High-redshift radio galaxies and quasars at submillimetre wavelengths: assessing their evolutionary status

D. H. Hughes,1,2 J. S. Dunlop1 and S. Rawlings2

1Institute of Astronomy, Department of Physics and Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ
2Astrophysics, Nuclear Physics Laboratory, Oxford University, Keble Road, Oxford OX1 3RH

Accepted 1997 March 20. Received 1997 January 30; in original form 1996 August 28

ABSTRACT
We present new results of a study of the submillimetre continuum emission from a sample of nine radio galaxies and four radio-quiet quasars at redshifts $z=0.75-4.26$. The observations were made at 800 µm, using the single-element bolometer UKT14 on the James Clerk Maxwell Telescope (JCMT), reaching a typical rms sensitivity of $\sigma_{\text{rms}} \approx 4$ mJy, and they represent some of the deepest submillimetre extragalactic measurements made to date. Three detections were achieved, of which two are secure (4C 41.17 and H1413 + 117) and one (53W002) is tentative, whilst comparable upper limits were obtained for seven of the 10 remaining sources. We use these data as the motivation for a detailed discussion of the conversion from submillimetre and millimetre continuum fluxes to dust/gas masses and star formation rates at high redshift, and determine these quantities from our own and other data on high-redshift radio galaxies and quasars. In particular, we investigate the impact of the four main sources of uncertainty in deriving physical quantities from such data, namely (i) potential contamination by Galactic cirrus, (ii) uncertainty in the value of the dust rest-frequency mass-absorption coefficient, (iii) difficulty in constraining the dust temperature, and (iv) estimation of the appropriate gas-to-dust ratio in high-redshift objects. Our discussion emphasizes how important it will be to quantify and, where possible, minimize such uncertainties (via, for example, appropriate observational strategies) in order to capitalize fully on the 10-fold improvement in sensitivity offered by the imminent arrival of the next generation of bolometer arrays, such as SCUBA on the JCMT.

Taking these uncertainties into account, we show that whilst the high-redshift galaxies discussed in this paper are amongst the most dust-rich and luminous objects discovered to date, their far-infrared properties are more comparable with those of the most luminous nearby interacting galaxies than with those expected of primaeval giant ellipticals. This conclusion is rather insensitive to the adopted dust temperature, and the appropriateness of our adopted gas-to-dust ratio is supported by the molecular line detections of lensed objects. Indeed, despite all of the uncertainties peculiar to studying galaxy evolution at submillimetre wavelengths, the current uncertainty over the true value of $\Omega_0$ is probably the most important factor affecting our conclusions.

Key words: stars: formation – dust, extinction – galaxies: active – galaxies: formation – quasars: general – radio continuum: galaxies.
1 INTRODUCTION

Over the past four years, we have undertaken a number of submillimetre observations of high-redshift radio galaxies and quasars (using the single channel 4He bolometer UKT14 on the JCMT) aimed at determining the evolutionary status of these objects on the basis of the strength of their rest-frame far-infrared (FIR) continuum emission. Since the arrival of the new generation of submillimetre bolometer arrays is now imminent, this seems an appropriate time to summarize the existing observational results (including our own data presented here), to review the main sources of uncertainty which affict the meaningful physical interpretation of such data, and, in the light of recent Keck and HST results (Steidel et al. 1996; Illingworth 1997), to reappraise the importance of deep submillimetre observations for the study of galaxy evolution and formation (Hughes 1996).

The original motivation for attempting to detect submillimetre emission in high-redshift galaxies, despite the relative insensitivity of existing submillimetre detectors was the realistic possibility that at least some massive galaxies formed the majority of their stars in a relatively short (< 1 Gyr) starburst at high redshift, and that the resulting necessarily high star formation rates (SFRs ~ 100–1000 M⊙ yr⁻¹) could give rise to strong rest-frame FIR thermal emission from dust. This motivation remains as strong as ever, despite the recent discovery at optical wavelengths of a population of star-forming galaxies at redshifts z ~ 3 (Steidel et al. 1996). While the space-density of these Lyman-limit galaxies at z ~ 3 indicates that we may be seeing the progenitors of a substantial fraction of present-day bright galaxies, their rather moderate star formation rates (SFRs ~ 10 M⊙ yr⁻¹) would have to be sustained for virtually a Hubble time to produce the most massive elliptical galaxies which exist in the present-day Universe (of stellar mass ~ 10¹¹ M⊙). The implication is that, while in the Lyman-limit galaxies we may be seeing the formation of the bulges of spiral galaxies and the cores of some ellipticals (an interpretation supported by their compact spheroidal appearance; Giavalisco, Steidel & Macchetto 1996), certainly for the most massive galaxies the SFRs must have been substantially greater (≥ 10⁵ M⊙ yr⁻¹) at higher redshifts.

Indeed, we now possess rather strong evidence that this must have been the case. First, the basic properties of present-day elliptical galaxies, namely low molecular gas and dust masses, < 10⁴ M⊙ (Knapp & Patten 1991; Lees et al. 1991; Wilkinds & Henkel 1995), enormous stellar masses ~ 10¹¹–10¹² M⊙, determined from the K-band luminosities (≥ 2 x L*; Taylor et al. 1996) of the host galaxies of low-z radio galaxies, radio-loud quasars (RLQs) and the most luminous radio-quiet quasars (RQQs), and uniform optical–infrared colours (Bower, Lucey & Ellis 1992) that are dominated by a well-evolved stellar population, indicate that the bulk of their stars were formed in a relatively short-lived starburst at high redshift. Secondly, rather more severe constraints on what the phrase ‘high-redshift’ must actually mean have been recently provided by Dunlop et al. (1996), who have presented spectroscopic evidence that star formation ceased in a z = 1.55 radio galaxy at least 3.5 Gyr prior to the epoch at which the galaxy is observed. Such a great age formally excludes an Einstein–de Sitter cosmology for a Hubble constant H₀ > 50 km s⁻¹ Mpc⁻¹ and thus indicates an extreme formation redshift (z ≥ 5) for this galaxy in almost any cosmological model. This object is not a freak; a second, apparently even older radio galaxy has now been discovered at a similar redshift (Dunlop 1997), and spectroscopy of radio-quiet ellipticals in the cluster around the z = 1.26 radio galaxy 3C 324 indicates similarly old ages for the vast majority of their stellar populations (Dickinson 1997). Thirdly, a radio galaxy has recently been discovered at z = 4.41 (Rawlings et al. 1996); this demonstrates that at least some massive galaxies were in place at early epochs, and its properties (e.g., low rest-frame ultraviolet flux) are not obviously those of a young star-forming system. In summary, despite the important discovery of the star-forming population at z = 3 (Steidel et al. 1996), a growing body of evidence in fact indicates that we have yet to discover the formation epoch of the most massive galaxies and that, given the available cosmological time, the formation of these objects must have been short-lived and hence should be spectacular in at least one wavelength regime.

These last two studies illustrate the key role which radio galaxies continue to play in studies of high-redshift galaxy evolution and formation. The main reason for this is that all low-redshift radio galaxies are associated with giant elliptical galaxies (Owen & Laing 1989), and thus it is reasonable to assume that they can be used to trace the evolution of the most massive galaxies back to high redshifts, and early cosmic epochs.

However, while we can be reasonably confident that the hosts of high-redshift radio sources are the progenitors of giant elliptical galaxies, recent years have seen a growing concern that, at least in the most powerful sources, the direct or indirect effects of their active nuclei might stymie any attempt to determine their evolutionary status at optical–infrared wavelengths. For example, the discovery of multimodal optical structures aligned along the radio axis of high-redshift radio galaxies (Chambers, Miley & van Breugel 1987; McCarthy et al. 1987) seemed at first sight to indicate the assembly of giant elliptical galaxies from the merging of low mass clumps at relatively recent redshifts, as expected in certain hierarchical models of structure formation. However, in subsequent years there has been much debate about whether this is true, and about the evolutionary status of high-redshift radio galaxies in general. Early arguments that z > 2 radio galaxies contained old evolved stars (e.g. Lilly 1988, 1989) have been questioned (e.g. Chambers & Charlot 1990; Eales & Rawlings 1993), but there has been a distinct lack of proof that any of the stellar systems are demonstrably young (although arguments have been made that this is the case, e.g., 53W002 – Windhorst et al. 1991 and 0902 + 34 – Eales et al. 1993). The few hints of ‘primevality’, gleaned from ultraviolet–infrared observations, have remained hard to prove, largely because of the way in which high-redshift radio galaxies are typically selected by virtue of their extreme radio luminosity. An inescapable consequence of high radio luminosity appears to be significant non-stellar emission across the ultraviolet, optical and infrared bands (e.g. Rawlings & Saunders 1991; Dunlop & Peacock 1993; Eales & Rawlings 1996). In other words, huge narrow emission lines, large ultraviolet luminosities and multimodal structures (which naive one might interpret as evidence for extremely high star formation rates
and dynamically young systems) are now often attributed to the action of the powerful jets or quasar light emanating from the active nuclei of these extreme objects. On the other hand, even when radio galaxies are faint (e.g., the \( z = 4.41 \) radio galaxy studied by Rawlings et al. 1996), it is impossible to disprove huge SFRs since, as in the case for some local ultraluminous IRAS galaxies (Sanders et al. 1988), star formation activity may be enshrouded in dust.

