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Dust in 3C 324

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ABSTRACT

The results of a deep submillimetre observation using SCUBA of the powerful radio galaxy 3C 324, at redshift $z = 1.206$, are presented. At 850 μm, emission from the location of the host radio galaxy is marginally detected at the 4.2σ level, 3.01 ± 0.72 mJy, but there is no detection of emission at 450 μm to a 3σ limit of 21 mJy. A new 32-GHz radio observation using the Effelsberg 100-m telescope confirms that the submillimetre signal is not associated with synchrotron emission. These observations indicate that both the mass of warm dust within 3C 324 and the star formation rate lie up to an order of magnitude below the values recently determined for radio galaxies at $z \sim 3$–4. The results are compared with dust masses and star formation rates derived in other ways for 3C 324.

Key words: dust, extinction – galaxies: active – galaxies: individual: 3C 324 – galaxies: ISM – radio continuum: galaxies.

1 INTRODUCTION

Searches for emission from distant galaxies at millimetre and submillimetre wavelengths provide a direct method of investigating the star formation activity of these galaxies, since a large proportion of the optical and ultraviolet luminosity is reprocessed by dust to these longer wavelengths (e.g. Soifer & Neugebauer 1991). In addition, the strong negative K-correction caused by the steepness of the Rayleigh–Jeans tail of the thermal dust spectrum means that at submillimetre wavelengths equivalent objects will appear as bright at redshift $z \sim 10$ as they do at $z \sim 1$ (Blain & Longair 1993). Powerful radio galaxies can be observed out to extreme redshifts, $z > 4$ (e.g. Rawlings et al. 1996), and therefore provide a probe through which the star formation history of massive galaxies can be investigated.

The optical and ultraviolet morphologies of powerful radio galaxies with redshifts $z \gtrsim 0.6$ are dominated by emission elongated and aligned along the direction of the radio axis (McCarthy et al. 1987; Chambers, Miley & van Breugel 1987). The precise details of this so-called 'alignment effect' remain unclear, with scattered quasar light, nebular continuum emission and jet-induced star formation all likely to contribute at some level (e.g. see Röttgering & Miley 1996). Underlying this aligned emission, however, the host galaxies of radio sources with redshifts $z \sim 1$ are well-formed ellipticals whose stellar mass is dominated by an old stellar population (e.g. Stockton, Kellogg & Ridgway 1995), and which have settled down into a stable $r^{1/4}$ law profile (Best, Longair & Röttgering 1998b). These galaxies are amongst the most massive at their epoch, with stellar masses of a few times 10^{11} $M_{\odot}$, and often appear to lie at the centre of young or forming clusters (Dickinson 1997; Best et al. 1998b). Although a proportion of the aligned emission may be associated with young stars, forming at a rate of order 100 $M_{\odot}$ yr^{-1} (e.g. Best, Longair & Röttgering 1996, 1997, Cimatti et al. 1996), the few galaxies that have been studied in detail so far show no strong signatures in the rest-frame ultraviolet/optical spectra that would indicate star formation at significantly higher rates (Cimatti et al. 1996, 1997).

At redshifts $z \gtrsim 2$, powerful radio galaxies have much more clumpy optical morphologies, with extreme examples showing many separate bright emission regions within a spatial extent of 50 to 100 kpc (Pentericci et al. 1998). The individual emission clumps have sizes of 2 to 10 kpc, and their profiles and colours are similar to those of the UV-dropout galaxies at $z \sim 3$ (Giavalisco, Steidel & Macchetto 1996). Although these radio galaxies overall display a strong alignment effect, a significant proportion of the individual clumps lie away from the radio axis, suggesting that their blue colours are not directly associated with the alignment effect, but that these are more likely to be star-forming objects, each with star formation rates of order 10 $M_{\odot}$ yr^{-1}.

