst galaxy Arp220 (z=0.018, $L_{\text{FIR}} \sim 3 \times 10^{12} L_\odot$, SFR $\sim 300 M_\odot \text{yr}^{-1}$) at 450$\mu$m (dashed line), 850$\mu$m (solid line), 1350$\mu$m (dashed-dotted line) and 2000$\mu$m (dotted line) as predicted for both an Einstein-de Sitter (LH panel) and low-$\Omega_0$ (RH panel) universe.

by atmospheric absorption, but the limited aperture size of such facilities (often restricted to $< 4$–m), results in larger beam sizes and inevitably a greater vulnerability to galactic and extragalactic source confusion (Helou & Beichman 1990, Gautier et al. 1992). Within the next decade new ground-based, airborne and satellite telescopes will provide the powerful combination of large collecting area, sub-arcsec resolution, significant instantaneous sky coverage (using large format ($\sim 1000$ pixel) arrays) and spectral coverage between 60$\mu$m – 3mm, all of which are necessary if sub-mm astronomy is to continue to build on its recent impact on cosmological studies.

The reason that sub-mm observations of starburst galaxies at cosmological distances are at all possible is illustrated in figure 1. When attempting to observe most types of astronomical object out to extreme redshifts, observational cosmologists usually suffer the ‘triple whammy’ of cosmological dimming, a steeply declining luminosity function, and $+$ve k-corrections. However, the steep spectral-index of the Rayleigh-Jeans emission from dust ($F_\nu \propto \nu^{2+\beta}$, $\beta \simeq 1.5$) radiating
at $30 - 70K$ produces a negative k-correction at $850\mu m$ of sufficient strength to completely compensate for cosmological dimming beyond $z \approx 1$, with the result that, certainly in an Einstein-de Sitter universe, a dust-enshrouded starburst galaxy of a given luminosity should be as easy to detect at $z \approx 10$ as at $z \approx 1$. The situation is inevitably less favourable for low values of $q_0$, but nevertheless the $850\mu m$ flux density is only expected to decrease by a factor of a few between $z = 1$ and $z = 10$ before falling dramatically at $z > 10$ as the redshifted peak of the SED ($\lambda_{\text{rest}} \sim 60 - 200\mu m$) moves to longer wavelengths through the filter passband. This relative ‘ease’ of access to the very high-redshift universe is unique to sub-mm cosmology.

Figure 1 also shows that the choice of the optimal observing wavelength for high-redshift studies has to be made with care. Four competing factors influence the decision: (i) the observed-frame spectral shape, which is a function of temperature, optical-depth and the frequency dependence of the grain emissivity; (ii) the presumed formation epoch of massive galaxies; (iii) instrumental sensitivity, and (iv) the adopted cosmological model ($\Omega_0$).

The sensitivities of bolometer instruments on all major sub-mm/mm facilities have been summarised by Hughes & Dunlop (1998) and Stark (1998) and indicate that observations at $850\mu m$ with SCUBA, operating on the JCMT, currently provide the most sensitive combination of instrument, telescope, observing wavelength and atmospheric conditions. For example, if the high-redshift universe contains starburst galaxies with FIR properties similar to Arp220 ($z = 0.018, L_{\text{FIR}} = 3 \times 10^{12} L_\odot$, SFR $\sim 300 M_\odot/\text{yr}$), then at $850\mu m$, SCUBA can detect a similar galaxy at $z = 1 - 10$, with known position, in $\sim 3$ hours, or can fully sample a random extragalactic field covering an area 6 arcminutes$^2$ in $\sim 30$ hours (e.g., the Hubble Deep Field, §5) and identify active star-forming galaxies previously undiscovered through optical, IR or radio surveys (see figure 2). Whilst in the absence of significant lensing amplification ($A > 10$) it will continue to be impossible to detect normal galaxies with moderate star formation rates ($\ll 10 M_\odot/\text{yr}$) at $z > 0.5$, the new sub-mm/mm bolometer arrays are sufficiently sensitive that we can now expect to observe a short-lived luminous formation phase of the most massive galaxies which may exist at $z > 2$ provided that the SFRs exceed $\sim 100 M_\odot/\text{yr}$. Again we note that the required integration times are significantly longer in an open universe.