This latter point provides the prime motivation for the study described here. A more robust signature of massive star formation than ultraviolet continuum and emission lines is intense FIR emission from dusty, molecular material, where the rate of dust production is proportional to the SFR. The dust is heated primarily by the embedded O and B stars which evolve quickly and dispense their surrounding material on similarly short time-scales (~10^7 yr, Wang 1991). Hence the FIR luminosity provides a measure of the current SFR of massive stars, 

\[
SFR = \varepsilon 10^{10} \frac{L_{\text{FIR}}}{L_{\odot}} \text{ M}_\odot \text{ yr}^{-1},
\]

where \( \varepsilon = 0.8-2.1 \) (Scoville & Young 1983; Thronson & Telesco 1986). If galaxies at high redshift have FIR luminosities comparable to or greater than low-z ultraluminous infrared galaxies (ULIRGs, \( L_{\text{FIR}}/L_{\odot} \geq 10^8 \)), hence SFRs > 100 M_\odot yr^{-1}, then it is possible that they convert 10^{11}-10^{12} M_\odot of gas into stars in a burst of duration < 1 Gyr.

In the Milky Way and local disc galaxies a significant fraction (30 per cent) of the bolometric luminosity \( (L_{\text{bol}}) \) is reradiated at FIR wavelengths, and hence the SFR (Miller & Scalo 1986) and the ratio \( L_{\text{FIR}}/L_{\text{bol}} \) cannot have evolved much with look-back time. However, the situation is very different for elliptical galaxies. Mazzei, de Zotti & Xu (1994) have modelled the photometric evolution of elliptical galaxies and show that, whilst at the current epoch ellipticals emit < 1 per cent of their bolometric luminosity at FIR wavelengths, within the first 1–2 Gyr of their formation this fraction was significantly higher with \( L_{\text{FIR}}/L_{\text{bol}} \sim 0.3 \) (see Fig. 1).

Whilst the details of the evolution are sensitive to the assumed initial mass function (IMF) and SFR (where the steeper IMF and higher SFR produces a more luminous, but shorter, burst of star formation), it is hard to escape the conclusion that the formation of giant elliptical galaxies is expected to be a spectacular and luminous phenomenon in the rest-frame FIR. Indeed, this should be true irrespective of whether ellipticals form via the collapse of a single gaseous halo, or grow through the rapid merging of smaller mass clumps at high \( z \), particularly since the mass dependence of metallicity and mass-to-light ratio in elliptical galaxies indicates that early star formation in massive ellipticals should be strongly biased towards high-mass stars (Zepf & Silk 1996).

Any attempt to detect this thermal radiation from dust in high-redshift radio galaxies would fail were it not for the fact that the expected FIR emission peak (at \( \lambda \sim 60–100 \) \( \mu \)m), due to grains radiating at temperatures of 30–70 K, is shifted into the submillimetre region (\( \lambda > 300 \) \( \mu \)m) at the redshifts of interest. Fig. 2(a) demonstrates that, in an Einstein–de Sitter universe and at wavelengths \( \geq 800 \) \( \mu \)m, the effects of cosmological dimming on a typical starburst galaxy spectrum are offset between redshifts \( z = 1–10 \) by the strongly negative \( K \)-correction (which arises as the submillimetre filters effectively climb the Rayleigh–Jeans tail of the thermal dust emission with increasing redshift). The situation for a low-density universe is not as advantageous (Fig. 2b), where the observed flux density for a redshifted object continues to fall, albeit more slowly, in all submillimetre and millimetre wavelength passbands.

In this paper we report on an attempt to exploit the ‘detectability’ of thermal emission from dust at high redshift to determine the evolutionary status of known high-redshift radio galaxies and quasars. The aim is to use submillimetre continuum photometry to estimate, or at least constrain, the mass of dust in high-redshift objects, with a view to determining both the SFR and, more importantly, the mass of gas which has yet to be turned into stars in these potentially young galaxies.

While gas masses can in principle be derived from molecular-line observations, we have chosen to concentrate on a submillimetre continuum approach for three reasons. First, comparable assumptions and uncertainties also complicate attempts to derive an accurate H_2 mass from detections of CO emission. Secondly, despite determined efforts, with the exception of BR 1202 – 0725 (Ohta et al. 1996; Omont et al. 1996a), no significant detection of molecular gas has been achieved in any high-z radio galaxy or quasar (Barvainis & Antonucci 1996; Evans et al. 1996; van Ojik et al. 1997) unless it has been greatly magnified by gravitational lensing (Barvainis et al. 1994; Eisenhardt et al. 1996). Thirdly, it is in submillimetre continuum astronomy that the greatest advances in sensitivity are likely to be forthcoming in the immediate future.

As explained above, we have chosen to concentrate on radio galaxies because of their likely association with the high-redshift counterparts of massive elliptical galaxies, but we have also observed a few RQQs in an attempt to confirm previously published detections. Our submillimetre observations are described in Section 2. In Section 3 we present a detailed point-by-point analysis of the various uncertainties.
which afflict attempts to accurately estimate the dust mass of a high-redshift galaxy from submillimetre observations. Then, in Section 4, we derive our best estimates of the dust masses of these high-redshift objects and use this information to assess their evolutionary status, by estimation of both the SFR and the amount of molecular gas which, at the time of observation, has yet to be converted into stars. Finally, in Section 5 we discuss explicitly, and endeavour to quantify, the realistic uncertainties in these extrapolations, in particular the gas-to-dust ratio at high redshift.

Throughout the paper we assume $q_0 = 0.5$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ unless stated otherwise, and correct previously published data to the same cosmology to allow a comparison of all physical quantities.

2 SUBMILLIMETRE OBSERVATIONS

2.1 Target selection strategy

As Fig. 2 illustrates, if one wishes to attempt to detect high-redshift ($z > 1$) objects at submillimetre wavelengths, little if anything is lost in terms of sensitivity between $z \approx 1$ and $z \approx 10$. Consequently, since the SFR in elliptical galaxies is expected to be highest at early times (Fig. 1) it make sense to start with the most distant known objects. We thus selected our primary targets (see Table 1) from among the most distant known radio galaxies, concentrating on objects which have been well studied in the optical-infrared while also attempting to span a meaningful range of radio luminosities and redshifts. 4C 41.17 and 8C 1435 + 643 are extremely luminous radio sources and each, at the time they were observed, held the title of the most distant known galaxy in the Universe. B2 0902 + 34 is an extremely well-studied object and has been hailed as one of the best known candidates for a primeval galaxy (Eales et al. 1993). 6C 0032 + 412 and MG 2141 + 192 are two of the most distant known galaxies at more moderate radio luminosities, while 53W002 is the most distant mJy radio galaxy (Windhorst et al. 1991). 3C 257 was selected because it is the most distant 3CR radio galaxy and because near-infrared spectroscopy has indicated that Lyman $\alpha$ emission in this source is attenuated by dust. Two additional radio galaxies at intermediate redshifts ($z \approx 1$) were selected because of circumstantial evidence suggesting the presence of dust; 3C 318 is the most distant radio galaxy detected by IRAS (Heckman, Chambers & Postman 1994), and 3C 65 has an extremely red $r-K$ colour (Lilly 1989; Dunlop & Peacock 1993). Lastly, we observed four RQQs, again spanning the redshift range $z = 1-4$, both to attempt to confirm or refute claimed IRAM detections at millimetre wavelengths, and to enable
Table 1. 800-μm photometry of high-redshift radio galaxies (RGs) and radio-quiet quasars (RQQs). The flux density limits quoted in column 6 are given at the 3σ level. The references in column 7 give the positions, redshifts and details of other relevant observations.

<table>
<thead>
<tr>
<th>Source name</th>
<th>type</th>
<th>z</th>
<th>R.A. (J2000)</th>
<th>Dec (J2000)</th>
<th>S_{800\mu m} (mJy)</th>
<th>refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 318</td>
<td>RG</td>
<td>0.752</td>
<td>15 20 05.49</td>
<td>+20 16 05.1</td>
<td>&lt;33</td>
<td>1</td>
</tr>
<tr>
<td>3C 65</td>
<td>RG</td>
<td>1.176</td>
<td>02 23 43.48</td>
<td>+40 00 52.7</td>
<td>&lt;11</td>
<td>1, 2</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>RQQ</td>
<td>1.334</td>
<td>16 34 28.97</td>
<td>+70 31 32.4</td>
<td>&lt;11</td>
<td>3</td>
</tr>
<tr>
<td>53W002</td>
<td>RG</td>
<td>2.290</td>
<td>17 14 14.78</td>
<td>+50 15 30.4</td>
<td>6.9 ± 2.3</td>
<td>4, 5</td>
</tr>
<tr>
<td>3C 287</td>
<td>RG</td>
<td>2.474</td>
<td>11 23 09.40</td>
<td>+05 30 17.8</td>
<td>&lt;11</td>
<td>6, 7, 8</td>
</tr>
<tr>
<td>H1413+117</td>
<td>RQQ</td>
<td>2.546</td>
<td>14 15 46.26</td>
<td>+11 29 43.7</td>
<td>66 ± 7</td>
<td>9</td>
</tr>
<tr>
<td>2132+0126</td>
<td>RQQ</td>
<td>3.194</td>
<td>21 35 10.61</td>
<td>+01 39 31.3</td>
<td>&lt;12</td>
<td>10</td>
</tr>
<tr>
<td>B2 0902+34</td>
<td>RG</td>
<td>3.391</td>
<td>09 05 30.10</td>
<td>+34 07 57.3</td>
<td>&lt;14</td>
<td>6, 11, 12</td>
</tr>
<tr>
<td>MG 2141+192</td>
<td>RQQ</td>
<td>3.594</td>
<td>21 44 07.52</td>
<td>+19 29 14.2</td>
<td>&lt;11</td>
<td>8, 10</td>
</tr>
<tr>
<td>0345+0130</td>
<td>RQQ</td>
<td>3.638</td>
<td>03 48 02.29</td>
<td>+01 39 18.4</td>
<td>&lt;25</td>
<td>11</td>
</tr>
<tr>
<td>6C 0032+412</td>
<td>RG</td>
<td>3.665</td>
<td>00 34 53.09</td>
<td>+41 31 31.5</td>
<td>&lt;14</td>
<td>8, 13</td>
</tr>
<tr>
<td>4C 41.17</td>
<td>RG</td>
<td>3.800</td>
<td>06 50 52.36</td>
<td>+41 30 31.5</td>
<td>17.4 ± 3.1</td>
<td>14, 15, 6</td>
</tr>
<tr>
<td>8C1435+643</td>
<td>RG</td>
<td>4.252</td>
<td>14 36 37.19</td>
<td>+63 19 14.2</td>
<td>&lt;13</td>
<td>16, 17</td>
</tr>
</tbody>
</table>


