

# Detection of dust in the most distant known radiogalaxy

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## ABSTRACT

A search for millimetric continuum emission from eight optically-selected, radio-quiet quasars and a radiogalaxy with  $3.7 < z < 4.3$ , has been undertaken using a highly sensitive 7-channel bolometer on the IRAM 30-m Millimetre Radio Telescope. Detections of a potentially dust-rich quasar, and of 8C1435+635, the most distant known radiogalaxy, are reported. An extrapolation of the steepening centimetric radio spectrum of 8C1435+635 accounts for less than one per cent of the observed 1.25-mm flux density, indicating that the emission is most likely from warm dust, although the present data cannot discriminate against synchrotron emission. If the emission is thermal, then the derived dust mass lies in the range,  $2 \times 10^9 < M_d < 8 \times 10^7 M_\odot$  for  $20 < T_d < 100$  K, or  $M_d \sim 1.6 \times 10^8 M_\odot$  for  $T_d = 60$  K, similar to that derived for 4C41.17, suggesting a molecular gas mass of between  $4 \times 10^{10}$  and  $9 \times 10^{11} M_\odot$ . The quasar, PC2047+0123 at  $z = 3.80$ , has no detectable centimetric emission and the 1.25-mm continuum detected here probably also originates from  $1.5 \times 10^8 M_\odot$  of dust (again for  $T_d = 60$  K). Upper limits have been obtained for four quasars, corresponding to dust mass limits of around  $3\sigma < 2 \times 10^8 M_\odot$ ; less useful limits have been set for a further three quasars.

**Key words:** quasars: general – cosmology: observations – radio continuum: galaxies – galaxies: ISM – galaxies: individual: 8C1435+635.

## 1 INTRODUCTION

There are approximately 50 known quasars and radiogalaxies (RGs) with  $z \sim 4$ . It is natural to employ these objects as observational probes of the early stages of galaxy formation; for example, low-redshift RGs represent a relatively homogeneous group in many respects, and comparison with RGs at higher redshifts gives some perception of their evolutionary traits, always bearing in mind fears about sample bias, e.g. the alignment effect (McCarthy et al. 1987; Chambers, Miley & Van Breugel 1987).

Young quasars and RGs are likely to be the sites of active star formation, and they are therefore an obvious place to search for thermal emission from dust and line emission from molecular gas (McMahon et al. 1994). Evidence already supports the idea that there are vast reservoirs of dust-rich gas in several high-redshift objects, notably in the radio-quiet quasar BR1202–0725 (Isaak et al. 1994; McMahon et al. 1994), the Cloverleaf quasar (Barvainis et al. 1994), and the RG 4C41.17 (Dunlop et al. 1994; Chini & Krugel 1994), all of which have been detected in the rest-frame far-infrared. A thermal origin for the millimetric emission from these objects would indicate dust masses of around  $10^8$ – $10^9 M_\odot$ , and it is hard to explain their submillimetre spectral indices ( $\alpha \sim 3$ –4, where  $F_\nu \propto \nu^\alpha$ ) by anything *other* than emission from dust (e.g. Hughes et al. 1993).

Determining the evolutionary phase of these objects

(e.g. whether a ‘proto-galactic’ label applies) is not straightforward. One could measure the fraction of their gas which has been converted into stars, but this relies on knowledge of the relative gas-to-dust ratios over a range of redshifts, which emphasizes the importance of both continuum and molecular-line data. The millimetric continuum data presented here will be complemented by centimetric spectral-line observations of CO (Ivison et al., in preparation), which should yield estimates of several important physical parameters, not least the mass and temperature of the gas and dust.

## 2 BOLOMETER ARRAY MEASUREMENTS

The data were obtained during 1995 February 17–22 using the MPIFR 7-channel  $^3\text{He}$ -cooled bolometer array (see Kreysa 1993) and the 30-m IRAM Millimetre Radio Telescope on Pico Veleta, Spain. The individual beamsizes are 11–12 arcsec (HPBW), and the bolometers are separated by 22 arcsec in a hexagonal arrangement surrounding a central pixel. During our observing session we employed a 1-arcmin azimuthal chop-throw, at a rate of 2 Hz; the telescope was also position-switched by 1 arcmin every 10 s in the standard symmetric ON-OFF-OFF-ON mode. The nett result was that one third of the total observing time was spent on the source.