The earliest sub-mm continuum observations of high-redshift sources were attempts to detect known powerful radio galaxies and radio-quiet quasars at $800\mu m$ (UKT14 – JCMT) and $1300\mu m$ (MPIfR 7-channel bolometer array – IRAM 30-m), and although a few detections demonstrated the potential power of such observations (e.g., Barvainis et al. 1994, Dunlop et al. 1994, Chini et al. 1994, Isaak et al. 1994, Ivison 1995, Omont et al. 1996b, Hughes, Dunlop & Rawlings 1997), many more continuum, but especially spectral-line observations, were unsuccessful for the possible reasons described below.

An assessment of the evolutionary status of the hosts of high-redshift AGN, based on these collective sub-mm/mm continuum data taken before 1997, was presented by Hughes, Dunlop & Rawlings (1997) who concluded that the FIR properties of high-redshift radio galaxies and radio-quiet quasars were more comparable with those of low-redshift interacting and star-forming ultraluminous FIR galaxies than with those expected of primaeval massive ellipticals, if
Figure 2. The $S_{850\mu m} - z$ relationship normalised to the 850$\mu m$ flux-density of Arp220 (see figure 1) which has a SFR $\sim 300 M_\odot$ yr$^{-1}$ (solid curve). Also shown are curves for a galaxy with a FIR luminosity and SFR $\times 10$ (dot-dashed curve) and $\times 0.1$ (dashed curve) that of Arp 220. The heavy and light horizontal lines show the 3-σ flux densities currently achievable with SCUBA when used in MAPPING (a single fully-sampled pointing) and PHOTOMETRY modes in integration times of 3, 30 and 150 hours respectively. The predicted $S_{850\mu m} - z$ relationship is shown for two alternative cosmologies.
such objects formed the bulk of their present-day stellar populations in a single major star-burst at high-redshift (and thus might be expected to have SFRs > 500M_☉/yr and molecular gas masses M_{H_2} > 5 \times 10^{11}M_☉ - see §2).

The apparently greater success rate of sub-mm observations of high-redshift RQQs (Omont et al. 1996b), compared to that of radio galaxies, may be due to lensing which could have aided their initial identification in optical flux-limited samples, and which also amplifies their rest-frame FIR luminosity. It might also suggest that the hosts of high-redshift radio-quiet quasars are more gas rich than their radio-loud counterparts. However, it may simply reflect the greater number of extremely luminous AGN available for study in optical quasar samples compared to radio surveys because, interestingly, in both cases it is the objects of greatest luminosity (M_B < −27 in the case of QSOs, and log(P_{408 MHz}/WHz^{-1}sr^{-1}) > 27.5 in the case of radio galaxies - see next section) which have proved to be most easily detected at sub-mm wavelengths (Dunlop et al. 1994, Ivison et al. 1998a, Omont et al. 1996b). If confirmed, such a correlation between sub-mm luminosity and AGN activity at high-redshift might arise for a number of reasons, including an underlying correlation with host galaxy mass (see §4).

Some obvious possible explanations for the failure to detect large numbers of high-redshift active galaxies are that (i) elliptical galaxies do not form during the collapse of single massive halo with a luminous, but short-lived burst of starformation, and instead form through the hierarchical clustering and merging of lower-mass gas clouds, which may already have formed their first generation of stars at an even higher redshift; (ii) that the formation phase is more intense than expected, but with a proportionately shorter timescale, making it harder to “catch one in the act”; (iii) that massive elliptical galaxies are more or less fully assembled, and the bulk of their stars have formed, prior to z ≃ 4, and/or (iv) that we live in an open universe and our observations are therefore effectively less sensitive.

The imaging capabilities and greater sensitivity of SCUBA will alleviate most of these difficulties by allowing pointed observations of high-redshift AGN and wide-field surveys that cover a much larger region of parameter space (redshift, radio power, FIR luminosity, dust and gas mass). This will lead to a clearer understanding of the extent to which AGN hosts are reliable probes of the evolution of massive galaxies, and the relationship between the properties of the AGN and its host galaxy. Furthermore the sub-arcsec resolution of future interferometers (where 1 arcsec corresponds to ~ 6 kpc at z = 4) may enable follow-up observations to discriminate whether the source of the FIR emission originates from a single luminous galaxy, or multiple merging galaxies. In the remainder of this paper we describe the first observations of high-redshift radio galaxies with SCUBA, and the prospects for the first deep ‘blank field’ surveys which, at the time of writing, we are currently undertaking.