2.2 Selection of observing wavelength

Obviously we have no a priori knowledge of the exact spectral shape of the continuum at FIR-mm wavelengths in the rest-frame of the high-redshift radio galaxies. However, since our aim is to test whether these galaxies are undergoing an intense burst of star formation at early epochs, it seems reasonable to assume that their rest-frame FIR-mm continuum spectra will be similar in form to those of massive galactic star-forming regions and low-z starburst galaxies. At the highest redshifts the FIR spectral peaks of such star-forming regions fall conveniently into the region of two submillimetre wavelength atmospheric windows at 350 and 450 μm, and it might seem that observations would be most profitably made at these wavelengths. However, the 750- and 850-μm atmospheric windows provide more suitable and, in practice, preferential alternatives. At redshifts z > 2 the observed flux density ratio S_{400\mu m}/S_{800\mu m} of a starburst galaxy spectrum is significantly smaller than that at z ~ 0 (Fig. 3) and is no longer sufficient to offset the observational disadvantages of increased sky noise and reduced sky transparency, A^{\text{trans}} \text{ at } 450 \mu m \text{ compared to } 800 \mu m, \text{ under even the driest atmospheric conditions } [\text{precipitable water vapour } (\text{p.w.v.}) \approx 0.5 \text{ mm}] \text{ when } A^{\text{trans}}(450 \mu m/800 \mu m) \text{ is} \leq 0.7.

Therefore all observations were initially made in the 850- and 750-μm windows using a broad-band filter at ∼800 μm (λ_{\text{c}} \approx 781 μm, Δλ ∼ 200 μm). In the event of a detection at 800 μm, follow-up observations were made at 450 μm. An additional theoretical point also strongly favours the use of a filter at ∼800 μm over shorter wavelength filters since, as discussed in Section 3.3.2, a single photometric measurement at λ ≪ 800 μm is virtually useless for constraining the dust masses in sources at z > 1.

2.3 Observations and results

Sensitive continuum observations of radio galaxies and RQQs in the redshift range 0.8 ≤ z ≤ 4.3 were made at 800 μm using the single-element 3He bolometer UKT14 (Dun-
2.3.1 High-redshift radio galaxies

A highlight of this study has been the clear detection of 4C 41.17 at 800 μm, together with a significant upper limit of 3σ < 56 at 450 μm (Dunlop et al. 1994). This detection was subsequently confirmed by an IRAM observation at 1.25 mm (Chini & Krügel 1994) at a level consistent with the thermal dust model presented by Dunlop et al. (1994). We have also achieved a marginal 3σ detection at 800 μm of 53W002 at a considerably fainter flux density of 6.9 ± 2.3 mJy. Yamada et al. (1995) have a similarly tentative detection of 12CO(1–0) in 53W002, leading to an H_2 mass gas of 2 × 10^2 M_☉. Whilst we have had no opportunity to confirm our continuum result, treating the 800-μm observation as a limit of 3σ ≤ 7 mJy (M_2 = 1.5 × 10^2 M_☉; see Section 3.2) allows us to place an unlikely lower limit on the gas-to-dust ratio of > 13,000, and hence casts doubt on the validity of the CO detection. At the time of observation it seemed somewhat surprising that no 800-μm detection of B2 0902 + 34 was obtained given the claimed IRAM detection at 1.3 mm (Chini & Krügel 1994). However, recent 105-GHz observations (Downes et al. 1996; Yun & Scoville, private communication) now suggest that a significant fraction (probably the majority) of the 1.3-mm continuum in B2 0902 + 34 is due to non-thermal emission (see Section 3.1). No detections were achieved for the remaining six radio galaxies at z > 2; our non-detection of 8C 1435 + 643 could be regarded as casting some doubt on the validity of the IRAM detection by Ivison (1995), but in fact our 3σ upper limit for this source is still just consistent with a greybody fitted through the 1.25-mm data point (see Section 3.1).

2.3.2 High-redshift radio-quiet quasars

Continuum observations at 800 μm (Barvainis, Antonucci & Coleman 1992; Isaac et al. 1994) and at 1.25 mm (Andreani, La Franca & Cristiani 1993; McMahon et al. 1994; Ivison 1995; Omont et al. 1996b) have suggested that thermal emission from dust has been detected in high-redshift RQs. In an attempt to confirm some of these more marginal results and facilitate direct comparison with our sample of high-redshift radio galaxies, we made 800-μm observations of two (2132 + 0126 and 0345 + 0130) of the three RQs detected by Andreani et al. (1993). In 2132 + 0126 the 1.25-mm detection (11.7 mJy) and our measured 800-μm flux density limit (< 12 mJy) produce a spectal index $\alpha < 0.06$ ($\xi$, $\nu^\alpha$) over the rest-frame wavelength range 298–191 μm. This is inconsistent with that expected from a thermal dust spectrum with a grain temperature $T \geq 20$ K. Our result therefore casts serious doubt on the 1.25-mm IRAM detections or on the proposed thermal nature of the submillimetre continuum, unless the dust grains are significantly colder than observed in low-redshift quasars (Chini et al. 1989a; Hughes et al. 1993). Our flux limit of $3\sigma < 25$ mJy at 800 μm for 0345 + 0130 is just consistent with the flux density expected from an extrapolation of the 1.25-mm detection (assuming an isothermal 50-K spectrum with a grain emissivity index $\beta = 2$), and thus provides no additional constraint on the nature of the FIR spectrum or the dust mass in this object.

In the light of the recent detections of the Cloverleaf quasar (H1413 + 117) at 1.25 mm, 100 μm and 60 μm (Barvainis et al. 1995), which indicated it to have a peculiar spectral energy distribution (SED) (Fig. 4), we de-archived and recalibrated the original submillimetre data of Barvainis et al. (1992). Our recalibration at 350 and 450 μm agrees with those of Barvainis et al. (1992), whilst suggesting a flux density at 800 μm of 66 ± 12 mJy, 50 per cent higher than that in the original paper. This prompted us to make a new 800-μm observation of H1413 + 117 in 1996 March, which confirmed our recalibration with a detection of 66 ± 9 mJy (R. Ivison & J. Stevens, private communication), giving a weighted mean of 66 ± 7 mJy for the two independent data sets, which differs from the published 800-μm detection of Barvainis et al. (1992) at the 2σ level and is much more consistent with that expected from a greybody fit to the other data points (Fig. 4). The SED of the Cloverleaf quasar

![Figure 4](https://academic.oup.com/mnras/article-abstract/289/4/766/1062120/219342)

Figure 4. The mid-infrared to millimetre spectral energy distribution of the Cloverleaf quasar (H1413 + 117). The open circles show the data presented by Barvainis et al. (1995). The solid circle shows our new observation at 800 μm that is consistent with various optically thin isothermal greybody spectra (30 K, $\beta = 2$ — solid curve; 50 K, $\beta = 1$ — dot—dash; 76 K, $\beta = 1$ — dot—dot—dot—dash). Also shown for completeness are greybodies assuming 30 K, $\beta = 1$ (dashed curve) and 50 K, $\beta = 2$ (dotted curve). The alternative greybody spectra are normalized at 1300 μm.
is now one of the most well-defined for a high-z object in the FIR–millimetre wavelength regime, and it illustrates the difficulty in constraining the dust temperature within the range 30 < T_d < 70 K (Fig. 4; see also Section 3.3.2).

2.4 Comparison of high-z and low-z AGN at submillimetre wavelengths

In Table 2 we list all galaxies and RQQs with redshifts z > 2 that have published detections at one or more wavelengths between 350 and 1300 μm, regardless of whether they have been confirmed. For the purposes of this paper a 'detection' is defined as any published photometry with a signal-to-noise ratio ≥ 3. The reliability of any detection will be discussed when appropriate.

