AzTEC 1.1 mm images of 16 radio galaxies at 0.5<z<5.2 and a quasar at z=6.3

A. Humphrey1, M. Zeballos1, I. Aretxaga1, D. H. Hughes1, M. S. Yun2, R. Cybulski2, Grant W. Wilson7, J. Austermann3, H. Ezawa4, R. Kawabe4, K. Kohno5,6, T. Perera7, K. Scott2,8, D. Sánchez-Arguelles1, R. Gutermuth9

1 Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Aptdo. Postal 51 y 216, 72000 Puebla, Pue., Mexico
2 Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA
3 Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA
4 Nobeyama Radio Observatory, National Astronomical Observatory of Japan, Minamimaki, Minamisaku, Nagano 384-1305, Japan
5 Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan
6 Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
7 Department of Physics, Illinois Wesleyan University, Bloomington, IL 61701, USA
8 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
9 Smith College, Northampton, MA 01063, USA

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ABSTRACT
We present 1.1 mm observations for a sample of 16 powerful radio galaxies at 0.5<z<5.2 and a radio quiet quasar at z=6.3, obtained using the AzTEC bolometer array mounted on the ASTE or the JCMT. This paper more than doubles the number of high-z radio galaxies imaged at millimetre/sub-millimetre wavelengths. We detect probable millimetre-wave counterparts for 11 of the active galaxies. The 6 active galaxies which do not have a probable millimetre counterpart in our images nevertheless have one or more likely associated millimetric source. Thus, we conclude that powerful (radio-loud) active galaxies at high-z are beacons for finding luminous millimetre/sub-millimetre galaxies at high-z. The flux densities of our AzTEC counterparts imply star formation rates ranging from <200 to ∼1300 M⊙ yr−1. In addition, we find that for the radio galaxies the 1.1 mm flux density is anticorrelated with the largest angular size of the radio source.

We also present new Spitzer imaging observations of several active galaxies in our sample. Combining these with archival data, we examine the mid-infrared colours of our sample. We find that radio galaxies for which we have detected a probable 1.1 mm counterpart have mid-infrared colours consistent with dusty starbursts, and are usually bluer than high-z Spitzer-selected active galaxies. In addition, we find arcs of 24 µm sources extending across ∼200-500 kpc, apparently associated with three of the radio galaxies.

Key words: galaxies: high-redshift – galaxies: active – quasars: general – galaxies: starburst, submillimetre – cosmology: observations – submillimetre – dust

1 INTRODUCTION
Powerful, high-z radio galaxies (z≥0.5: HzRGs) continue to play a key role in cosmological investigations. Their high luminosities at radio and optical wavelengths make them useful as beacons for finding massive elliptical galaxies and their progenitors out to redshifts (e.g. Dunlop et al. 1996; Röttgering et al. 1997; McLure et al. 1999), and provide unique opportunities to study their host galaxy and environment (e.g. Venemans et al. 2007).

Many HzRGs are embedded within haloes of ionized gas which are extended on spatial scales of tens of kpc, and which emit luminous emission lines from various species (e.g. McCarthy, Spinrad & van Breugel 1995; Reuland et al. 2003a; Villar-Martín et al. 2003). Spatially resolved kinematic studies of these haloes suggest that the cold gas comprising many of these haloes is in infall towards the centre of the host galaxy (Humphrey et al. 2007), while in others...
it is being strongly disturbed by the radio jets (e.g. Best, Röttgering & Longair 2000; Nesvadba et al. 2006). In most cases, ratios between emission lines imply that the radiation field of the AGN is the dominant ionization mechanism for the haloes, although shocks may make a fractional contribution in some cases (e.g. Vernet et al. 2001; Humphrey et al. 2008). Modelling of the flux ratio Ly/HeII λ1640 measured from one-dimensional spectra has revealed an excess of Lyα emission above the predictions of AGN photoionization models (Villar-Martín et al. 2007), which suggests the presence of star forming regions in the giant gaseous haloes (see also Hatch et al. 2009).
Millimetre emission provides an alternative means by which the star formation history of HzRGs can be probed. Several tens of HzRGs have now been detected at millimetre wavelengths, with the detection rate rising from ∼15 per cent at z<2.5 to ≥75 per cent at z>2.5 (Archibald et al. 2001; Reuland et al. 2003). Millimetric observations are sensitive to cold dust that is re-radiating emission received from young stars: implied rates of star formation are sensitive to cold dust that is re-radiating emission received from young stars: implied rates of star formation.

In the process of selecting our sample, no strong preference was given to any other observational properties of the galaxies, but several strong biases necessarily exist due to processes involved in the initial identification of the radio galaxies. Firstly, the galaxies are all near the top of the radio luminosity function for radio galaxies, and the majority of them were selected from radio catalogues on the basis of their ultra-steep radio spectra (\(S\) \(\propto v^{-\alpha}\) where \(\alpha<1\); e.g. Chambers et al. 1996). In addition, these galaxies all have luminous UV-optical continuum emission, as required for the identification of the optical counterpart. They also all emit luminous UV-optical emission lines from spatially extended regions of cold gas, photoionized by the active nucleus: such conditions are necessary for obtaining a spectroscopic redshift. In summary, our sample is a subset of high-z radio galaxies which have very powerful, steep-spectrum radio sources, together with luminous UV-optical continuum and line emission.