4. SCUBA observations of high-redshift radio galaxies

4.1. Study design

An initial step towards an understanding of the FIR properties of the galaxies in the first few Gyr of the universe (i.e. at z > 2) has been to make pointed
Figure 3. The radio-luminosity:redshift \((P - z)\) plane of high-z galaxies selected from progressively deeper radio surveys (3C - open circles; 6C - filled squares; 7C - crosses; LBDS - filled circles) to be observed at sub-mm wavelengths. Using sub-mm observations of these samples we can quantify the contribution of an AGN to the rest-frame FIR luminosity, and trace the evolution of gas mass and star-formation rate as function of redshift and radio luminosity. The dashed line delineates the region of parameter space \(\log\left(\frac{P_{408\text{MHz}}}{\text{WHz}^{-1}\text{sr}^{-1}}\right) > 27.0\) to which we are currently confining our SCUBA observations, in order to be able to quantify the cosmological evolution of dust and gas in radio galaxies of fixed radio luminosity. The sub-mm data for the subset of radio galaxies observed to date are presented in table 1.

observations of known high-redshift active galaxies (radio galaxies and radio-quiet quasars). The criteria used to determine which sources are selected as prime candidates for sub-mm observations are mixed, and include strong ultra-steep spectrum radio emission (e.g. Dunlop et al. 1994, Hughes, Dunlop & Rawlings 1997), bright optical emission (e.g. Omont et al. 1996a,b), and high lensing amplification (Barvainis et al. 1994). An exciting development has been the recent sub-mm imaging of two intermediate-redshift lensing clusters (Smail, Ivison & Blain 1997), which provide a small amplification \(A \approx 1.5 - 3\) of the high-redshift universe, and which has in turn resulted in the discovery of an ultraluminous active galaxy at \(z \sim 2.8\) (Ivison et al. 1998b).

We have concentrated on studies of steep-spectrum radio galaxies primarily because, as mentioned above, their low-redshift counterparts are exclusively massive ellipticals and object selection on the basis of extended radio emission
should be essentially free from lensing bias. Thus, while radio galaxies may not be the easiest high-redshift objects to detect at sub-mm wavelengths, there is a genuine prospect that their sub-mm emission (or lack of it) can provide some meaningful constraints on the evolution of massive ellipticals. Consequently our collaboration is currently endeavouring to build on the work of Dunlop et al. (1994) and Hughes, Dunlop & Rawlings (1997), and to attempt to address the question “how and when did massive elliptical galaxies form?” by conducting a systematic 850µm survey of radio galaxies spanning the redshift range $z \approx 0 - 5$ and a wide range of radio power (24.0 $< \log(P_{408MHz}/\text{WHz}^{-1}\text{sr}^{-1}) < 28.5$).

With observations of a large sample of steep-spectrum, extended radio galaxies selected from progressively deeper low-frequency radio surveys (3C, 6C, 7C, LBDS) we can avoid non-thermal contamination of the sub-mm emission, minimize any bias in the interpretation due to lensing, and break the correlation between redshift and radio luminosity which arises in a survey with a single radio flux limit (Figure 3).

4.2. Uncertainties in derived physical parameters

In principle it is a straightforward exercise to derive the relevant physical parameters for high-redshift galaxies (such as rest-frame FIR luminosity, SFR, dust mass, molecular gas mass) from sub-mm continuum data, but in practice one has to proceed with caution. The first step is to use, if possible, a measure of the sub-mm spectral index to reject self-absorbed non-thermal synchrotron emission in favour of thermal re-radiation from dust grains as the source of the FIR luminosity (Chini et al. 1989, Hughes et al. 1993). Second one has to establish that this thermal emission is unambiguously associated with the source, and not, for example, with galactic cirrus. Third there are a number of properties related to the grains and their emission that must be constrained (such as grain size, density, temperature distribution and frequency dependence of emissivity). Fourth, one must be able to exclude or quantify any gravitational lensing amplification. Fifth one has to be aware of the effect of an uncertain cosmology. Sixth, to convert dust mass into total gas mass requires assumptions to made about, or constraints to be placed upon, the molecular gas:dust ratio and also the metallicity of the ISM in massive galaxies at early epochs (Eales & Edmunds 1996). A full discussion of all of these uncertainties, and how at least some of them can best be minimized is given by Hughes, Dunlop & Rawlings (1997).