In Fig. 5 we compare the 800-μm flux densities and limits for the high-redshift galaxies listed in Table 2 with the 800-μm flux densities observed for a variety of starburst galaxies and AGN at low redshift (Hughes, Davies & Ward 1997, in preparation). The redshift dependence of the 800-μm flux density of the starburst galaxy M82, previously shown in Fig. 2, is reproduced here, together with the rest-frame FIR luminosity of M82 (3 x 10^{10} L_⊙). This plot illustrates a number of basic but important points in a rather transparent manner. First, with the exception of IRAS 10214+4624 for which, in this plot, we indicate the inferred 800-μm flux density after correcting for lensing (Eisenhardt et al. 1996), there is an obvious absence of sources, at any redshift, with S_{800μm} < 7 mJy. This simply reflects the current sensitivity limits of submillimetre bolometers such as UKT14; it is clear from the figure that our 800-μm observations of the high-z sources are amongst the faintest 800-μm observations made to date. Secondly, the lines on this plot indicate that for sources at z > 1, such flux density limits correspond to FIR luminosities which are several hundred times greater than low-redshift AGN. Thirdly, this plot shows that with an improvement in sensitivity of a factor of 10 (as is promised by new submillimetre bolometer array detectors such as SCUBA on the JCMT) it should be possible to detect objects comparable to the most luminous starburst galaxies and ULIRGS seen in the local Universe (e.g., Arp 220 and Mrk 231), with luminosities L_{FIR} ≥ 10^{12} L_⊙ out to z ∼ 10. We also note that little effort has been invested in making submillimetre observations of galaxies in the intermediate-redshift interval 0.1–1.

The important physical property which can be derived directly from these submillimetre detections/upper limits is the mass of dust in a given galaxy. From this one can then go on to assess the evolutionary status of the object in question, either through estimation of the 'current' SFR, or by estimating the mass of the object (by adopting a given gas-to-dust ratio). However, in several recent papers this crucial process has been described with misleading simplicity. In fact, even the first stage in this process (calculating the dust mass) has to be undertaken with great care, because there exist at least five potential sources of significant uncertainty. Thus, before attempting to derive the physical properties of the objects listed in Table 2, to assess their evolutionary status (which we do in Section 4), in the next section we present a detailed description of these five sources of uncertainty, assess their relative importance and outline the prospects for improvements in each area.

3 Uncertainties in determining the dust masses of high-redshift objects

In this section we describe, roughly in order of increasing subtlety, the problems which afflict the accurate determination of dust masses from submillimetre observations of high-redshift galaxies. First, we consider how one can establish that the detected emission is indeed from dust, rather than being, for example, synchrotron emission (an import-

Table 2. Summary of all published continuum data measuring thermal emission from dust in galaxies at z > 2 with at least one detection at wavelengths between 350 μm and 1.25 mm. Flux density limits quoted at the 3σ level.

<table>
<thead>
<tr>
<th>Source name</th>
<th>z</th>
<th>type</th>
<th>S_{25mm} (mJy)</th>
<th>S_{800μm} (mJy)</th>
<th>S_{1450μm} (mJy)</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRAS10214+4724</td>
<td>2.286</td>
<td>IRAS</td>
<td>24 ± 5</td>
<td>50 ± 5</td>
<td>273 ± 45</td>
<td>1</td>
</tr>
<tr>
<td>3S0002</td>
<td>2.300</td>
<td>RG</td>
<td>6.9 ± 2.3</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>H1413+2617</td>
<td>2.546</td>
<td>BALQSO</td>
<td>18.2 ± 2.0</td>
<td>66 ± 7</td>
<td>224 ± 38</td>
<td>189 ± 56</td>
</tr>
<tr>
<td>Q0157+1055</td>
<td>3.15</td>
<td>RQQ</td>
<td>3.7 ± 1.2</td>
<td>&lt; 14</td>
<td>&lt; 99</td>
<td>2,5</td>
</tr>
<tr>
<td>B2 0902+34</td>
<td>3.391</td>
<td>RG</td>
<td>2.5 ± 0.4</td>
<td>17.4 ± 3.1</td>
<td>&lt; 56</td>
<td>5,6</td>
</tr>
<tr>
<td>4C 41.17</td>
<td>3.800</td>
<td>RG</td>
<td>2.5 ± 0.4</td>
<td></td>
<td></td>
<td>1,5</td>
</tr>
<tr>
<td>PC2047+0123</td>
<td>3.800</td>
<td>RQQ</td>
<td>1.9 ± 0.5</td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>BR1117-1329</td>
<td>3.96</td>
<td>RQQ</td>
<td>4.09 ± 0.81</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>BR1144-0723</td>
<td>4.14</td>
<td>RQQ</td>
<td>5.85 ± 1.03</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>8C1345+1643</td>
<td>4.252</td>
<td>RG</td>
<td>2.6 ± 0.4</td>
<td>&lt; 13</td>
<td></td>
<td>2,7</td>
</tr>
<tr>
<td>BRI1335-0417</td>
<td>4.40</td>
<td>RQQ</td>
<td>10.26 ± 1.04</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>BR1035-0115</td>
<td>4.43</td>
<td>RQQ</td>
<td>2.75 ± 0.63</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>BR1033-0327</td>
<td>4.51</td>
<td>RQQ</td>
<td>3.45 ± 0.65</td>
<td>12 ± 4</td>
<td></td>
<td>4,8,9</td>
</tr>
<tr>
<td>BR1202-0725</td>
<td>4.69</td>
<td>RQQ</td>
<td>10.5 ± 1.5</td>
<td>50 ± 7</td>
<td>92 ± 38</td>
<td>4,8,9</td>
</tr>
</tbody>
</table>

Figure 5. A comparison of the measured 800 μm flux densities of various high-z and low-z active galaxies: starbursts (solid stars), Seyferts (dotted circles), ULIRGs (crossed circles), radio galaxies (open stars), radio-quiet quasars (solid circles), taken from Hughes et al. (1993), Hughes, Ward & Davies (1997, in preparation) and referenced data included in Table 2 (this paper). The flux densities of IRAS 10214 +4724 and the Cloverleaf quasar (H1413+117) have been corrected for their amplification due to lensing; see Section 4. The error bar associated with IRAS 10214 +4724 represents the uncertainty in the amplification factor at FIR wavelengths. An expanded version of this figure between redshifts 0.5 and 10 is shown in the right-hand panel. The solid curve represents the predicted dependence of the 800 μm flux density with redshift for the nearby starburst galaxy M82. Also shown are curves for a galaxy with x10 (dashed), x100 (dot-dashed) and x1000 (dotted) the rest-frame FIR luminosity of M82 ($L_{\text{FIR}} = 3 \times 10^{10} M_\odot$).

3.1 Potential problem 1: Have we detected emission from dust?

To prove that any submillimetre emission detected from high-redshift galaxies is due to dust one must ideally demonstrate that the submillimetre SED is rising too steeply to be due to self-absorbed synchrotron radiation (e.g. Chini et al. 1989a; Hughes et al. 1993). In practice, this is extremely difficult to achieve (due to the low signal-to-noise ratio of the data and the fact that at high redshift one is not always observing the Rayleigh–Jeans tail of the expected thermal emission), but at the very least it is necessary to demonstrate that the observed submillimetre spectrum is rising towards shorter wavelengths.

A direct determination of a positive submillimetre index $\alpha$ (where $f(\nu) \propto \nu^\alpha$) at high redshift is limited to submillimetre/millimetre continuum observations of only four objects: H1413+117 (Barbainis et al. 1992, 1995), IRAS F10214 +4724 (Rowan-Robinson et al. 1993), 4C 41.17 (Chini & Krügel 1994; Dunlop et al. 1994) and BR 1202 –0725 (Isaak et al. 1994; McMahon et al. 1994). However, in certain circumstances, even on the basis of a single submillimetre or millimetre wavelength, one can be reasonably confident that the detected emission lies above any reasonable extrapolation of the radio emission. This point is well illustrated in Fig. 6, in which we present six examples of SEDs from the sources listed in Table 2. The SEDs of 4C 41.17, BR 1202 –0725 and H1413+117 represent good examples of sources whose observed submillimetre SED is well determined and for which there can be very little doubt...
that thermal emission from dust has been detected, whilst the remaining SEDs illustrate the importance, but also the limitations, of a detection at a single submillimetre or millimetre wavelength. For example, our 800-\mu m detection of 53W002, if real, appears to lie clearly above the extrapolation of its radio spectrum, whereas the millimetre detections of B2 0902 + 34 (Chini & Krügel 1994) could simply be a detection of the high-frequency tail of the radio emission from the unresolved core (Downes et al. 1996), which has a flatter spectrum and is more luminous (with respect to the submillimetre emission) than, for example, the radio-core in the ultrasteep-spectrum radio galaxy 4C 41.17 (Carilli, Owen & Harris 1994).

Fig. 6 demonstrates that with appropriate target selection...

Figure 6. Optical–radio SEDs of high-z radio galaxies and radio-quiet quasars showing that, except in the case of B20902 + 34 (see Section 3.1), the rest-frame submillimetre and FIR emission is in excess of an extrapolation of the total radio continuum. The SEDs of 4C 41.17 and B20902 + 34 show both the core emission and the steeper large-scale lobe emission. In each case, isothermal greybody spectra, assuming an emissivity index $\beta = 1.5$, are shown for 30 K (dashed), 50 K (solid) and 70 K (dot-dashed). The submillimetre and millimetre data are given in Table 2. The radio, infrared and optical continuum fluxes for these objects have been taken from the following papers: 4C 41.17 – Chambers et al. (1990), Carilli et al. (1994); BR 1202 – 0725 – Isaak et al. (1994); H1413 + 117 – Barvainis et al. (1995), Barvainis & Antonucci (1996); 53W002 – Windhorst et al. (1991); 8C 1435 + 643 – Lacy et al. (1994); B20902 + 34 – Lilly (1988), Carilli et al. (1994), Downes et al. (1996), Yun & Scoville (1996, private communication).
(e.g., ultra steep-spectrum radio sources) and with sensitive submillimetre and millimetre photometry one can prove that thermal emission from dust has indeed been detected, but that this must be determined with care on a source-by-source basis. However, even if it can be convincingly demonstrated that the detected emission is due to dust, one must then address the issue of how confident one can be that the dust lies at the redshift of the source. We therefore now address this often-overlooked but important issue.