It is important to note that roughly 30 per cent of high-z radio galaxy candidates do not show bright optical/UV emission lines (e.g. Miley & De Breuck 2008), meaning that samples selected in the above way may not be completely representative of high-z radio galaxies. Interestingly, it has been suggested that these ‘no-line’ radio galaxies are very dusty, based on millimetre/sub-millimetre detections thereof (Reuland et al. 2003b; Reuland 2005).

Our sample also covers a substantial range in the (projected) size of the radio source, with diameters ranging between 0.2 kpc and 390 kpc, in order to study the possible relationship between the growth or containment of the radio source and the millimetric properties of the galaxy. The sample purposefully contains some radio galaxies that are known to reside in clusters or proto-clusters (e.g. PKS 1138-262: Pentericci et al. 1997), some radio galaxies which do not appear to reside in overdense environments (e.g. MRC 2048-272: Venemans et al. 2007), as well as radio galaxies for which cluster/overdensity analyses have yet to be undertaken.

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ponent analysis; (iii) to calibrate and bin the bolometer signals to produce a map for each individual observation, with a pixel size of $2''\times2''$ for 4C+41.17 or $3''\times3''$ for the rest of the sample; and (iv) to co-add maps and apply a Wiener filter. The observations, the data reduction and the source detection/extraction are described in greater detail by Zeballos et al. (in preparation).

### 2.2 AzTEC 1.1 mm observations

In the pilot of this programme, the field of 4C+41.17 was mapped utilising unchopped raster scans, using the AzTEC bolometer array (Wilson et al. 2008) with the James Clerk Maxwell Telescope (JCMT) during December 2005. The rest of our sample were observed during May to October 2007 or July to December 2008, with AzTEC at the Atacama Submillimetre Telescope Experiment (ASTE), using a Lissajous pattern centred on the targeted active galaxy. The observations were made under excellent weather conditions, with effective atmospheric opacities for each field falling within the range $0.03\leq r\leq0.06$. Integration times varied between 16 and 35 h per field. The resulting maps cover areas ranging from 170 to 300 arcmin$^2$ for a 50 per cent coverage cut.

The data reduction procedure is given in Scott et al. (2008) with modifications discussed by Scott et al. (2010) and Downes et al. (2011). The basic steps are (i) to clean the raw time-stream data of spikes due to cosmic rays and instrumental glitches; (ii) to then clean using principal component analysis; (iii) to calibrate and bin the bolometer signals to produce a map for each individual observation, with a pixel size of $2''\times2''$ for 4C+41.17 or $3''\times3''$ for the rest of the sample; and (iv) to co-add maps and apply a Wiener filter. The observations, the data reduction and the source detection/extraction are described in greater detail by Zeballos et al. (in preparation).

### 2.3 Spitzer Imaging

The Spitzer (Werner et al. 2004) observations of the active galaxies come from both archival data and observations from PID 50610 (PI: M. S. Yun). Fifteen of the galaxies were observed with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) at 24 µm, and fourteen were observed with the Infrared Array Camera (IRAC; Fazio et al. 2004) at 3.6, 4.5, 5.8, and 8.0 µm. Our new observations (PID 50610) consist of 5 MIPS maps (MRC 2201-555; MRC 2008-068; MRC 0355-037; TN J2009-3040; TN J1338-1942) and 3 IRAC maps (MRC 2201-555; MRC 2322-052; MRC 0355-037) of HzRG fields. The new IRAC maps are composed of a 4x3 grid of pointing positions, and at each position there are 15 dithered frames of 100 sec exposure time each. The new MIPS maps are comprised of a 6x6 grid of pointing positions, and with each position mapped twice with an individual 30 sec exposure time.

From the Spitzer Science Center’s basic calibrated data (BCD) frames we build mosaics for each field using a customized IDL package (Gutermuth et al. 2008). A number of common bright source artifacts (banding, jailbars, muxbleed, and pulldown effects) are corrected in the individual BCD frames as a first step. Then the code performs a rejection of transients and accounts for distortions introduced by rotation and sub-pixel offsets in building the mosaics. One additional calibration step, performed only on the MIPS observations, is a self-calibration to remove systematic artifacts (like bright and dark latents) from the maps. For each MIPS astronomical observation request (AOR), a flat-field map is made by taking the median of the background.