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**Table 1.** 1.25-mm photometry.

| Source name  | Object type | $z$  | Adopted coordinates (B1950) |             | $\lambda_0$<br>/ $\mu\text{m}$ | UT Date<br>(1995 Feb) | Flux Density<br>( $\pm\sigma$ ) /mJy | Note<br>/Reference      |
|--------------|-------------|------|-----------------------------|-------------|--------------------------------|-----------------------|--------------------------------------|-------------------------|
|              |             |      | $\alpha$                    | $\delta$    |                                |                       |                                      |                         |
| PC0027+0521  | RQQ         | 4.21 | 00 27 30.10                 | +05 21 39.0 | 240                            | 20.6                  | $-0.27 \pm 4.66$                     | 1, SSG94                |
| BR10151-0025 | RQQ         | 4.20 | 01 51 05.90                 | -00 25 44.0 | 240                            | 20.7                  | $0.71 \pm 2.25$                      | 1, S94                  |
| PC1301+4747  | RQQ         | 4.00 | 13 01 50.80                 | +47 47 35.0 | 250                            | 21.2                  | $1.20 \pm 1.77$                      | SSG91, SSG94, SVSG92    |
| 8C1435+635   | RG          | 4.26 | 14 35 27.50                 | +63 32 12.8 | 238                            | 17.3                  | $3.03 \pm 0.85$                      | 2, 3, L94, S95          |
|              |             |      |                             |             |                                | 19.3                  | $2.61 \pm 0.70$                      | 3, 4                    |
|              |             |      |                             |             |                                | 22.2                  | $2.26 \pm 0.67$                      | 3, 5                    |
|              |             |      |                             |             |                                | 18.3                  | $1.08 \pm 1.13$                      | SSG91, SSG94, SVSG92    |
| PC1640+4628  | RQQ         | 3.70 | 16 40 37.20                 | +46 28 01.0 | 266                            | 18.3                  | $1.08 \pm 1.13$                      | SSG91, SSG94, SVSG92    |
| PC1643+4631A | RQQ         | 3.79 | 16 43 33.50                 | +46 31 38.0 | 261                            | 18.5                  | $0.11 \pm 1.00$                      | 6, SSG91, SSG94, SVSG92 |
| PC1643+4631B | RQQ         | 3.83 | 16 43 52.40                 | +46 31 02.0 | 259                            | 19.5                  | $-0.95 \pm 0.81$                     | SSG91, SVSG92           |
| PC1644+4744  | RQQ         | 3.70 | 16 44 48.40                 | +47 44 24.0 | 266                            | 20.5                  | $-0.03 \pm 0.95$                     | SSG94                   |
| PC2047+0123  | RQQ         | 3.80 | 20 47 50.70                 | +01 23 56.0 | 260                            | 17.5                  | $1.51 \pm 0.91$                      | 7, SSG91, SVSG92        |
|              |             |      |                             |             |                                | 19.6                  | $1.97 \pm 1.19$                      | 7                       |
|              |             |      |                             |             |                                | 22.4                  | $2.11 \pm 0.64$                      | 5, 7                    |

1: high rms due to poor weather; 2:  $\tau = 0.31$ ; 3: weighted mean is  $2.57 \pm 0.42$  mJy ( $6.1\sigma$ ); 4:  $\tau = 0.12$ ; 5:  $\tau = 0.08$ ; 6: 5-arcsec SW of SSG94 position; 7: weighted mean is  $2.08 \pm 0.47$  mJy ( $4.4\sigma$ ); L94: Lacy et al. (1994); S94: Smith et al. (1994); S95: Spinrad et al. (1995); SSG91: Schneider, Schmidt & Gunn (1991); SSG94: Schneider, Schmidt & Gunn (1994); SVSG92: Schneider et al. (1992).

Typically 15–20 samples were obtained for each of the targets (separated by pointing, focusing, opacity tips and calibration scans of Uranus and Mars, for which  $T_b$  of 101 and 205 K were assumed, respectively), each consisting of forty 10-s sub-samples. The weighted mean of the outer channels was subtracted from the central channel — an effective method of reducing the effects of sky-noise, i.e. the fraction of atmospheric emission that remains after chopping. The samples were then concatenated, tested for spikes, and corrected both for atmospheric attenuation and for a gain-elevation dependence,  $G_{\text{el}}$ , of the form:

$$G_{\text{el}} = (\cos(\text{el} - 45^\circ)^2 + 0.4 (\sin(\text{el} - 45^\circ)^2)^{-1} . \quad (1)$$

The sky transparency at 1.25 mm was virtually constant during each session; it varied from night to night, but was generally good, with the opacity ranging from 0.06 to 0.44. All the sources were observed at low zenith distances ( $< 45^\circ$ ). The pointing characteristics of the telescope were excellent, with rms fluctuations at 20 per cent of a single-channel HPBW.