3.2 Potential problem 2: What dust has been detected?: possible contamination by Galactic cirrus

Even if, as in the case of 4C 41.17 and BR 1202−0725, it can be shown that a rising submillimetre SED has been detected, it must be remembered that extragalactic observations at submillimetre wavelengths are made in the presence of foreground thermal emission from dust grains in the Galactic ISM heated by the interstellar radiation field (Low et al. 1984), hereafter cirrus. Indeed, given its fractal nature (e.g. Bazell & Désert 1988), it is possible that cirrus has significant structure on scales less than the typical 30−60 arcsec chop-throw employed in submillimetre observations (e.g. Diamond et al. 1989; Meyer 1990) and hence, since this foreground emission may not be completely removed with the usual technique of position beam-switching, it may represent a significant source of additional noise. In the limit this ‘confusion’ noise may place a fundamental constraint on the useful depth of searches for high-z galaxies, and it is therefore important to quantify the contribution of cirrus emission both to the current faint submillimetre observations described in this paper and to future submillimetre high-redshift surveys.

To achieve this, we have reduced the IRAS raw detector data (CRDD) at 12, 25, 60 and 100 μm at the positions of all the high-redshift objects listed in Tables 1 and 2, using the procedure described by Hughes, Appleton & Schombert (1991). Not surprisingly, none of the high-redshift objects were actually detected. The 100 μm surface brightness \( < I_{100 \mu m} \) of the foreground cirrus was measured towards all of the high-redshift galaxies after the subtraction of any zodiacal emission, which can still be significant in the FIR at low ecliptic latitudes.

The average noise level at 100 μm due to cirrus, on scales of a few arcminutes, was \( \sim 0.3 \text{ MJy sr}^{-1} \) which, when extrapolated to 800 μm, assuming an isothermal dust spectrum and emissivity index \( \beta = 2 \) (Rowan-Robinson 1992), gives a brightness of \( < 0.3 \text{ MJy sr}^{-1} \), equivalent to \( < 1 \text{ mJy beam}^{-1} \), for cirrus temperatures \( > 12 \text{ K} \). In other words, it is extremely unlikely that the 800 μm detections, \( > 7 \text{ mJy} \), in Table 2 are due to cirrus unless the dust grains are significantly colder than the generally accepted range of cirrus temperatures, \( 15 < T < 40 \text{ K} \) (Rowan-Robinson 1986; Terebey & Fich 1986; van Steenberg & Schull 1988) regardless of grain size or composition. However, as a caveat we mention, first, that if \( \beta \neq 2 \), the submillimetre emission can increase by a factor \( \sim 10 \) as \( \beta \) varies between 2 and 1 and, secondly, that the cirrus temperatures are generally derived from a 60 μm/100 μm intensity ratio which is highly sensitive to the contribution from a small fraction of hot grains in the cloud, and hence the average grain temperature that dominates the mass of the cloud is often overestimated. At sub-millimetre wavelengths our observations are significantly more sensitive to emission from a colder component than in the FIR.

A noise level of \( \sim 1 \text{ mJy at} \sim 800 \mu m \) is similar to the theoretical predictions of the cirrus confusion on scales equivalent to the chop-throw at submillimetre wavelengths (Helou & Beichman 1991; Gautier et al. 1992) assuming that the spatial power spectrum of cirrus, as determined at 100 μm by IRAS (between scales of 8 deg and 2 arcmin), continues unbroken to smaller spatial scales (\( \sim 30 \text{ arcsec} \)), and that the empirical relationship between the amplitude of the variations and the cirrus surface brightness in the FIR is valid at longer submillimetre wavelengths.

While these calculations provide reassurance that detections at the level of those described in the present paper are unlikely to be seriously contaminated by cirrus emission, they also demonstrate that cirrus contamination could become a more serious issue with the increased instrumental sensitivity offered from the new generation of submillimetre receivers (e.g., SCUBA). With such instruments it will be possible to reach noise levels of \( \sim 0.3 \text{ mJy beam}^{-1} \) or 0.08 MJy sr\(^{-1} \) in just a 3-h integration and, as a result, future observations of high-redshift galaxies will be sensitive to faint, hence possibly unresolved, clumps of cirrus with temperatures \( > 15 \text{ K} \). This result is generalized in Fig. 7, which shows the surface brightness at 800 μm of Galactic cirrus as a function of temperature. The three extrapolated models cover the brightness range of cirrus at 100 μm (0.1 < \( I_{100 \mu m} < 10.0 \text{ MJy sr}^{-1} \)) towards the positions of the high-redshift galaxies given in Tables 1 and 2, and are typical of the cirrus background away from the Galactic plane.

---

**Figure 7.** Surface brightness at 800 μm of Galactic cirrus as a function of dust temperature. The curves are extrapolations of optically thin, isothermal models with a grain emissivity index \( \beta = 2 \), assuming a 100 μm intensity of 10 MJy sr\(^{-1} \) (solid line), 1 MJy sr\(^{-1} \) (dashed line), 0.1 MJy sr\(^{-1} \) (dot–dashed line). The shaded region represents the range of the surface brightness of the 800 μm detections in Table 2, and illustrates that for \( T > 15 \text{ K} \) the contribution from cirrus is negligible. The horizontal line represents the intensity level at \( \sim 800 \mu m \) that can be reached in a 3-h integration with the future generation of submillimetre receivers, and indicates that deep cosmological studies may suffer from source confusion due to Galactic cirrus emission.
3.3 Potential problem 3: uncertainties in the properties and temperatures of the dust grains

If it is assumed the submillimetre 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

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

where $z$ is the redshift of the source, $S_{\text{obs}}$ is the observed flux density, $B(v_{\text{rest}}, T)$ is the rest-frequency value of the Planck function from dust grains radiating at a temperature $T$, and $D_l$ is the luminosity distance (see Section 3.4).

Thus, for a given cosmology and excluding the measurement uncertainty of the continuum flux density, the robustness of dust mass determinations from submillimetre photometry depends on the uncertainty in $k_d$ and $T$. The existing constraints on these two parameters are now briefly discussed in turn.

3.3.1 Uncertainty in $k_d(\lambda)$

Draine (1990) has pointed out that the acknowledged advantage of using optically thin submillimetre emission to determine the dust mass in galaxies is offset somewhat by increased uncertainty in the properties of interstellar dust, and hence the value of $k_d$ as $\lambda$ is increased from FIR to submillimetre wavelengths. A reasonable estimate of the maximum fractional uncertainty in $k_d$ at 800 $\mu$m is $\approx 7$, with the values of $k_d$(800 $\mu$m) ranging between 0.04 m$^2$ kg$^{-1}$ (Draine & Lec 1984) and 0.3 m$^2$ kg$^{-1}$ (Mathis & Whiffen 1989) with intermediate values of 0.15 m$^2$ kg$^{-1}$ (Hildebrand 1983) and 0.12 m$^2$ kg$^{-1}$ (Chini, Krügel & Kreyss 1986). In order to extrapolate $k_d$ to shorter rest-wavelengths, appropriate for high-$z$ galaxies, we have assumed that $k_d \propto \lambda^{-1.5}$ and have adopted an average value of $k_d$(800 $\mu$m) = 0.15 ± 0.09 m$^2$ kg$^{-1}$. A different choice of $k_d$ should therefore only be expected to result in dust mass estimates which differ from those which we calculate in Section 4 by at most a factor of $\approx 2$.

3.3.2 Uncertainty in $T$

The temperature of dust grains that radiate at submillimetre wavelengths and dominate the FIR luminosity in nearby starburst galaxies, low-metallicity dwarf galaxies, ULIRGs, Seyferts and RQs is typically 50 ± 20 K (Chini et al. 1989a,b;Hughes et al. 1993;Hughes, Davies & Ward 1997, in preparation). There is no a priori reason to believe that the dust radiating at FIR rest-wavelengths in high-redshift radio galaxies and RQs should be significantly different if the star formation processes that exist at early epochs are similar to those in the local Universe.

The fractional uncertainty in the dust mass which results from ignorance of the dust temperature within the range $T_1 < T < T_2$ is given by

$$\frac{M_d}{M_d^0} = \frac{\int^{T_2}_1 e^{\frac{b_{\text{rest}}}{k_d T_1} - 1} dT}{\int^{T_2}_1 e^{\frac{b_{\text{rest}}}{k_d T_1} - 1} dT}$$

which increases rapidly as $T_{\text{rest}}$ moves above the Rayleigh–Jeans tail of the thermal dust emission. Dust mass estimates derived from rest-frame submillimetre photometry therefore have the benefit of being relatively insensitive to uncertainties in temperature, as compared to dust masses derived from FIR data (i.e., $\lambda_{\text{rest}} < 200$ $\mu$m).

At $z \approx 0$, where 800 $\mu$m photometry samples the Rayleigh–Jeans tail of the thermal dust emission, dust mass estimates have the benefit of being relatively insensitive to uncertainties in temperature, as compared to dust masses derived from FIR data (i.e., $\lambda_{\text{rest}} < 200$ $\mu$m).