At redshifts $z \gtrsim 3$, targeted millimetre and submillimetre observations have succeeded in detecting a number of powerful radio galaxies (see Hughes, Dunlop & Rawlings 1997 for a review, Ivison

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et al. 1998, Cimatti et al. 1998, Röttgering et al. 1998, Hughes & Dunlop 1998). The masses of warm dust implied by these observations are a few times 10^8 $M_{\odot}$ and the corresponding star formation rates are extreme. If it is assumed that all of the dust is heated by young stars, then thousands of solar masses per year of star formation must be on-going. These results are frequently interpreted as being the burst of star formation that forms the bulk of the stellar mass of these galaxies. Supporting evidence for this hypothesis comes from a deep Keck spectrum of the radio galaxy 4C 41.17 ($z = 3.8$) at rest-frame ultraviolet wavelengths, which shows strong absorption features indicating that the ultraviolet continuum of this galaxy is dominated by hot young stars forming at rates of up to 1100 $M_{\odot}\,yr^{-1}$ (Dey et al. 1997).

Despite the successes at the highest redshifts, submillimetre observations of powerful radio galaxies at redshifts $z \sim 1$ have been sparse and unsuccessful (e.g. see Hughes & Dunlop 1998). Studies of these galaxies are of great importance, first for understanding the continued evolution of the interstellar medium of massive galaxies, and secondly for investigating the extent to which the powerful active galactic nucleus (AGN) can be responsible for heating the dust within the radio galaxies. The advent of highly sensitive instruments such as the Submillimetre Common-User Bolometer Array (SCUBA; Holland et al. 1999) on the James Clerk Maxwell Telescope[1] (JCMT) has opened up the possibility of more detailed studies of these objects.

In this letter we present submillimetre observations of one such radio galaxy, 3C 324 at redshift $z = 1.206$. The very strong alignment effect and the scattering properties of this galaxy, together with a central absorption feature in the *Hubble Space Telescope* (*HST*) image, make it one of the most promising candidates in the 3CR $z \sim 1$ sample for a large dust mass (Best et al. 1996; Cimatti et al. 1996). In Section 2 we describe the observations of 3C 324 and the data reduction. In Section 3 we present our results and discuss their implications. Throughout this letter we adopt $q_0 = 0.5$ and $H_0 = 50\,\mathrm{km\,s^{-1}Mpc^{-1}}$.

2 OBSERVATIONS

2.1 SCUBA observations

3C 324 was observed using SCUBA on the JCMT for a total of 105 minutes on source during the nights of 1997 November 30 and December 2. SCUBA has two arrays of bolometric detectors, cooled to 0.1 K. The short-wavelength (SW) array has 91 feedhorns and can be operated at 350 or 450 μm; the diffraction-limited beamwidth at 450 μm has a half-power diameter of 7.5 arcsec. The long-wavelength (LW) array has 37 feedhorns and can be operated at 750 or 850 μm; at 850 μm the beamwidth is 14 arcsec. A dichroic beam-splitter enables observations using both arrays simultaneously.

In the standard SCUBA photometry mode, observations are made using the central pixels of each array, which are aligned with each other to within about an arcsecond. A jiggling procedure is employed whereby the secondary mirror is jiggled around a nine-point filled square, with a 2 arcsec offset between each pointing. This method has been shown to produce the best photometric accuracy (cf. Ivison et al. 1998). The integration time for each pointing of the jiggle is 1 second. During this period the secondary mirror is chopped at 7 Hz between the source and a reference sky position, usually with a chop-throw of between 60 and 180 arcsec in azimuth. Following the 9-second jiggle, the telescope is nodded so that the chop position is placed at the opposite side of the source and the jiggle pattern is repeated.

The observations of 3C 324 were made at 850 and 450 μm using the two-bolometer photometry mode, which is an adaptation of the standard photometry mode. In this mode the chop–throw is not fixed in azimuth, but is fixed such that, in the primary nodding position, the source is chopped to the centre of one of the other bolometers of the LW array. This 'chop bolometer' is chosen to be one for which the chop-throw lies as nearly as possible in azimuth, and whose position corresponds closely to that of a bolometer in the SW array. In two-bolometer mode, the source is thus observed for half of the total integration time in the central bolometer, plus a further quarter in the chop bolometer, improving the observing efficiency. Owing to the apparent curvature of the arrays on the sky, the chop–throw in the reference nodding position does not centre the source on a bolometer. A three-bolometer photometry mode would maximize the observing efficiency and is planned for SCUBA, but was not operational at the time of these observations.