| Source name | z | $\lambda_{rest}$ (µm) | RA (J2000) (hh:mm:ss.ss) | Dec (J2000) (dd:mm:ss.s) | ID | $S_{1.1}$ (mJy) | $r$ (") | P | Log ($L_{FIR}/L_{\odot}$) | SFR (M$_{\odot}$ yr$^{-1}$) |
|-------------|---|----------------------|--------------------------|--------------------------|----|----------------|------|---|--------------------------|-----------------------------|
| MRC 2201-555 | 0.51 | 730 | 22:05:04.83 | -55:17:44.0 | I | 6.1±0.8 | 2.5 | 8×10$^{-6}$ | 12.86 | 720 |
| MRC 2008-068 | 0.55 | 710 | 20:11:14.22 | -06:44:33.6 | R | 8.6±0.9 | 3.5 | 4×10$^{-6}$ | 13.04 | 1100 |
| MRC 2322-052 | 1.19 | 500 | 23:25:19.62 | -04:57:36.6 | I | <2.1 | (20.7) | 0.049 | <12.60 | <400 |
| TXS 2322-040 | 1.51 | 440 | 23:25:10.23 | -03:44:46.7 | R | 2.3±0.6 | 2.3 | 0.0006 | 12.68 | 480 |
| MRC 2048-272 | 2.06 | 360 | 20:51:03.49 | -27:03:03.7 | I | 2.3±0.8 | 11.4 | 0.02 | 12.68 | 480 |
| MRC 0555-037 | 2.15 | 350 | 03:57:48.06 | -03:34:09.5 | I | 3.5±0.7 | 6.6 | 0.002 | 13.02 | 1040 |
| PKS 1138-262 | 2.16 | 350 | 11:40:48.35 | -26:29:08.6 | R | <3.6 | (14.3) | 0.007 | <12.85 | <710 |
| 4C+23.56 | 2.48 | 320 | 21:07:14.82 | +23:31:45.1 | R | <1.5 | (21.4) | 0.005 | <12.46 | <290 |
| MRC 2104-242 | 2.49 | 320 | 21:06:58.27 | -24:05:09.1 | R | 3.7±0.9 | 6.9 | 0.002 | 12.87 | 740 |
| PKS 0529-549 | 2.58 | 310 | 05:25:23.45 | -54:54:23.3 | I | 6.4±0.7 | 3.7 | 2×10$^{-5}$ | 13.10 | 1270 |
| MRC 0316-257 | 3.13 | 270 | 03:18:12.14 | -25:35:10.2 | I | <2.1 | (17.3) | 0.009 | <12.55 | <350 |
| TN J2009-3040 | 3.16 | 260 | 20:09:48.08 | -30:40:07.4 | K | 3.3±0.9 | 12.9 | 0.005 | 12.79 | 610 |
| 4C+41.17 | 3.79 | 230 | 06:50:52.35 | +41:30:31.4 | O | 3.5±1.0 | 6.6 | 0.001 | 12.78 | 610 |
| TN J2007-1316 | 3.83 | 230 | 20:07:53.22 | -13:16:43.4 | R | 2.8±0.9 | 4.0 | 0.002 | 12.68 | 480 |
| TN J1338-1942 | 4.10 | 220 | 13:36:23.26 | -19:42:33.6 | R | <5.0 | (15.7) | 0.0008 | <12.90 | <790 |
| TN J0924-2201 | 5.19 | 180 | 09:24:19.91 | -22:01:41.5 | I | 3.6±0.9 | 13.9 | 0.006 | 12.74 | 560 |

SDSS J1030+0524 | 6.28 | 150 | 10:30:27.10 | +05:24:55.0 | I | <1.4 | (22.7) | 0.02 | <12.30 | <200 |

Table 1. Basic properties of the sample of radio galaxies. Columns are as follow. (1) Name of the active galaxy. (2) Active galaxy redshift. (3) Rest-frame wavelength, in units of µm, corresponding to 1.1 mm in the observer frame. (4) and (5) are the RA and Dec of the active galaxy. (6) The wavelength regime from which the position of the active galaxy was determined, where R = radio, I = mid-IR (3.6 and 4.5 µm), O = optical (R-band) and K = near-IR (K-band). (7) 1.1 mm flux density of the millimetre counterpart to the active galaxy. Errors in S$_{1.1}$ are 1σ, and upper limits are 3σ. (8) The observed offset of the mm counterpart relative to the position of the active galaxy. In the absence of a probable counterpart we show in parentheses the offset to the closest mm detection. (9) P-statistic of the probable mm counterpart. Again, in the absence of a probable counterpart we show in parentheses the P-statistic of the nearest mm detection. (10) Log of the far-IR luminosity of mm counterparts. For non-detections, we give 3σ upper limits. (11) The star formation rate implied by the far-IR luminosity. Included at the bottom of the table is the radio-quiet quasar SDSS J1030+0524.
at each BCD pixel. Then the median background map is
normalized, and all BCD images for that AOR are divided
by the normalized flat field map. The final calibrated, cor-
corrected mosaics for IRAC and MIPS were then resampled to
a scale of 0.86″ pix⁻¹ and 1.80″ pix⁻¹, respectively.

Photometric measurements were performed on the mosaics using the IDL routine APER with an aperture diameter of 3.8″. We apply aperture corrections in the IRAC bands of [1.40, 1.38, 1.55, 1.70], and for MIPS we use a correction of 2.00. The corrections are determined by selecting isolated sources, having no neighboring detection at 5σ within 10″ identified by Source Extractor (Bertin & Arnouts 1996), and taking the ratio of the fluxes of those isolated sources with apertures of 12.4 and 3.8″ diameter. The differences between our aperture corrections and those listed in the IRAC Instrument Handbook are as one would expect for our 3.8″ diameter photometry aperture. For each map the median of these flux ratios is taken, and then the overall aperture correction is chosen as the mean of the set of corrections derived for each band. Small field-to-field variations in the median aperture corrections introduce some systematic uncertainties in our photometry, and so the standard deviation of the aperture corrections derived in our maps is added in quadrature to the statistical photometric errors for the Spitzer bands. In the event that we do not detect an active galaxy, we give a 3σ upper limit.

Ten of the radio galaxies in our sample have Spitzer photometry reported in the literature (Villar-Martín et al. 2006; Seymour et al. 2007). For all but one of these (PKS 0529-549), our photometry is consistent with the previously published measurements. In the case of PKS 0529-549, we measure the 24 μm flux to be significantly lower than that reported by Seymour et al. (2007); we obtain 632±27 μJy compared to the 942±71 μJy of Seymour et al. (2007). The higher flux density measured by Seymour et al. is probably due to the presence of a second 24 μm source located ~6″ SW of the radio galaxy, which would have contributed significantly to the light measured in their relatively large 13″ diameter aperture, but significantly less so in our 3.8″ aperture.