If one assumes or can establish that the sub-mm continuum ($\lambda_{\text{rest}} > 200\mu m$) is due to optically-thin emission from heated dust grains with no additional contribution from bremsstrahlung or synchrotron radiation, a measure of the dust mass $M_d$ can be determined directly from the relationship,

$$M_d = \frac{1}{(1 + z)} \frac{S_{\text{obs}} D_L^2}{k_d^\text{rest} B(\nu_{\text{rest}}, T)}$$

where $z$ is the redshift of the source, $S_{\text{obs}}$ is the observed flux density, $k_d^\text{rest}$ is the rest-frequency mass absorption coefficient, $B(\nu_{\text{rest}}, T)$ is the rest-frequency value of the Planck function from dust grains radiating at a temperature $T$, and the luminosity distance, $D_L$, is given by
\[ D_L = \frac{2c}{H_0\Omega_0^{1/2}} \left\{ \Omega_0 z + (\Omega_0 - 2)[(\Omega_0 z + 1)^{1/2} - 1] \right\} \] (2)

4.3. Results

We have recently commenced this major SCUBA programme by concentrating on observations of radio galaxies in the highest decade of radio luminosity for which radio galaxies can be found at all redshifts \( z = 0.5 - 5 \) (i.e. objects in our sample with \( \log(P_{408\text{MHz}}/\text{WHz}^{-1}\text{sr}^{-1}) > 27.0 \) - see figure 3). The subsample observed to date is listed in Table 1 which gives redshift, radio power, and the new measurements of 850\( \mu \text{m} \) flux density for each galaxy. We also give our best estimates of the physical quantities which can be derived directly from the 850\( \mu \text{m} \) measurement – FIR luminosity, SFR and dust mass. The FIR properties of these high-redshift radio galaxies are compared against the properties of local starforming galaxies in figure 4. These new SCUBA data reinforce our earlier conclusion that many of these high-redshift ellipticals display much more intense starforming activity and contain much larger masses of dust and gas than their low-redshift counterparts (Chini et al. 1989, Knapp & Patten 1991, Hughes et al. 1993). However, figure 4 also demonstrates that while unusually active in the FIR compared to low-redshift radio galaxies and other ellipticals, very few high-redshift radio galaxies appear to be forming stars at a rate significantly higher than is found in low redshift ULIRGS. This appears to also be true for radio-quiet quasars, particularly if one allows for the possibility of significant lensing of FIR emission from extreme objects such as BR1202–0725 (Ohta et al. 1996, Omont et al. 1996a). Thus, with the possible exception of 4C41.17 and 8C1435+635, none of the high-redshift radio galaxies we have observed to date appears to have the extreme FIR emission expected from a massive elliptical galaxy forming the bulk of its eventual stellar massive in a \( \approx 1-\text{Gyr} \) star-burst.

Nevertheless, 4C41.17 and 8C1435+635 are undeniably interesting objects, in that they lie at extreme redshift (\( z \approx 4 \)) and they are also the two most radio-luminous objects in our sample. One of the most important questions to answer, therefore, is whether their extreme sub-mm properties are primarily related to their extreme redshift or their extreme radio power. Extension of our radio-galaxy survey to lower radio luminosities (at high-redshift) should help to answer this question. Ultimately, however, to properly quantify the level of star-formation at \( z > 4 \) requires unbiased blank-field sub-mm surveys, the first of which we now briefly discuss in the concluding section of this paper.