If $z \approx 3$ the difference in dust mass between assuming $T = 30$ and 70 K is a factor of 15 and 5 at 450 and 800 $\mu$m respectively. Consequently, our ignorance of the most appropriate value of $T_{\text{dust}}$ in high-redshift galaxies is a dominant source of uncertainty in the derived dust masses, and it is worth considering the implications of such an uncertainty in future cosmological studies at submillimetre wavelengths.

It is clear that the more one benefits from the increased flux levels offered by interrogating the thermal spectrum nearer the rest-frame 100-$\mu$m peak, the greater uncertainty there is in the derived dust mass determined from a single submillimetre continuum measurement. As we have summarized in Table 2, almost all photometric observations at millimetre and submillimetre wavelengths of high-$z$ galaxies have been restricted to filters at $\lambda \approx 800$ $\mu$m, with the exception of IRAS 10214 + 4724, 4C 41.17, H1413 + 117 and BR 1202 – 0725. Thus the majority of data have been made in

$\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{Temperature-dependent uncertainty in dust masses deduced from submillimetre photometry in various wavebands plotted as a function of source redshift. If we consider a fractional error in dust mass of greater than 5 to be unacceptable, then photometry at 800 $\mu$m is of little use for observations of galaxies at $z > 4$, while photometry at $\approx 400$ $\mu$m is of little worth (on its own) for $z > 1$.}
\end{figure}$

3.4 Potential problem 4: uncertain cosmology

The luminosity distance $D_L$, which appears in equation (2), is given by

$$D_L = \frac{2c}{H_0 \Omega_0^{1/2}} \left[ (\Omega_0 - 2)[(\Omega_0 + 1)^{1/2} - 1] \right]. \quad (4)$$

The (apparently now-decreasing) uncertainty in the value of the Hubble constant $H_0$ obviously affects the calculated values of dust mass to some extent, but comparison of the properties of low- and high-redshift galaxies is unaffected because $M_{dust}$ simply scales as $H_0^{-2}$.

More serious is our current ignorance of $\Omega_0$. At $z \approx 4$, if one adopts a low-density universe (i.e., $\Omega_0 \approx 0.1$), the derived dust masses are a factor $\approx 5$ greater than if one assumes an Einstein–de Sitter universe, and this uncertainty factor rises to $\approx 15$ at redshifts $z \approx 10$. The value of pointing out the size of this uncertainty is that it puts into perspective the relatively minor errors which are introduced by our ignorance of the precise value of such parameters as $k_d$.

Bearing these uncertainties in mind, we now proceed to calculate our best estimates of the dust masses of the high-redshift objects listed in Table 2, and hence to infer their evolutionary status.

4 DERIVATION OF PHYSICAL PARAMETERS FOR HIGH-REDSHIFT GALAXIES

4.1 The dust masses of high-redshift galaxies

At first sight the preceding section may read as a rather depressing litany of ever-increasing sources of error. However, our objective is not to denigrate the usefulness or importance of submillimetre cosmology, but rather to delineate and quantify the main sources of error, and to identify what strategies must be adopted to maximize the usefulness of submillimetre and millimetre continuum photometry. In fact, for most of the sources listed in Table 2, the current observational constraints indicate that we can still derive realistic and meaningful estimates of their dust masses, with appropriate choices of parameters. First, as illustrated in Fig. 6, for most of these sources we can be confident that the detected submillimetre emission is produced by dust. Secondly, while it appears that cirrus confusion may be a significant problem for deeper surveys, our estimates of the background cirrus noise for the sources detected here indicate that these detections are unlikely to be significantly effected. Thirdly, we can minimize the effect of disagree-

ment of $k_d$ by choosing an average value. Fourthly, for at least some sources (e.g., 4C41.17, BR 1202–0725 and H1413 +117) there exists sufficient observational data to set a meaningful upper limit on the dust temperature, and hence a lower limit on the dust mass. Fifthly, while it is obviously beyond the scope of this paper to address the issue of the true value of $\Omega_0$, by adopting a high-density universe we can at least ensure that our dust mass estimates are conservative.

We have therefore calculated dust masses for the sources listed in Table 2 using equation (2), assuming $k_d(800 \ \mu m) = 0.15 \ m^2 \ kg^{-1}$, $\beta = 1.5$, $T_{dust} = 50 \ K$ and $\Omega_0 = 1$. The results are presented in Table 3 and are in the range $1 \times 10^{-2} - 2 \times 10^8 M_\odot$ allowing for amplifications of order $\approx 140$ (Barvainis et al. 1994) and $\approx 10-40$ (Eisenhardt et al. 1996) for the FIR luminosity in the lensed sources H1413 +117 and IRAS 10214 +4724 respectively.

These dust mass estimates can be used to infer the evolutionary status of the galaxies in two alternative ways. First, one can estimate the 'current' SFR of the galaxy. Secondly, one can attempt to estimate the amount of molecular gas in the galaxy which remains to be converted into stars at the epoch of observation. We now consider each of these calculations in turn.

4.2 Star formation rates in high-redshift galaxies

As described in the introduction, one can estimate the SFR at the far-infrared from their rest-frame FIR luminosities which have been calculated between rest-wavelengths of 2 mm and 10 μm assuming an optically thin isothermal 50 K greybody spectrum (see Table 3), which can be reasonably justified in the case of 4C41.17, BR 1202–0725 and H1413 +117 (Fig. 6; see also Section 4.1), normalized to the millimetre and submillimetre flux densities in Table 2. In the absence of any contribution from an AGN or amplification due to lensing, the rest-frame FIR luminosities, which lie in the range $4 \times 10^{12} - 6 \times 10^{13} L_\odot$, imply large current SFRs of greater than several $100 M_\odot$ yr$^{-1}$. A comparison of the 1000–8 μm luminosities of low-z ULIRGs (Sanders et al. 1991) with those calculated from a single 50-K isothermal model indicates that we have underestimated the FIR luminosities of the high-z galaxies by a factor of $\approx 2.5$ if they contain contributions from hotter dust ($T > 100 \ K$) components which radiate strongly at mid-IR wavelengths. Hence the FIR luminosities and SFRs in Table 3 should be treated as lower limits when compared to those of lower redshift galaxies. Further, albeit controversial, evidence for extreme SFRs and young galaxy ages ($< 1 \ Gyr$) has been found in the rest-frame UV–optical morphologies and SEDs of 53W002 and 4C41.17 (Chambers & Charlot 1990; Windhorst et al. 1991; Mazzetti & de Zotti 1996).

Thus, despite the uncertainties described in Section 3, we can still conclude that the high-z radio galaxies and RQQs which have been detected at submillimetre/millimetre wavelengths, are extremely dusty, with dust masses $> 10 \times$ larger than observed in their low-z ($z < 0.5$) counterparts (Chini et al. 1989a; Knapp & Patten 1991; Hughes et al. 1993), and with levels of star formation and star-forming efficiencies similar to, or exceeding, those observed in low-z ULIRGs (see Fig. 9).
Table 3. Dust masses, molecular gas masses, FIR luminosities and star formation rates (SFRs) of high-z galaxies. Corrections for the amplification of the FIR emission due to lensing have been applied to the values for IRAS 10214 + 4724 and H1413 + 117 (see Section 4.1).

<table>
<thead>
<tr>
<th>Source name</th>
<th>z</th>
<th>log $M_d/M_\odot$</th>
<th>log $M_{H_2}/M_\odot$</th>
<th>log $L_{FIR}/L_\odot$</th>
<th>SFR (M$_\odot$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C318</td>
<td>0.752</td>
<td>&lt; 9.16</td>
<td>&lt; 11.86</td>
<td>&lt; 13.78</td>
<td>&lt; 6025</td>
</tr>
<tr>
<td>3C65</td>
<td>1.176</td>
<td>&lt; 8.72</td>
<td>&lt; 11.42</td>
<td>&lt; 13.35</td>
<td>&lt; 2239</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>1.334</td>
<td>&lt; 9.35</td>
<td>&lt; 12.04</td>
<td>&lt; 13.97</td>
<td>&lt; 9332</td>
</tr>
<tr>
<td>IRAS10214+4724</td>
<td>2.286</td>
<td>8.02</td>
<td>10.72</td>
<td>12.64</td>
<td>436</td>
</tr>
<tr>
<td>53W002</td>
<td>2.390</td>
<td>8.45</td>
<td>11.15</td>
<td>13.08</td>
<td>1202</td>
</tr>
<tr>
<td>3C267</td>
<td>2.474</td>
<td>&lt; 8.65</td>
<td>&lt; 11.35</td>
<td>&lt; 13.27</td>
<td>&lt; 1862</td>
</tr>
<tr>
<td>H1413+117</td>
<td>2.546</td>
<td>8.42</td>
<td>11.22</td>
<td>13.04</td>
<td>1096</td>
</tr>
<tr>
<td>Q1017+1055</td>
<td>3.15</td>
<td>8.67</td>
<td>11.37</td>
<td>13.29</td>
<td>1949</td>
</tr>
<tr>
<td>B20002+34</td>
<td>3.591</td>
<td>8.61</td>
<td>11.31</td>
<td>13.24</td>
<td>1738</td>
</tr>
<tr>
<td>MG2141+192</td>
<td>3.591</td>
<td>&lt; 8.58</td>
<td>&lt; 11.28</td>
<td>&lt; 13.20</td>
<td>&lt; 1585</td>
</tr>
<tr>
<td>4C41.17</td>
<td>3.800</td>
<td>8.76</td>
<td>11.46</td>
<td>13.39</td>
<td>2455</td>
</tr>
<tr>
<td>FC2047+0123</td>
<td>3.800</td>
<td>8.36</td>
<td>11.06</td>
<td>12.99</td>
<td>977</td>
</tr>
<tr>
<td>BR1117−1329</td>
<td>3.96</td>
<td>8.62</td>
<td>11.32</td>
<td>13.24</td>
<td>1737</td>
</tr>
<tr>
<td>BR1144−0723</td>
<td>4.14</td>
<td>8.77</td>
<td>11.47</td>
<td>13.40</td>
<td>2511</td>
</tr>
<tr>
<td>8C1356+643</td>
<td>4.252</td>
<td>8.46</td>
<td>11.16</td>
<td>13.08</td>
<td>1202</td>
</tr>
<tr>
<td>BR1135−0417</td>
<td>4.40</td>
<td>8.97</td>
<td>11.67</td>
<td>13.61</td>
<td>4074</td>
</tr>
<tr>
<td>BR1052−0115</td>
<td>4.43</td>
<td>8.43</td>
<td>11.13</td>
<td>13.05</td>
<td>1122</td>
</tr>
<tr>
<td>BR1033−0327</td>
<td>4.51</td>
<td>8.57</td>
<td>11.27</td>
<td>13.19</td>
<td>1549</td>
</tr>
<tr>
<td>BR1202−0725</td>
<td>4.69</td>
<td>9.18</td>
<td>11.88</td>
<td>13.81</td>
<td>6436</td>
</tr>
</tbody>
</table>