3 RESULTS

Figs. 1 and 2 show 160″×160″ ‘postage stamps’ cut out from the full-size signal-to-noise maps, with contours starting at 2σ and increasing linearly by 1σ. Bars indicate the orientation of the radio source, where applicable. Most of the active galaxies in our sample have been observed at a variety of wavelengths and spatial resolutions, meaning that there are various different ways by which one can define the position of the galaxy. For this study, we will adopt the coordinates that are most likely to mark the position of the galactic nucleus. Our preferred position is that of the radio core, since it corresponds to the active nucleus itself. For active galaxies for which the radio core has not been detected, or which are radio quiet, our second choice is to use the centroid of the SPITZER IRAC emission, averaged across the 3.6 and 4.5 μm bands. For type 2 (i.e., narrow line) objects this emission is expected to trace the evolved stellar population, which is likely to be more dynamically relaxed than young stellar populations which, if present, could dominate at shorter optical-IR and longer (i.e. MIPS) wavelengths. For type 1 (broad line) objects, this emission is likely to be dominated by the active nucleus. Finally, in the absence of both a radio core detection and IRAC data, we adopt the position of the optical or near-IR emission. The postage stamp images are centred on our fiducial ‘radio-optical’ position, the coordinates of which are listed in Table 1.

3.1 Association between millimetre sources and radio galaxies

In this paper we adopt a source detection threshold such that the peak S/N is 3.0 and also that the spatial FWHM is consistent with, or larger than, the full width at half maximum (FWHM) of the filtered point spread function (i.e., FWHM>34″). We have attempted to identify sources associated with our active galaxies as follows. First, we have calculated the Poisson probability that a detected mm source is merely a chance association, rather than being associated with the active galaxy. This is given by

\[ P = 1 - e^{-\pi r^2 N} \]  \hspace{1cm} (1)

where \( r \) is the angular distance of the mm source from the optical/IR/radio position of the active galaxy, and \( N \) is the surface density of mm sources in blank fields that have 1.1 mm flux densities greater than or equal to that of the detected mm source (Downes et al. 1986). For \( N \) we adopt the number counts from the AzTEC/SHADES survey (Austermann et al. 2010). We consider a mm source to be associated with the active galaxy when the P-statistic is less then 0.05, i.e., the null hypothesis of chance association is significant at the <5 per cent level. All 17 of the active galaxies in our sample have at least one associated 1.1 mm source.

However, we must apply an additional criterion in order to determine whether any of the associated mm sources are consistent with being at the position of the active galaxy. In other words, are the optical/IR/radio and mm positions consistent, taking into account the observational errors in the position of the mm source? The 1σ positional error of an observed mm source is

\[ \sigma_{\text{pos}} = \sqrt{\frac{0.6 \ \text{FWHM}}{S/N_d}} + \sigma_{\text{pnt}}^2 \]  \hspace{1cm} (2)

where FWHM is that of the filtered beam, \( S/N_d \) is the deboosted signal to noise ratio of the millimetre counterpart, and \( \sigma_{\text{pnt}} \) is the 1σ uncertainty in the pointing of the map (adapted from Ivison et al. 2007). We conservatively assume that \( \sigma_{\text{pnt}} \sim 1″ \) (Scott et al. 2010). As an illustration, a source with \( S/N_d = 3.0 \) would have a positional error \( \sigma_{\text{pos}} \sim 6.9″ \). Note that equation (2) does not take into account any systematic absolute offset in the map, i.e., residuals after pointings corrections.

We classify an AzTEC source as the 1.1 mm counterpart to the radio galaxy or quasar when \( P < 0.05 \) and when the spatial offset from the radio-optical position \( r \) is less than 2.7σpnt.1 There are 11 AzTEC sources which satisfy our criteria for classification as 1.1 mm counterparts to the

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1 The positional error distribution is non-Gaussian. 2.7σpnt corresponds to a 95 per cent cumulative probability.
radio galaxies or quasar. Notice that 6 active galaxies have both P \leq 0.05 and r > 2.7 \sigma_{pos}; this means they have a statistically significant association with a millimetre galaxy which is not likely to be the active galaxy host. The results from this analysis are shown in Table 1.

Finally, while the presence of other (bright) sources within \sim 30-60'' can potentially skew the centroid of a millimetre source due to the negative side-lobes of the telescope beam, our tests show this effect is negligible for our entire sample: all such centroid shifts are \leq 1'' and do not affect our counterpart vs. non-counterpart classification.

3.2 Consistency with previous millimetre/sub-millimetre measurements

A number of the galaxies in our sample have been imaged previously at millimetre or sub-millimetre wavelengths. These are 4C+41.17 (Ivison et al. 2000; Stevens et al. 2003; Greve et al. 2007), PKS 1138-262 (Stevens et al. 2003), TN J1338-1942 (De Breuck et al. 2004) and SDSS J1030+0524 (Priddey, Ivison & Isaak 2007). Taking into account the (usually) lower spatial resolution of our new observations, we find good agreement with the images and photometry from the literature. In two cases (PKS 1138-262 and TN J1338-1942), several discrete sources detected by SCUBA or MAMBO are blended together in our images, due to their relatively lower spatial resolution.