5. Sub-millimetre Surveys

Over the last few years giant strides have been made in the study of galaxy evolution/formation at optical/near-infrared wavelengths. The completion of the first major galaxy surveys reaching \( z \approx 1 \) (e.g. Lilly et al. 1995), the development of sophisticated spectral/dynamical/chemical models of galaxy evolution (e.g. Jimenez et al. 1998; Baugh, Cole & Frenk 1996, Kauffman & Charlot 1998) and HST/Keck observations of high-redshift galaxies (e.g. Pettini et al. 1997; Dunlop et al. 1996, Ellis 1998) have combined to revolutionize the field.
Table 1.  Physical parameters\(^a\) derived from \(850\mu m\) flux densities of high-redshift radio galaxies, including radio power, FIR luminosity, star formation rate and dust mass.

| Source     | \(z\) | \(S_{850\mu m}\) (mJy) | \(\Delta S_{850\mu m}\) (mJy) | \(\log P_{408\,MHz}\) (WHz\(^{-1}\)sr\(^{-1}\)) | \(\log L_{\text{FIR}}\)\(^b\) (L\(_\odot\)) | \(\text{SFR}\)\(^c\) (M\(_\odot\)/yr) | \(\log M_{\text{dust}}\) (M\(_\odot\)) |
|------------|-------|------------------------|-------------------------------|---------------------------------|------------------|-----------------|-----------------|
| 53W002     | 2.39  | 0.9                    | 1.1                           | 26.79                           | <12.83           | <674            | <8.20           |
| 3C340      | 0.78  | 1.0                    | 1.2                           | 27.10                           | <12.91           | <810            | <8.28           |
| 3C277.2    | 0.76  | 1.8                    | 1.1                           | 27.17                           | <12.87           | <734            | <8.24           |
| 6C0901+35  | 1.91  | -1.9                   | 1.2                           | 27.18                           | <12.90           | <803            | <8.28           |
| 3C217      | 0.89  | 0.2                    | 0.8                           | 27.32                           | <12.75           | <562            | <8.12           |
| 6C1204+37  | 1.78  | 0.8                    | 1.0                           | 27.38                           | <12.84           | <684            | <8.21           |
| 6C0930+38  | 2.39  | 1.5                    | 1.1                           | 27.39                           | <12.82           | <674            | <8.20           |
| 3C265      | 0.81  | -1.1                   | 1.0                           | 27.39                           | <12.83           | <684            | <8.21           |
| 6C0905+39  | 1.88  | 2.8                    | 0.9                           | 27.54                           | 12.79            | 627             | 8.17            |
| 6C0032+412 | 3.67  | 2.4                    | 1.6                           | 27.67                           | <12.90           | <792            | <8.27           |
| B20902+34  | 3.39  | 1.9\(^d\)              | 1.5                           | 27.72                           |                  |                 |                 |
| 3C324      | 1.21  | 2.4                    | 1.0                           | 27.73                           | <12.86           | <727            | <8.24           |
| 6C0140+326 | 4.41  | 3.0                    | 1.5                           | 27.75                           | <12.83           | <679            | <8.21           |
| 3C241      | 1.62  | 3.1                    | 1.5                           | 27.88                           | <13.02           | <1052           | <8.39           |
| 6C1232+39  | 3.22  | 3.9                    | 1.0                           | 27.89                           | 12.84            | 689             | 8.22            |
| 3C294      | 1.78  | 1.2                    | 0.8                           | 27.92                           | <12.74           | <547            | <8.11           |
| 3C257      | 2.47  | 3.9                    | 1.1                           | 28.08                           | 12.89            | 784             | 8.27            |
| 4C41.17    | 3.80  | 12.3                   | 1.8                           | 28.14                           | 13.30            | 1996            | 8.68            |
| 8C1435+635 | 4.25  | 8.3                    | 0.7                           | 28.56                           | 13.10            | 1275            | 8.48            |

\(^a\)\(H_0 = 50\,\text{km/s/Mpc}, \Omega = 1.0\)

\(^b\)assumes isothermal 50K

\(^c\)SFR/(M\(_\odot\)/yr\(^{-1}\)) \simeq 10\(^{-10}\)L\(_{\text{FIR}}\)/L\(_\odot\)