350 18-second integrations were made of 3C 324, split into seven sets of 50 integrations. Telescope pointing checks were made using 1611+343 before each set of integrations; the offsets were small, typically below 2 arcsec. Skydips were made at intervals of about 2 hours throughout both nights, and showed the sky to be stable. On November 30 the atmospheric zenith opacity was consistently about 0.12 at 850 μm all night and between 0.55 and 0.65 at 450 μm. On December 2 the opacity was about 0.25 at 850 μm and 1.6 ± 0.3 at 450 μm. The observations were made whilst 3C 324 was at low airmass (mean value 1.24). Calibration observations, using 3C273 on the first night and IRC+10216 on the second, were taken using the same two-bolometer photometry mode, the fluxes of these objects being bootstrapped to Mars. The calibration uncertainty for these data is estimated to be $\lesssim$10 per cent at 850 μm, but possibly as much as 25 per cent at 450 μm.

The data were reduced using the SCUBA software, SURF (Jenness 1997). The reference measurements were subtracted from the signal beams, the bolometers were flat-fielded using the standard SCUBA flatfield, and the extinction correction was applied. Noisy integrations and strong spikes in individual bolometers were rejected; this removed a little under 5 per cent of the data. The residual sky background was removed by subtracting the mean signal from the off-source bolometers in the inner ring around the central bolometer, excluding those bolometers that had significantly higher than average noise (see also Ivison et al. 1998).

The integrations were then concatenated to form a single data set, and the consistency of this data set was investigated using a two sample Kolmogorov–Smirnov (KS) test. In this way, periods when the changes in, for example, the atmospheric conditions or the telescope focus may have affected the data quality can be identified and removed (Jenness 1997). The data was split into subsamples, and the first two samples were compared for consistency. The second sample was rejected if the probability that the two samples are drawn from the same parent sample was below a given limit; otherwise, it was concatenated with the first sample. The resulting sample was then compared with the third subsample, the process was repeated, and so on. For each wavelength the KS test was run on both the central bolometer and the chop bolometer with a variety of inputs: the number of subsamples, the order in which they were supplied, and the limit for rejecting the samples were all varied. The results obtained were consistent, and rejected about 5 per cent of the data.

[1] The JCMT is operated by the observatories on behalf of the UK Particle Physics and Astronomy Council, the Netherlands Organisation for Scientific Research (NWO) and the Canadian National Research Council.

At 850 μm, the signal measured in the central bolometer was 3.65 ± 1.17 mJy, and that in the chop bolometer 4.46 ± 2.55 mJy (the error in the latter measurement is higher since this bolometer was only on-source for half as long as the central bolometer). Combined, these give 3.78 ± 1.05 mJy, a signal with a 3.6σ significance. 3C 324 has also been observed using SCUBA by Hughes & Dunlop (1998). They determine a flux density at 850 μm of 2.4 ± 1.0 mJy. Combining this with our data gives a combined signal of 3.01 ± 0.72 mJy, a marginal detection at the 4.2σ level. At 450 μm no signal was detected to a 3σ upper limit of 21 mJy.

2.2 Effelsberg observations

3C 324 was observed using the 100-m Effelsberg Telescope on 1998 July 15, at a central frequency of 32 GHz. The three-feed receiver system installed in the secondary focus was used in a multibeam mode. Each horn feeds a two-channel receiver with an IF polarimeter providing full Stokes information simultaneously. The bandwidth was 2 GHz.

The observations were made using a cross-scan in the equatorial coordinate system, with the main beam scanning a distance of 4 arcmin at a scanning speed of 10 arcsecs^{-1}. The offset feeds were used to efficiently remove atmospheric noise. 32 such sub-scans were made of 3C 324 (16 in a north–south direction, and 16 east–west), and the data in the combined scan was sampled at 3.8 arcsec intervals.

Four sub-scans of the source 3C286 were also made, and used to calibrate the flux density of 3C 324, taking the flux density of 3C286 at 32 GHz to be 1.779 Jy according to the scale of Ott et al. (1994), which corresponds to the Baars (1977) scale at lower frequencies. The flux density of 3C 324 at 32 GHz was thus determined to be 32.4 ± 9 mJy.