In addition, eight of our sample have been targeted with SCUBA photometry (4C+23.56, 4C+41.17: Archibald et al. 2001; PKS 1138-262, MRC 0316-257; TN J2007-1316, TN J1338-1942, TN J0924-2201; Reuland et al. 2004; SDSS 1030+0524: Priddey et al. 2003). For seven of these galaxies, we find good agreement between our flux density measurements and the SCUBA photometry. (We use a scaling factor of 2.5 between 850\mu m and 1.1 mm, assuming T_{dust}=40 K and \beta=1.5; see §3.5.)

TN J0924-2201 is the exception. Reuland et al. (2004) derived a 3\sigma limit of \leq 3.2 mJy at 850\mu m, which implies a 1.1 mm flux density of \lesssim 1.3 mJy, whereas we measure a 1.1 mm flux density of 3.6\pm 0.9 mJy. The reason for this discrepancy is not clear. It may suggest that the 1.1 mm source we identify with the radio galaxy is not the true 'counterpart', and instead is a companion MMG offset from the position of the radio galaxy host (see §6). Maps with higher spatial resolution and S/N will be needed to address this issue.

3.3 Stacking

Next we derive average values of S_{1.1} for various subsets of our sample. To do this we stack the AzTEC images at the position of the active galaxy, allowing us to include information from the individual observations wherein the active galaxy counterpart was not detected at \geq 3\sigma significance. First, we spatially registered the images. In the case of 4C+41.17, we resampled the image to a scale of 3'' pixel^{-1}. Next, we assigned to each image a weighting proportional to \sigma^{-2}. We then stacked all the images in our sample (Fig. 3, top left). From this stacked image, we measure an average S_{1.1}=3.4\pm 0.2 mJy at the position of the active galaxy. We repeat this using only the radio galaxy images, and obtain an average S_{1.1}=3.2\pm 0.2 mJy (Fig. 3, top right). Repeating for the 6 active galaxies for which we did not detect a millimetre counterpart, we measure an average flux density S_{1.1}=2.0\pm 0.3 mJy (Fig. 3, middle left). Finally, for the 5 undetected radio galaxies we stack to obtain an average flux density S_{1.1}=2.4\pm 0.3 mJy (Fig. 3, middle right).

We have also investigated whether the millimetre emission is more extended along the radio axis of the radio galaxies in our sample. This is motivated in part by the fact that the ultraviolet and optical emission from powerful radio galaxies is usually aligned with the radio source (e.g. McCarthy et al. 1987; Chambers, Miley & van Breugel 1987), and the apparent alignment between the radio source and the large scale distribution of MMGs found by Stevens et al. (2003) in a sample of 7 radio galaxies at 2.2 \leq z \leq 4.3. To this end, the AzTEC images were registered, rotated such that the radio axis runs horizontally, and subsequently stacked (Fig. 3, bottom left). Along the radio axis in the stacked image, we measure FWHM=39.3\pm 0.6'', compared to FWHM=40.8\pm 0.6'' measured orthogonally to the radio axis. Thus, we conclude that there is no significant trend for the millimetre emission to be more elongated along the radio axis than it is along the orthogonal axis, at least at the spatial resolution of our observations.
3.4 Synchrotron emission

Before using the our 1.1 mm flux densities to estimate the infrared luminosity and the implied rate of star formation, we must first consider the impact of synchrotron emission from the radio source at 1.1 mm. Indeed, previous studies have shown that in some high-z radio galaxies, the synchrotron emission has sufficiently high luminosity and/or a sufficiently flat SED at high frequencies to be detectable in the mm-wave regime (e.g. Archibald et al. 2001; Vieira et al. 2010).

To quantify the possible contribution at 1.1 mm from synchrotron emission $S_{ext}$, we have extrapolated a power law of the form $S_v \propto \nu^{\alpha_{\nu}}$ from the two highest frequency photometric data points of the observed radio spectra separated in $\nu$ by a factor of $\geq 1.2$. When more than one measurement is available at 'similar' frequencies, which we define as when the ratio between frequencies is $\leq 1.2$, we have conservatively used the measurement that would result in the highest value of $S_{ext}$ (e.g. MRC 0355-037). In Fig. 4, we show the radio-IR spectral energy distributions of the radio galaxies in our sample, including our extrapolations to 1.1 mm of the synchrotron emission.

In the first instance, we have used radio photometric measurements that represent flux densities integrated across the entire spatial extent of the radio source, as these data are readily available for all of the radio galaxies in our sample. However, extrapolating the radio lobe SED to the mm regime is less than ideal. With the possible exceptions being the two smallest radio galaxies (MRC 2008-068 and TXS 2322-040), this photometry is dominated by the extended radio lobes (see e.g. Carilli et al. 1997; Pentericci et al. 2000). Lobe spectra usually steepen towards higher frequencies (e.g. Muxlow, Pelletier & Roland 1988; Murgia et al. 2000). Lobe spectra usually steepen towards higher frequencies (e.g. Muxlow, Pelletier & Roland 1988; Murgia et al. 2000). Moreover, the radio lobes are unable to provide sufficient synchrotron flux at 1.1 mm to be responsible for the flux densities we measure at that wavelength, despite our use of a very favourable set of assumptions. Furthermore, it seems likely that any enhancement by synchrotron emission is smaller than the 1$\sigma$ uncertainty in our flux density measurements, i.e., insignificant, in essentially all cases. Thus, we prefer not to apply any correction for synchrotron contamination to our measured values of $S_{1.1}$, because the extrapolation of the synchrotron flux density is so uncertain. Finally, we comment that the issue of possible synchrotron contamination would be resolved with observations at longer millimetric wavelengths (e.g. 2-3 mm).