\(^d\)non-thermal flat-spectrum radio core dominates sub-mm emission
Figure 4. The physical properties of high-z radio galaxies (this paper - open stars and limits) and radio-quiet quasars (Omont et al. 1996b - filled circles), which lie within the parallelogram, have been derived from sub-mm or mm continuum detections (assuming $T = 50$ K, $M_{H_2}/M_d = 500$) and are compared to those of starburst galaxies (filled stars) and ULIRGs (crossed circles) in the local universe. The diagonal lines indicate constant $L_{FIR}/M_{H_2}$. The vertical dashed-line shows the gas mass boundary, to the right of which is a region of the parameter space marked “PGs” where one might expect to find the progenitors of the most massive, $> 5 	imes 10^{11} M_\odot$, elliptical galaxies if they form by monolithic collapse. This figure is adapted from Hughes, Dunlop & Rawlings (1997).
Figure 5. Alternative example predictions for the cumulative redshift distribution of sources detected in a deep 850µm image of the Hubble Deep Field reaching a complete flux-density limit of 1.5 mJy. Two alternative predictions have been produced by subjecting the local IRAS luminosity function to i) pure luminosity evolution ($L(z) \propto (1 + z)^3$ out to $z = 2$ with no further evolution (either positive or negative) at higher redshifts (solid line), and ii) evolution of the form displayed by powerful radio galaxies, with a decline in space density beyond the peak at $z \approx 2 - 3$ (Dunlop & Peacock 1990).

Particular exciting has been the discovery of a substantial population of high-redshift galaxies which has not been detected via nuclear activity (Steidel et al. 1996). This has led to (arguably premature) attempts to delineate the entire cosmological history of star formation out to $z \approx 4$, with initial analyses (e.g. Madau et al. 1996) suggesting that star-formation activity peaked at relatively modest redshifts $z \approx 1 \rightarrow 1.5$ (a result hailed as a success for CDM-dominated models of hierarchical structure formation). However, such optically-based studies are always vulnerable to the effects of dust which can lead both to under-estimation of star-formation rates in those UV-bright objects that are detected, and to potentially serious incompleteness at high redshift if a significant amount of star-formation takes place in dust-enshrouded environments.

The unbiased nature of radio-based selection at high-z, coupled with the near-identical evolution of radio and star-formation activity out to $z \approx 1$, led Dunlop (1997) to suggest that the evolution of radio activity should be regarded as the current best predictor of the true evolution of star-formation activity. The implication is that starformation at $z > 2$ has been underestimated by a factor
\( \simeq 5 \) and interestingly factors of \( 3 \rightarrow 10 \) have recently been suggested by Pettini et al. (1997) and Heckman (1998) due to the obscuring effect of dust on the UV light from starburst galaxies. However even this may not be the complete story since the evolution of radio-source activity may mirror a secondary phase of star-formation activity due to merging, with the primary epoch of star-formation lying at significantly higher redshift (as indicated by the large age of at least some high-z galaxies; Dunlop et al. 1996).

The key challenge in this field for the next few years is therefore to properly quantify the level of star-formation activity in the high-z universe. If the large FIR luminosities of 4C41.17 and 8C1435+643 are in fact typical of massive galaxies at high redshift, then deep sub-mm surveys can be expected to contain large numbers of high-redshift galaxies.

At the time of writing we and our colleagues are performing the first deep SCUBA sub-mm survey of the sky, aimed at obtaining a deep 850\( \mu m \) image of the Hubble Deep Field reaching a 3-\( \sigma \) flux density limit of \( \simeq 1-1.5 \) mJy. To whet the appetite we provide, in Figure 5, predicted cumulative redshift distributions for sources which should be detected in such a survey under two alternative scenarios for the cosmological evolution of the dust-enshrouded star-burst population. In the first case (dashed line) we have assumed that the evolution of the IRAS galaxy luminosity function mirrors that of the active galaxy radio luminosity function (as it certainly does out to \( z \simeq 1 \)) at all redshifts, with the population peaking in luminosity at \( z \simeq 2-3 \) and declining at higher redshifts (Dunlop & Peacock 1990). Such a scenario leads to a prediction of approximately 4 sources in the HDF with \( S_{850\mu m} > 1.5 \) mJy, all of which would be expected to lie at \( z > 1 \) but with none expected to lie at \( z > 3 \) due to the enforced high-redshift 'cutoff'. In the second case (solid line), a very similar level of luminosity evolution \( (L(z) \propto (1+z)^3) \) has been applied out to \( z = 2 \), with no further evolution in the luminosity function (either positive or negative) at higher redshift. Such a scenario would predict \( \simeq 10 \) sources, approximately half of which could lie at \( z > 4 \). Clearly such an observation has the power to determine whether or not substantial amounts of dust-enshrouded star-formation occurred during the first Gyr of our Universe.

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