3 DISCUSSION

In Fig. 1 we plot the results of these SCUBA observations, together with the flux densities of the synchrotron emission at radio wavelengths from the literature (using the compilation of Herbig & Readhead (1992), and new 5- and 8-GHz measurements from Best et al. 1998a), and our new Effelsberg data.

The radio synchrotron emission of double radio sources steepens at high frequencies owing to electron cooling, the precise details of the steepening depending upon the synchrotron ageing model adopted. The radio spectrum of 3C 324 was compared with the three popular ageing models, and the best fit was provided using a KP model (Kardashev 1962; Pacholczyk 1970). This is shown on Fig. 1: the fitted synchrotron spectrum passes more a factor of 10 below the 850 μm SCUBA signal. It is beyond the scope of this letter to discuss in detail the synchrotron ageing models: we merely note that although the KP model reflects a somewhat unphysical situation, since it does not allow a uniform distribution of pitch angles, Carilli et al. (1991) showed that this model also provides the best match to the lobe emission of Cygnus A, a low redshift analogue of 3C 324; therefore, it provides an acceptable template.

The hotspots and radio core, where the electrons are continuously injected, may, however, show less spectral steepening. The radio core flux densities at 5 and 8 GHz are only 0.17 and 0.14 mJy respectively (Best et al. 1998a; see Fig. 1), and so its flux density at 850 μm will be negligible. The hotspots, which lie towards the extremes of the SCUBA 850-μm beam (the radio source angular extent is 11.5 arcsec, compared to a beam FWHM of 14 arcsec), cannot be resolved from the lobe emission even in our high-resolution 8-GHz maps, and so precisely determining their contribution to the radio source flux density is not possible. The poor agreement of a continuous injection synchrotron model with

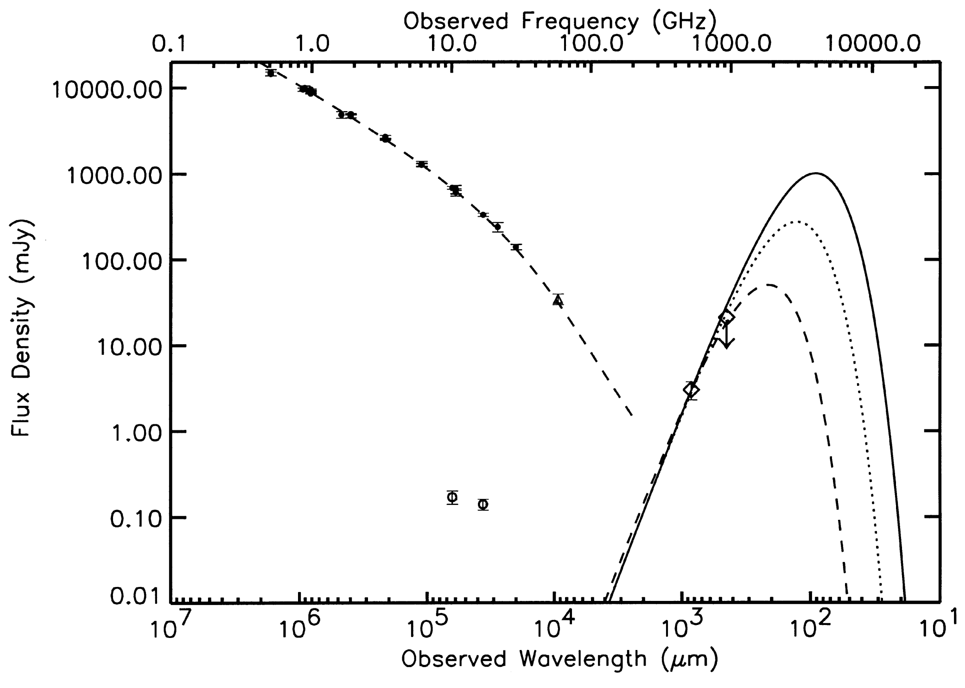

Figure 1. The spectral energy distribution of 3C 324. The open diamonds represent the current SCUBA data, and the solid, dotted and dashed lines represent isothermal grey-body emission with an emissivity index $\beta = 2$ for dust at temperatures of 70, 50 and 30 K respectively. The filled circles are the radio flux densities of 3C 324, taken from Herbig & Readhead (1992) and Best et al. (1998a). The open triangle is our new 32 GHz data point. The dashed line shows a single power-law fit to the synchrotron emission at radio frequencies below 10 GHz. The open circles are the flux densities of the radio core emission only, taken from Best et al. (1998a).