3.5 Implied star formation rates

In order to convert our measured flux densities into far-IR luminosities ($L_{FIR}$) and star-formation rates (SFR), we adopt a grey-body emission template with an emissivity index $\beta$ and a dust temperature $T_{dust}$. This gives

$$M_{dust} = \frac{S_{obs} D_l^2}{(1+z)\kappa_{\nu_{rest}} B_{\nu_{rest}}(T_{dust})}$$

(3)

$$L_{FIR} = \frac{8\pi h \kappa_{\nu_{rest}}}{c^2 \nu^2} \left( \frac{kT_{dust}}{h} \right) \nu^\beta \Gamma(\beta+4)\zeta(\beta+4)M_{dust}$$

(4)

$$SFR = \frac{L_{FIR}}{10^{10}L_{\odot}} M_{\odot} yr^{-1}$$

(5)

where $M_{dust}$ is the mass of dust, $S_{obs}$ is the observed flux density, $D_l$ is the luminosity distance, $\kappa_{\nu}$ is the mass absorption coefficient of the dust at rest-frame frequency $\nu_{rest}$, and $B_{\nu_{rest}}(T_{dust})$ is the Planck function at $\nu_{rest}$ (e.g. Archibald et al. 2001). $\Gamma$ is the Gamma function, and $\zeta$ is the Riemann zeta function. A Salpeter initial mass function has been assumed. Throughout this paper, we assume $T_{dust}=40$ K, $\beta=1.5$ (after Archibald et al. 2001). We adopt $\kappa_{375GHz}=0.15$ m$^2$ kg$^{-1}$ (Hildebrand et al. 1983), and extrapolate to other frequencies assuming $\kappa_{\nu} \propto \nu^\beta$ (Chini et al. 1986).

The values we have measured for $S_{1.1}$ imply star formation rates ranging from $<$200 to $\sim$1210 $M_{\odot}$ yr$^{-1}$. The sample averaged $S_{1.1}$ we obtained from our stacking analysis implies an average SFR$\sim$600 $M_{\odot}$ yr$^{-1}$.

4 COMPARISON WITH RADIO AND OPTICAL PROPERTIES

4.1 Anticorrelation between $S_{1.1}$ and radio source size

It is interesting to examine what, if any, relationship there might be between mm/sub-mm flux density measurements and the radio source size. This is motivated by a number
of relatively recent observational results suggesting that the presence of intense star-formation in high-z radio-loud galaxies is anticorrelated with the size of the radio source (Best, Longair & Röttgering 1996; Willott et al. 2002; Humphrey et al. 2006).

For the purpose of this analysis, we define radio source size as the largest projected extent of the radio emission: we have measured the largest angular extent from published radio images, using high spatial resolution images wherever possible. Whenever possible we use high spatial resolution images (FWHM $\lesssim 0.5''$). For sources which are not well resolved, or which do not have a radio image published in the literature, we adopt the largest angular size, or the upper limit thereto, listed in the literature. Angular sizes were converted to physical units of kpc, using the conversion dictated by our preferred cosmology.

For high-z radio galaxies, the published radio images tend to be sensitive enough only to detect the relatively compact and high surface brightness parts of the radio source, i.e., hotspots and the core. Therefore, in classical double/triple radio galaxies, the largest angular size typically represents the angular distance between the most distant hotspot, relative to the nucleus, in each of the two jets. It is important to be aware that it is quite possible that radio emitting structures too faint to be detected lie yet farther from the nucleus (see e.g. Coma A: van Breugel et al. 1985; 3C171: Blundell 1996; B3 J2330+3927 at z=3.087; Pérez-Torres & De Breuck 2005). In this case, our measured radio source sizes would underestimate the true size. While we clearly cannot ascertain whether the hotspot separations are genuinely representative of the total radio source sizes in our high-z sample, we find it encouraging that in low-
Table 2. Extrapolation of a powerlaw from radio to millimetre wavelengths. The columns are organised as follows. (1) Name of the radio galaxy; if the radio core has been detected at more than one radio wavelength, it is also included in this table. (2) Redshift z of the radio galaxy. (3) Observed flux density of the radio galaxy’s 1.1 mm counterpart. (4) The extrapolated 1.1 mm flux density of the integrated radio source, or radio core where appropriate. (5) Radio spectral index of the integrated radio source, or the radio core where appropriate. (6) and (7) The wavelengths of the two radio photometric data points used in the extrapolation. (8) References to photometric data from the literature which we have used in this paper; references have been abbreviated to the first two letters of the first author’s surname and the last two digits of the publication year; the abbreviations are appended to their corresponding full references at the end of this paper.