Figure 9. A representation of the data given in Table 3 for the detected high-z radio galaxies and radio-quiet quasars, compared to their lower redshift counterparts, ULIRGs and elliptical galaxies. The symbols have the same meaning as in Fig. 5, with additional low-z powerful radio galaxies (Mazzarella et al. 1993), ULIRGs (Sanders et al. 1991) and elliptical galaxies (Lees et al. 1991) detected in CO marked as solid stars, crossed circles and solid squares respectively. The diagonal lines indicate constant $L_{FIR}/M_{H_2}$, while the vertical dashed line shows the gas mass boundary, to the right of which one can expect to find the progenitors of the most massive elliptical galaxies. The parallelogram encloses the high-z galaxies, which lie along the lower boundary, and depicts the typical range of the increase in their FIR luminosities and SFRs due to a contribution from hotter ($T > 50$ K) dust (see Section 4.2). This figure demonstrates that it is difficult, except possibly in the case of BR 1202 − 0725 (although it may be lensed; see Section 5), to describe any of the high-z galaxies detected at submillimetre and millimetre wavelengths as genuinely primordial, since they lie outside the shaded region marked 'PGs' which represents the parameter space populated by primeval galaxies, with our definition of $M_{H_2} > 5 \times 10^{11}$ M$_\odot$ and SFR > 500 M$_\odot$ yr$^{-1}$. Varying the assumed dust temperature through a reasonable range (30−70 K), as illustrated by the representative locus passing through 4C 41.17, struggles to change this basic conclusion, except perhaps for 4C 41.17 itself.
Particularly if regarded as lower limits, these inferred SFRs are sufficiently high to be at least consistent with the formation of a giant elliptical galaxy in $\sim 1$ Gyr. However, such a calculation is open to two important criticisms. First, for the active objects considered here it is unclear whether the dust is heated primarily by young stars or by a quasar nucleus, although this argument can be at least partially countered by the fact that the very existence of such large masses of dust indicates extensive recent star-formation. A second, and more important, criticism is that an estimate of the “current” SFR can never shed any light on the length of time over which such a high SFR has been maintained. In other words, it is clearly impossible to distinguish a brief, albeit violent, burst of star formation activity (triggered, perhaps, by an interaction) from the sort of sustained high-level star formation required to produce $\approx 10^{10} - 10^{11} M_\odot$ of stars. What is required is some estimate of the past and future star formation history of the galaxy. Such an estimate can be provided, to first order, by using the calculated dust mass of a galaxy to estimate its gas mass.

### 4.2.1 Are simple isothermal models adequate?

We have assumed that the rest-frame FIR luminosities in Table 3 are dominated by radiation from grains with an average temperature of 50 K, and that the SFRs can be derived from a single isothermal component. This is, of course, a simplification, since real galaxies clearly have a distribution of grain temperatures that contribute to the rest-frame emission between 200 and 500 $\mu$m. However, the thermal emission from grains which radiate at a temperature $T_\lambda$ with an efficiency $Q_{\text{abs}} \propto \nu^\beta$, has a peak in the spectrum of $S_\nu$ at a wavelength

$$\lambda_0 (\mu m) \approx \frac{5100}{T (K)} \left( \frac{3}{3 + \beta} \right),$$

and consequently there remains only a restricted range of temperatures (20–70 K) that contribute significantly to the rest-frame FIR.

In Fig. 10 we quantify the discrepancy between our calculations of the FIR luminosities in Table 3 and, where overlap exists, the bolometric starburst luminosities calculated from the more sophisticated radiative transfer models of Rowan-Robinson (1996) and the evolutionary synthesis models of Mazzei & de Zotti (1996). Fig. 10 demonstrates that in the absence of sufficient observational data to constrain models between 800 and 200 $\mu$m, the adoption of a single average grain temperature (50 K) provides extremely good agreement, to within 20 per cent, between the FIR and bolometric luminosities (and also the current SFRs) for galaxies expected to be undergoing vigorous star formation.

### 4.3 Molecular gas masses in high-redshift galaxies

A measure of the total ($\text{H}_2$) gas mass of a high-redshift galaxy is a very useful indicator of its evolutionary status because, as long as one can be reasonably confident that the galaxy in question is the progenitor of a present-day giant elliptical (as is the case for radio galaxies), it provides a measure of the fraction of the galaxy which has yet to be turned into stars at the epoch of observation. One way to determine the gas mass of a galaxy is to estimate its molecular ($\text{H}_2$) mass from a measurement of the intensity of CO. Unfortunately, in the absence of lensing, it has proved impossible to detect the molecular gas in high-$z$ galaxies directly (Barvainis & Antonucci 1996; Evans et al. 1996; van Ojik et al. 1997), with the possible exception of BR 1202–0725 (Ohta et al. 1996; Omont et al. 1996a). An alternative and potentially more productive approach is to convert dust mass to gas mass by adopting a “reasonable” value for the gas-to-dust ratio, $M_\text{H}/M_\text{d}$. However, $M_\text{H}/M_\text{d}$ is not a well-determined quantity in galaxies in the local Universe, let alone at high redshift. Studies of damped Lyman-$\alpha$ systems (DLAAS) currently provide the only opportunity to measure directly the dust content of the Universe at early epochs. At $z \approx 3$ it has been suggested that the gas-to-dust ratio in DLAAS is 400–2000 (Fall, Pei & McMahon 1989; Pettini et al. 1994), a value significantly higher than the Galactic value of 100–160 (Savage & Mathis 1979; Hildebrand 1983), and on average higher than that found in nearly spirals ($\sim 500$; Devereux & Young 1990), ellipticals ($\sim 700$; Wilkint & Henkel 1995) and ULIRGs ($540 \pm 290$; Sanders et al. 1991).

While it may be true that the ratio $M_\text{H}/M_\text{d}$ in high-redshift Lyman-$\alpha$ absorbers is significantly greater than in present-day galaxies, it seems likely that high-redshift radio galaxies, being the progenitors of present-day ellipticals, are considerably more evolved than Lyman-$\alpha$ absorbers at comparable redshift (which, it has been argued, are the progenitors of present-day disc galaxies). Thus there seems to be no clear justification for adopting an extreme gas-to-dust ratio, and so we have decided to adopt a conservative value of $M_\text{H}/M_\text{d} \sim 500$, consistent with the values reported for
These estimates of the $H_\alpha$ gas mass limits are consistent with the failure to detect large reservoirs of molecular gas directly in various CO transitions (Barvainis & Antonucci 1996; Evans et al. 1996; van Ojik et al. 1997), a fact which lends some circumstantial support to our adopted gas-to-dust ratio. Nevertheless, these gas masses are still extremely large and represent a significant fraction of the present-day stellar mass of the largest elliptical galaxies. The crucial issue of whether this ‘significant fraction’ could be sufficiently large to indicate that these objects deserve to be described as ‘primäval’ is considered below in the final section of this paper.

5 CONCLUSIONS: THE EVOLUTIONARY STATUS OF HIGH-REDSHIFT GALAXIES

We have presented sensitive continuum measurements at 800 $\mu$m of a sample of high-redshift galaxies and quasars. These observations were motivated by the goal of determining their evolutionary status in a relatively model-independent manner via a measure of their dust masses, star formation rates, and molecular gas masses. In addition to our 800-$\mu$m data presented here, we have taken the opportunity to gather together all other published millimetre and submillimetre observations of high-redshift galaxies and quasars at $z > 2$, and Table 3, in effect, summarizes the current status of submillimetre cosmology.

While it is expected that this subject will be revolutionized by the significantly more sensitive observations which should be possible in the very near future using new submillimetre continuum bolometer arrays such as SCUBA (Gear & Cunningham 1995), we have argued in this paper that there is much to be learned from considering the uncertainties which afflict the reliable interpretation of the existing, albeit sparse data set. In this spirit we conclude by considering what can be detected about the evolutionary status of high-redshift galaxies from the numbers presented in Table 3.