the 15- and 32-GHz data points, however, suggests that they do not dominate the flux density even at the highest radio frequencies. In conclusion, the shape of the high-frequency radio spectrum appears to rule out the high-frequency tail of the synchrotron emission as a possible origin of the 850-μm signal.

Although we cannot categorically state that a signal with 4.2σ significance constitutes a detection, the agreement between the signal we derived and that derived from an independently data set by Hughes & Dunlop (1998), and the consistency between the two bolometers and stability of the signal throughout the seven sets of 50 integrations in our observations (a positive signal was measured in 10 of the 14 measurements), adds support to its reality. For the remainder of this letter we shall perform calculations based upon an 850-μm flux density of 3.01 mJy: it should be realized, however, that the values derived should strictly be treated as upper limits instead of derived quantities.

The mass of warm dust, $M_{\rm d}$, can be calculated from the submillimetre flux using the equation

$$M_{\rm d} = \frac{S(\nu_{\rm obs}) D_{\rm L}^2}{(1+z)\kappa_{\rm d}(\nu_{\rm rest}) B(\nu_{\rm rest}, T_{\rm d})}$$

where S is the observed flux density, $\nu_{\rm obs}$ and $\nu_{\rm rest}$ are the observed and rest-frame frequencies, $D_{\rm L}$ is the luminosity distance, z is the redshift, $\kappa_{\rm d}$ is the mass absorption coefficient, B is the black-body Planck function, and $T_{\rm d}$ is the dust grain temperature. To allow comparison with the discussion of the $z \gtrsim 3$ radio galaxies (Hughes et al. 1997), we adopt a dust temperature $T_{\rm d} = 50\,{\rm K}$, and a mass absorption coefficient $\kappa_{\rm d} = 0.067(\nu_{\rm rest}/250\ {\rm GHz})^{\beta}\ {\rm m^2\,kg^{-1}}$ with $\beta = 2$. This provides a mass of warm dust in 3C 324 of $1.2 \times 10^8\ {\rm M_\odot}$. If it is assumed that this dust is heated primarily by young stars, then a simple scaling between the star-formation rate and the submillimetre luminosity can be obtained using nearby starbursts such as M82 (Hughes, Gear & Robson 1994), providing a current star formation rate for 3C 324 of 350 $\rm M_\odot\ yr^{-1}$.

Adoption of a lower temperature (the 450-μm SCUBA upper limit implies that if the 850 μm is real then the dust is at a temperature $T \lesssim 45\,{\rm K}$) would increase the dust mass, by about a factor of 2 for $T_{\rm d} = 30\,{\rm K}$. The dust mass would also increase if a flatter grain emissivity index were used (about a 50 per cent increase for $\beta = 1.5$). A full discussion of the uncertainties of these values can be found in Hughes et al. (1997). The dust masses derived are also strongly dependent upon H_0 and q_0 through the luminosity distance dependence: for $H_0 = 100\,{\rm km\,s^{-1}\,Mpc^{-1}}$ the mass would be a factor of 4 lower than that derived here; for $q_0 = 0$ it would be nearly a factor of 2 higher. All these conversion factors would, however, apply similarly to any star formation rates determined from the optical and ultraviolet emission, and (in the case of q_0, to an even greater extent) to the dust masses derived for the highest redshift radio galaxies.