| Source name | z   | S_{1.1} (mJy) | S_{ext} (mJy) | \alpha_{rad} | \lambda_1 (cm) | \lambda_2 (cm) | Radio data references |
|-------------|-----|---------------|---------------|--------------|----------------|----------------|----------------------|
| (1)         | (2) | (3)           | (4)           | (5)          | (6)            | (7)            | (8)                  |
| MRC 2201-555| 0.51| 6.1±0.8       | 0.8           | -1.60        | 3.6            | 6.0            | La81 Wr90 Gr94 Gi06 |
| MRC 2008-068| 0.55| 8.6±0.9       | 6.9           | -1.51        | 1.4            | 1.6            | Bo75 Ku81 Wr90 Gr95  |
| MRC 2322-052| 1.19| <2.1          | 0.2           | -1.65        | 3.6            | 6.0            | Go67 La81 Wr90 Gr95  |
| TXS 2322-040| 1.51| 2.3±0.6       | 0.9           | -1.62        | 3.6            | 6.0            | Wr90 Wh92 Gr95 Co96  |
| MRC 2048-272| 2.06| 2.3±0.8       | 1.1           | -1.15        | 6.2            | 73.4           | La81 Gi94 Do96 Pe00  |
| MRC 0355-037| 2.15| 5.0±0.8       | 0.3           | -1.25        | 21.4           | 73.4           | La81 Wh92 Do96 Co96  |
| PKS 1138-262| 2.16| <3.6          | 0.09          | -1.84        | 3.7            | 6.4            | La81 Wr90 Gr94 Si95  |
| PKS 1138-262 core| 0.02| -1.3          | 3.7           | 6.4            | Ca97           |                |
| 4C+23.56     | 2.48| <1.5          | 0.2           | -1.34        | 3.7            | 6.4            | P65a74 Wr90 Gi94 Do96  |
| MRC 2104-242| 2.49| 3.7±0.9       | 0.05          | -1.71        | 3.7            | 6.7            | La81 Gi94 Do96 Pe00  |
| MRC 2104-242 core| 0.0007| -1.6          | 3.7            | 6.7            | Pe00           |                |
| PKS 0529-549| 2.58| 6.4±0.7       | 1.3           | -1.15        | 1.6            | 3.5            | La81 Wr90 Gr94 Wm84 |
| MRC 0316-257| 3.13| <2.1          | 4.0           | -0.85        | 6.0            | 11.1           | La81 Wr90 Gr95 Do96  |
| TN J2009-3040| 3.16| 3.3±0.9       | 1.1           | -1.34        | 6.2            | 21.4           | Do96 DeB00           |
| 4C+41.17     | 3.79| 3.5±1.0       | 1.0           | -1.65        | 20.0           | 6.1            | Go67 VI75 F85 Ch90  |
| TN J2007-1316| 3.83| 2.8±0.9       | 1.7           | -1.42        | 21.4           | 82.0           | La81 Do96 DeB00 Re04 |
| TN J1338-1942| 4.10| <5.0          | 0.02          | -1.68        | 3.7            | 6.4            | Do96 Re04 DeB00 DeB04 Do07 |
| TN J1338-1942 core| 0.004| -1.0         | 3.7            | 6.4            | DeB00 Pe00     |                |
| TN J0924-2201| 5.19| 3.6±0.9       | 0.01          | -1.72        | 6.2            | 21.4           | Do96 vB99 DeB00 Re04 Ca07 |

z powerful radio galaxies the hotspot separation is usually representative of the total angular extent (see e.g. Black et al. 1992).

In Fig. 5 we plot $S_{1.1}$ versus the size of the radio emission for our sample. We find an L-shaped anticorrelation between $S_{1.1}$ and radio size. The three galaxies with the highest values of $S_{1.1}$ ($>5$ mJy: MRC 2201-555; MRC 2008-068; PKS 0529-549) have relatively small radio sources ($<22$ kpc), while those with relatively large radio sources ($>22$ kpc) all have relatively low $S_{1.1}$ ($<5$ mJy). To test the significance of this apparent anticorrelation in our AzTEC sample, we use Cox’s proportional hazard model (Isobe, Feigelson & Nelson 1986), which is able to treat censored data, i.e., upper limits. Using the null hypothesis that no correlation is present between $S_{1.1}$ and radio size, we obtain a global $\chi^2=8.3$, which corresponds to a significance level for independence of 0.003. Thus, the anticorrelation is highly significant.

An alternative test can be made via Poisson probability theory. In this case we adopt a null hypothesis such that the population of radio galaxies with relatively large radio sources ($>50$ kpc) has the same fraction of galaxies with $S_{1.1}>5$ mJy as does the population of radio galaxies with relatively small radio sources ($<50$ kpc). In our sample, there are 3 radio galaxies with $S_{1.1}>5$ mJy and $D_{rad}\leq50$ kpc; there are 3 with $S_{1.1}<5$ mJy and $D_{rad}\leq50$ kpc; there are 10 with $S_{1.1}<5$ mJy and $D_{rad}>50$ kpc; and there are none with $S_{1.1}>5$ mJy and $D_{rad}>50$ kpc. Under the null hypothesis, the probability of counting 0 radio galaxies with $S_{1.1}>5$ mJy and $D_{rad}>50$ kpc is $4.5\times10^{-5}$. Therefore, we reject the null hypothesis, and conclude that the AzTEC radio galaxy sample shows a highly significant anticorrelation between the 1.1 mm flux density and the apparent size of the radio source.

Shown in Fig. 6 is $S_{1.1}$ versus radio size for the AzTEC counterparts together with HzRGs that have been observed at 850$\mu$m using SCUBA (Archibald et al. 2001; Reuland et al. 2003b, 2004; Stevens et al. 2003). SCUBA 850$\mu$m flux densities have been scaled by 1/2.5 to extrapolate their 1.1 mm flux densities. This scaling factor is calculated assuming $T_{rad}=40$ K and $\beta=1.5$ ($\S\S.5$). Where an HzRG has been observed more than once at 1.1 mm and/or 850$\mu$m, we use the most sensitive of the flux density measurements. Using Cox’s proportional hazard model we find this combined dataset does not show a significant anticorrelation between $S_{1.1}$ or SFR and radio size ($P=0.18$), in agreement with the statistical analysis of Reuland et al. (2004). However, using Poisson probability theory we find that the absence of HzRGs at $S_{1.1}>2.5$ mJy and $D_{rad}>200$ kpc is significant at the 98 per cent level ($P=0.02$).