The  $z = 4.26$  RG, 8C1435+635, and the  $z = 3.80$  quasar, PC2047+0123, were each observed on three separate occasions in order to confirm that their emission was real. The flux-density measurements are presented in Table 1, together with redshifts, rest wavelengths and adopted coordinates.

### 3 RESULTS AND DISCUSSION

The data from Table 1 reveal that 8C1435+635, a  $z = 4.26$  RG (Lacy et al. 1994, hereafter L94; Spinrad et al. 1995, hereafter S95), was detected at the  $6.1\sigma$  level, and the radio-quiet quasar, PC2047+0123 at  $z = 3.80$ , was marginally ( $4.4\sigma$ ) detected. Limits of  $3\sigma < 3$  mJy have been set for four quasars, together with higher limits for a further three.

#### 3.1 8C1435+635

The integrated spectrum of 8C1435+635 steepens from  $\alpha = -1.2$  to  $-2.2$  via  $-1.5$  between 0.151, 1.5, 4.9 and 8.4 GHz;

it then continues at  $\alpha = -2.2$  to 15 GHz. 8C1435+635 was initially selected for blind spectroscopic observations by L94 on the basis of its steepening radio spectrum.

Fig. 1 shows the measurement obtained here for 8C1435+635, and those obtained by L94 and S95 at lower and higher frequencies. Flux densities upper limits from the *Infrared Astronomical Satellite* have also been estimated at 12, 25, 60 and 100  $\mu\text{m}$  by searching a 1 square degree field centred on the RG for sources from the *Faint Source Catalogue (FSC)*, adopting the faintest in each band as the upper limit. This crude method relies on the fact that if the *FSC*'s sophisticated search routines cannot find a point source, then the source must be below the  $3\sigma$  threshold. The method is probably as reliable as any other, and is less prone than some to providing misleadingly low limits.

If the cm-wave radio spectrum continues to decline above 15.2 GHz with  $\alpha = -2.2$  then the non-thermal contribution at 243 GHz would be 15  $\mu\text{Jy}$ . Between 15 and 243 GHz,  $\alpha = -0.3$ , making it a safe bet that its contribution to the 243-GHz flux density is completely insignificant, and that the 243-GHz emission is probably dominated by thermal emission from dust. Of course, it is not possible to discriminate against a synchrotron origin, and absolute confirmation of the emission mechanism must be obtained at frequencies above or below 243 GHz; the most reliable method would be to obtain photometry at 0.8 mm using UKT14 on the 15-m James Clerk Maxwell Telescope, where the thermal emission contribution would be around 15 mJy for  $\alpha = +4.0$  (contributions of +2.0 from both the dust emissivity and the Rayleigh-Jeans law) — within the capabilities of the instrument on an excellent night (e.g. Dunlop et al. 1994).

If the 243-GHz emission mechanism is thermal, and assuming a range of estimates for the dust temperature based on the  $z = 3.8$  RG, 4C41.17, and on samples of low-redshift quasars and RGs (Knapp & Patten 1991; Andreani, La Franca & Cristiani 1993; Chini & Krügel 1994; Dunlop et al. 1994), i.e.  $T_d = 20$ –100 K, and an Einstein - de Sitter universe where  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , then for optically thin emission we can determine the dust mass using (from Chini & Krügel 1994):

**Figure 1.** Spectral energy distribution of 8C1435+635. The line drawn in the rest-frame far-IR illustrates a 60-K greybody, with +2 frequency dependence for the dust-grain emissivity (neither parameter is reliably constrained).

$$M_d = \frac{F_{\nu_{\text{obs}}} D_L^2}{(1+z) \kappa_{\nu_0} B_{\nu_0}(T_d)} \quad , \quad (2)$$

where  $F_{\nu_{\text{obs}}}$  is the observed flux density,  $\nu_{\text{obs}}$  and  $\nu_0$  are the observed and rest-frame frequencies,  $\kappa_{\nu_0}$  is the dust absorption coefficient ( $10.5 \text{ cm}^2 \text{ g}^{-1}$  has been adopted here, from Krügel, Steppe & Chini 1990), and the luminosity distance is given by

$$D_L = \frac{2 c (1+z - (1+z)^{0.5})}{H_0} \quad . \quad (3)$$

For  $T_d = 60 \text{ K}$ , the resulting dust mass is  $1.6 \times 10^8 M_\odot$ , which is similar to that calculated for 4C41.17 using the same method. For  $20 < T_d < 100 \text{ K}$ ,  $2 \times 10^9 < M_d < 8 \times 10^7 M_\odot$ . Note that the above calculation is sensitive to parameters assumed for both the dust and the cosmology. Conversion from dust mass to gas mass is troublesome even in the Milky Way; but adopting  $M_g/M_d = 500$  (for a system which probably has a relatively low abundance of heavy elements) gives a gas mass,  $M_g$ , of  $8 \times 10^{10} M_\odot$  for  $T_d = 60 \text{ K}$ .