To focus the argument, we adopt the strict (and deliberately extreme) definition that a genuinely young elliptical galaxy would be expected to display a very high SFR ($> 500 M_\odot$ yr$^{-1}$), and to contain a total H i + H$_2$ gas mass equivalent to the majority of the stellar mass found in the most massive present-day giant ellipticals (e.g., $M_{H_\alpha} + M_{H_2} > 10^{11} M_\odot$). The adoption of such a large present-day mass can be justified on two levels. First, if one wants to prove unambiguously that the given high-redshift object is primäval on the basis of its gas mass, one needs to demonstrate that, even if its eventual present-day stellar mass is extremely large, the bulk of it remains in gaseous form at the high-$z$ epoch of observation. Secondly, since it is now well established that the most powerful radio sources and quasars in the low-redshift Universe reside in host galaxies with luminosities several times greater than $L^*$ (Taylor et al. 1996), it is not unreasonable to assume that the considerably more luminous active objects listed in Table 3 lie in still deeper potential wells.

Since we are unable to detect the contribution from 21-cm H i emission, which is shifted to 250–500 MHz at high redshift, we use the mean ratio of $M_{H_\alpha}$/$M_{H_\alpha}$ $\sim 1.0 \pm 0.9$ found in elliptical, early-type and interacting galaxies (Young & Knezek 1989; Lees et al. 1991) to place a lower mass limit of $M_{H_\alpha} > 5 \times 10^{10} M_\odot$ on the molecular gas content of the most luminous primäval or protoelliptical galaxies.

As illustrated in Fig. 9, when judged against these criteria of SFR and $M_{H_\alpha}$, although several of the detected objects in Table 3 may perhaps have adequate SFRs, only one source, the quasar BR 1202 – 0725, lies within the parameter space populated by primäval galaxies under the above definition. Given that both IRAS 10214 + 4724 and the Cloverleaf quasar would also have qualified as genuinely young on the basis of the $H_\alpha$ gas mass prior to correcting for the estimated effects of lensing, the suspicion, borne out by the recent CO detection (Ohta et al. 1996; Omont et al. 1996a) must be that BR 1202 – 0725 may also have amplified emission. Therefore, based on our analysis, the submillimetre properties of high-redshift AGN, which have been identified at optical/infrared/radio wavelengths, are more typical of a strong starburst in an otherwise well-formed galaxy than of genuinely primäval objects. Such a result could indicate that we are seeing the final stages of formation of these massive objects, or a starburst triggered by a galaxy–galaxy interaction which is also responsible for the observed AGN activity (in a hierarchical picture of galaxy formation these two alternatives could essentially amount to the same thing).

In judging the robustness of the basic conclusion that these high-$z$ galaxies are not primäval, it is important to consider in turn the effect of the dust temperature and adopted gas-to-dust ratio on the dust masses ($M_d$) in FIR luminosities ($L_{FIR}$) in Table 3, since both of the latter quantities are determined from an isothermal greybody fit to the submillimetre continuum.

First, the combined effect of the temperature uncertainty ($T_d \sim 50 \pm 20$ K) on the FIR luminosities and dust masses, which as discussed at length in Section 3.3.2, is illustrated in the representative locus passing through 4C 41.17 in Fig. 9. This locus, which is appropriate for galaxies at $z > 2$, shows that the upper limit in temperature (70 K) moves the high-$z$ sources away from the parameter space occupied by primäval galaxies and into a region requiring extremely high star-forming efficiencies ($\sim 100 L_\odot M_\odot^{-1}$). Conversely, while reducing the temperature to 30 K can increase the inferred gas mass to close to the required value, this is at the expense of the FIR luminosity and SFR which is reduced to $< 500 M_\odot$ yr$^{-1}$. In summary, our basic conclusion – that we are not seeing the primary formation even of these galaxies – is, with the possible exception of 4C 41.17, unaffected by varying the temperature of the dust between reasonable limits.

It is worth noting that while our adoption of a dust temperature of 50 K for these high-redshift objects results in values for $L_{FIR}/M_d \sim 100$ somewhat greater than is seen in isolated systems at low redshift (12 $\pm 3 L_\odot/M_\odot$) (Young et al. 1986; Solomon & Sage 1988), such values are not unreasonable and are comparable to that seen in the most luminous low-redshift interacting galaxies (78 $\pm 14 L_\odot/M_\odot$). Indeed, the location of the high-redshift sources in Fig. 9
seems perfectly consistent with an extrapolation of the upper envelope of star-forming efficiency defined by the most luminous ULIRGs.

Secondly, we address the issue of whether the uncertainty in the assumed ratio $M_{\text{H}_2}/M_d$ at high redshift is taken to extend to values of several thousand, as suggested by the analysis of Fall et al. (1989). However, as already discussed above, the relevance of the investigation of Lyman $z$ absorbers to the present study of high-redshift AGN is dubious. More significant is the good agreement between our adopted value and the mean $M_{\text{H}_2}/M_d$ ratio (426 ± 96) measured in the only three high-$z$ sources (H1413 + 117, IRAS 10214 + 4724, BR 1202 – 0725) with confirmed CO line and submillimetre continuum detections. The gas-to-dust ratio in these high-$z$ AGN should be relatively unaffected by lensing, assuming that, as in low-$z$ galaxies, the CO and submillimetre continuum have similar spatial distributions, and hence similar amplifications. Thus, taken at face value, these few CO detections of high-redshift objects support our view that $M_{\text{H}_2}/M_d$ ∼ 500 is appropriate for luminous galaxies out to $z \approx 5$, and explains why submillimetre continuum observations of high-redshift objects have been more successful than attempts to detect the molecular gas directly through CO line observations (and casts even more doubt on the claimed CO detection of 53W002; Yamada et al. 1995).

To summarize, Fig. 9 demonstrates that adoption of a dust temperature of 50 K and a gas-to-dust ratio of 500 leads one to conclude that the high-redshift objects listed in Table 3 would be better described as highly efficient starburst galaxies than genuinely primaeval objects. This conclusion is relatively immune to alteration of the adopted dust temperature. Indeed, to alter it significantly requires the adoption of a gas-to-dust ratio ∼5 times greater than has been assumed, and the low success rate of molecular CO line observations argued against this option. However, to finish on a cautionary note, there is one way to increase the inferred gas mass without increasing its detectability through line observations, and that is to relax the assumption of an Einstein–de Sitter universe. Ignorance of $\Omega_0$ is, of course, a problem that afflicts studies of galaxy evolution at all wavelengths but, as discussed in Section 3.4, at $z \approx 4$ adoption of $\Omega_0 \approx 0.1$ instead of $\Omega_0 = 1$ increases the inferred dust mass by a factor of 5 or so, all other things being equal, would increase the values of both $L_{\text{FIR}}$ and $M_{\text{H}_2}$ plotted in Fig. 9 by a factor of 5 for the high-redshift objects only. Under these circumstances, with SFRs $\sim 10^2 M_\odot$ yr$^{-1}$ and molecular gas masses $M_{\text{H}_2} \approx 5 \times 10^9 M_\odot$, it would be hard to escape the conclusion that essentially all of the high-redshift objects so far detected at submillimetre wavelengths are, in fact, primaeval galaxies (one could, for example, reduce the inferred gas mass by adopting a high dust temperature such as $T \approx 70$ K, but this would in turn imply a truly prodigious SFR).

Thus the unambiguous determination of the evolutionary status of the high-redshift objects detected to date at submillimetre wavelengths must await improved constraints on $\Omega_0$. However, we regard it as encouraging for the future of submillimetre cosmology that the uncertainties peculiar to the interpretation of these submillimetre data can be justified as being comparable in size to the current cosmological uncertainties. In general, continuum observations at submillimetre and millimetre wavelengths have proven to be more successful and have provided a comparable or lower $H_2$ mass limit than spectral line data obtained in an equal integration time. This observing efficiency, together with an expected improvement in our understanding of the dust emissivity and gas-to-dust ratio at high redshift, justified the continuation of this approach with the new generation of submillimetre continuum instruments (e.g., SCUBA), which will be sensitive to SFRs $< 100 M_\odot$ yr$^{-1}$ at $z = 3–5$ and hence will detect unlensed versions of IRAS 10214 + 4724 and H1413 + 117 with ease and also detect the equivalent of low-redshift ULIRGs (e.g., Arp 220 and Mrk 231) at $z > 4$. Given that the submillimetre properties of the high-redshift radio galaxies and quasars studied to date point towards a more dramatic formation event at yet higher redshift, it will be of particular interest to discover whether any of the objects detected by future submillimetre surveys meet the criteria defined in Fig. 9 for a genuinely primeval giant elliptical galaxy.

**ACKNOWLEDGMENTS**

We are indebted to the referee for helpful comments and suggestions that led to the improvement of this paper. We thank M. S. Yun and N. Z. Scoville for communicating their unpublished 105-GHz measurement of B20902 + 34. We are also grateful to Jason Stevens and Rob Ivison for confirming our 800-μm observations of H1413 + 117. The James Clerk Maxwell Telescope is operated by The Observatories on behalf of the Particle Physics and Astronomy Research Council (PPARC) of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada. We thank Jeff Cox, Alan Hatakeyama, Ed Lundin, Rusty Luthe, Kimberley Piscotta and Jim Pomeroy for their valuable assistance at the telescope. DHH gratefully acknowledges receipt of a PPARC PDRA during the course of this work.

**REFERENCES**


© Royal Astronomical Society • Provided by the NASA Astrophysics Data System