The derived mass of warm dust within 3C 324, $1.2 \times 10^8\ {\rm M_\odot}$, can be compared to dust masses derived in other ways for this radio galaxy. *HST* images of the galaxy show bright extended ultraviolet emission, but the central regions of the galaxy are obscured, probably by a dust lane with $E(B-V) \gtrsim 0.3$ (Longair, Best & Röttgering 1995; Dickinson, Dey & Spinrad 1996). The mass of this centrally concentrated dust can be related to the extinction using the equation $M_{\rm d} = \Sigma\langle A_{\rm B}\rangle/\Gamma_{\rm B}$, where Σ is the area covered by the dust extinction, $\langle A_B\rangle \approx 4E(B-V)$ is the mean B-band extinction, and $\Gamma_B \approx 8 \times 10^{-6}\ {\rm mag\ kpc^2\ M_\odot^{-1}}$ is the B-band mass absorption coefficient (Sadler & Gerhard 1985). The dust extinction in the central regions of 3C 324 covers an area of at least 2 by 2 kpc^2, requiring a minimum of $\sim 10^6\ {\rm M_\odot}$ of dust to be concentrated near the nucleus of the radio galaxy.

The extended emission of 3C 324 is strongly polarized owing to scattering of radiation from a hidden quasar nucleus, and the shape of the polarized flux spectrum indicates that, regardless of whether the scattering medium is electrons or dust, the scattered light must be dust reddened. In the case of pure dust scattering, a mass of at least a few times $10^6\ {\rm M_\odot}$ of dust must be distributed throughout the galaxy (Cimatti et al. 1996). In addition to scattering the AGN emission, this same dust would absorb some of the AGN radiation and reprocess this to submillimetre wavelengths. These two lower limits allow the mass of warm dust in 3C 324 to be constrained to within an order of magnitude even if the submillimetre derived value is considered as an upper limit.

The star formation rate of 350 $\rm M_\odot\ yr^{-1}$ deduced for 3C 324 from the SCUBA observations can be compared with a star-formation rate estimated from the rest-frame 2800-Å flux density. The Keck spectrum of Cimatti et al. (1996) provides a 2800-Å continuum flux density of $2.6 \times 10^{-18}\ {\rm erg\,s^{-1}cm^{-2}\AA^{-1}}$ from a 3.8 by 1 arcsec^2 slit along the galaxy. Extinction by a few times $10^6\ {\rm M_\odot}$ of dust spread evenly throughout this region would mean that the intrinsic flux would be about 50 per cent higher. However, the strong UV/optical polarization of this galaxy suggests that between 30 and 50 per cent of the 2800-Å flux density of 3C 324 is associated with a scattered component (Cimatti et al. 1996), and the nebular continuum contribution will also be highly significant, so only a fraction $0 < f \lesssim 0.3$ will be associated with young stars. Comparison with the results of Madau, Pozzetti & Dickinson (1998) for the 2800-Å luminosity expected for on-going star formation [for a Scalo (1986) IMF with upper and lower cut-offs of 125 and 0.1 $\rm M_\odot$ respectively, and solar metallicity], indicates that the rate of on-going star formation must be below $f \times 130\ {\rm M_\odot\ yr^{-1}}$. If, on the other hand, the star formation were associated with only a short burst induced by the radio source, about 5×10^6 yr old, the Bruzual & Charlot (1993) stellar synthesis codes show that the measured 2800-Å flux density corresponds to a star formation rate of $f \times 1050\ {\rm M_\odot\ yr^{-1}}$, just consistent with the value derived from the current submillimetre observations if f lies at the upper end of its allowed range.

With these star formation rate limits, powerful radio galaxies at redshift one cannot be undergoing anything more extreme than short-lived ($\lesssim 10^7$ yr) starbursts of a few hundred solar masses per year. This is in stark contrast to the situation in radio galaxies at redshifts $z \gtrsim 3$ where star-formation rates of several thousands of solar masses are derived. These values are based upon the assumption that the dust is heated by young stars rather than by the AGN. The current observations support that hypothesis: the AGN of the high-redshift galaxies have a similar intrinsic power to that of 3C 324, whilst the submillimetre emission from 3C 324 at least a factor of a few lower. Therefore, only a small fraction of the dust in the very distant galaxies can be heated by the AGN.

NOTE ADDED IN PRESS

On 1998 August 19, a deeper (64 subscans) Effelsberg 32-GHz observation of 3C 324 was made during better weather conditions, using the same observational set-up as described in the text. An improved flux density measurement of 38.5 ± 3.6 mJy was determined, strengthening the conclusion of a turn-over in the synchrotron spectrum.

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