Dust-rich gas in these quantities may explain the anomalously weak Lyman  $\alpha$  luminosity of this RG, as suggested by L94. Following Chini & Krügel (1994), in the idealized case where  $10^8 M_\odot$  of dust is distributed in a 50-kpc diameter sphere, the optical depth at  $1216 \text{ \AA}$  would be 1–2, sufficient to entirely absorb the Lyman  $\alpha$  photons assuming that neutral hydrogen is sufficiently abundant to make res-

onant scattering important (where scattering increases the path length and, accordingly, the optical depth to absorption by dust; see Eales & Rawlings 1993). This does not, however, explain why the Lyman  $\alpha$  luminosity of 8C1435+635 is low relative to 4C41.17, another distant, dust-rich radio-galaxy. S95 note that 8C1435+635 lies within the scatter of the Lyman  $\alpha$  luminosity—radio power relationship.

### 3.2 Quasars

We observed a total of eight radio-quiet quasars, all of which satisfy  $3.7 < z < 4.3$ . One was detected, PC2047+0123 at  $z = 3.80$ , with a signal-to-noise ratio of 4.4 after taking the weighted mean of data obtained on separate nights. There is nothing intrinsically flawed about this procedure, but we regard the detection as slightly marginal, and confirmation should be sought with one of the upcoming generation of submillimetre bolometer arrays. The rms flux densities for the remaining seven quasars (Table 1) yield  $3\text{-}\sigma$  upper limits of between  $10^8$  and  $10^9 M_\odot$  for their dust masses, using the same assumptions as for 8C1435+635.

Upper limits ( $3\sigma$ ) of 225 and  $120 \mu\text{Jy}$  were obtained for PC2047+0123 at 1.5 and 4.9 GHz by Schmidt et al. (1995) and Schneider et al. (1992), respectively; yielding a lower limit for the spectral index between 4.9 and 243 GHz of  $\alpha > +0.7$ . This provides evidence, always bearing in mind the marginal nature of the detection and the lack

of a measurement of the submillimetre spectral index, that the 1.25-mm flux density is dominated by thermal emission from dust, though again we cannot discriminate against a non-thermal mechanism. If dust is responsible, we estimate  $M_d = 1.5 \times 10^8 M_\odot$  (under the assumptions discussed in the previous section, and with  $\kappa_{\nu_0} = 8.7 \text{ cm}^2 \text{ g}^{-1}$ ).

#### 4 CONCLUDING REMARKS

In an attempt to increase the number of known gas-rich systems at  $z \sim 4$ , eight radio-quiet quasars and a RG, which satisfy  $3.7 < z < 4.3$ , have been observed using a sensitive 7-channel bolometer on the 30-m IRAM Millimetre Radio Telescope, resulting in the detection of 1.25-mm continuum emission from the radio-quiet quasar, PC2047+0123 at  $z = 3.8$ , and from 8C1435+635, the most distant known RG. Both are now prime targets for spectral-line observations of molecular gas. We have placed limits of  $3\sigma < 3 \text{ mJy}$  on a further four high-redshift quasars, which corresponds to approximately  $3\sigma < 2 \times 10^8 M_\odot$  of dust (for  $T_d \sim 60 \text{ K}$ ;  $q_0 = 0.5$ ;  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). Another three quasars have slightly less useful limits.

If the 1.25-mm emission from 8C1435+635 is dominated by thermal emission, which seems likely given the steep centimetric spectrum, then the derived dust mass is similar to those found in nearby radio-quiet quasars (Hughes et al. 1993), and 1–2 orders of magnitude higher than those found for nearby radio galaxies (e.g. Knapp, Bies & van Gorkom 1990; Knapp & Patten 1991). There is evidence, therefore, that spectral-line and sub-mm continuum observations of this RG will provide clues concerning the dynamical, physical and evolutionary state of some of the most ancient known material in the Universe, and there is a tantalizing possibility that the Very Large Array can be used to map the molecular gas with the same angular resolution as can be routinely obtained when observing CO in local galaxies ( $0.1 \text{ arcsec} \sim 1 \text{ kpc}$  at  $z \sim 4$ , for  $\Omega_0 = 0.5$  and  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ).

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