It seems plausible that this reduction in the significance of the trend is due to the different observational methods employed in our AzTEC/ASTE survey of HzRGs, compared to those predominantly used for the several SCUBA/JCMT surveys. Whereas our maps allows us to reject sources that are nearby to the radio galaxy’s position but unlikely to
be the counterpart, the SCUBA photometry employed by Archibald et al. (2001) and Reuland et al. (2004) simply obtains the flux density from a region of sky sampled by the telescope beam, and emission from a bright nearby companion MMG may contaminate such measurements, thereby adding scatter to the trend.

Finally, we point out that the trend discussed above would not change significantly if we were to include only millimetre/sub-millimetre measurements obtained from maps (e.g. from Ivison et al. 2000; Stevens et al. 2003; De Breuck et al. 2004; Greve et al. 2007; and this paper), i.e., excluding measurements obtained from simple SCUBA photometry. We would still find that, of the radio galaxies with radio sources smaller than 200 kpc, 50 per cent have $S_{1.1} < 5$ mJy. In §6 we discuss the origin and implications of this result.

4.2 The Ly$\alpha$ emission nebulae

In addition to heating the surrounding dust young stars also produce HII regions, which emit strong UV-optical emission lines. The strongest of these lines is Ly$\alpha \lambda 1216$, and its luminosity is primarily a function of the number of ionizing photons absorbed, and the quantity and geometry of dust. It is relatively insensitive to the metallicity or the gas density of the HII regions. Thus, Ly$\alpha$ carries useful information about dust associated with star forming regions.

At $z \gtrsim 2$, Ly$\alpha$ is redshifted into the optical regime, making this line accessible to ground-based telescopes. Indeed, all 11 of the $z \gtrsim 2.15$ radio galaxies in our sample have measurements in the literature for the narrow (FWHM $\lesssim 3000$ km s$^{-1}$) Ly$\alpha$ emission. In table 3, we list the Ly$\alpha$ luminosity for these 11 radio galaxies, measured from narrow band images (e.g. Knopp & Chambers 1997; Reuland et al. 2003a; Venemans et al. 2007), and/or from spectra with a long-slit placed along the major axis of the radio emission (e.g. De Breuck et al. 2000a).

It is interesting to compare these measured Ly$\alpha$ luminosities against the expected (intrinsic) Ly$\alpha$ luminosity of a massive starburst. First, we derive an approximate relationship between the Ly$\alpha$ luminosity and SFR or $L_{FIR}$, as

$$L_{Ly\alpha} \sim 10^{44}(SFR/100M_\odot yr^{-1}) \text{ ergs}^{-1}$$

$$L_{Ly\alpha} \sim 10^{44}(L_{FIR}/10^{12}L_\odot) \text{ ergs}^{-1}$$

which simplifies to become

$$L_{Ly\alpha}/L_{FIR} \sim 0.03$$

under the assumptions that (i) the starburst is continuous and has an age in the range $\sim 1-5$ Myr; (ii) all ionizing photons produced by the stars are absorbed in the surrounding HII region; and (iii) 67 per cent of photo-ionization
events lead to the emission of a Lyα photon (Binette et al. 1993). Of the 8 galaxies in our sample which have been detected in both Lyα emission and in 1.1 mm continuum emission, 3 have values of $L_{\text{Ly} \alpha}/L_{\text{FIR}}$ which are in order-of-magnitude agreement with the expected value $\sim \alpha$, and 5 have $L_{\text{Ly} \alpha}/L_{\text{FIR}}$ values more than an order of magnitude lower (Table 3).

Thus far, we have ignored another luminous source of ionizing radiation which is likely to contribute significantly to the production of Lyα photons − the active nucleus. The ratio between Lyα and HeII $\lambda$1640 is sensitive to the SED of the ionizing continuum and, therefore, it can be used to assess the extent to which stellar-photoionized HII regions contribute to the UV-optical emission line spectrum. Models for pure AGN photoionization predict $L_{\text{Ly} \alpha}/\text{HeII} = 8 – 15$ (e.g. Humphrey et al. 2008), depending on the spectral slope of the ionizing continuum between 13.6 eV and 54.4 eV. On the other hand, photoionization by young stars does not result in significant HeII emission relative to Lyα. Thus, a $L_{\text{Ly} \alpha}/\text{HeII}$ ratio significantly in excess of 15 would suggest a significant contribution from stellar-photoionized HII regions. A number of HzRGs, including 3 of our sample (TN J2009-3040, 4C+41.17 and TN J1338-1942), do indeed show such an excess of Lyα emission. Villar-Martín et al. (2007) examined the Lyα/HeII and Lyα/CIV ratios of 61 radio galaxies at 1.79$\leq z \leq$4.41, and identified a Lyα excess in 11 of their sample; they calculated that a SFR of $\sim 200 M_\odot\text{yr}^{-1}$ would be required to explain the most extreme objects.

Naively, one might expect there to be a correlation between detection of a Lyα excess and detection of millimetre continuum, since both are thought to be produced by powerful starbursts. In Fig. 7 we plot $S_{1.1}$ against the Lyα/HeII ratio for radio galaxies from our sample which have Lyα and HeII detections. We also plot radio galaxies which have been observed at 850 μm (from Table 1 of Villar-Martín et al. 2007), under the assumption that $S_{1.1}=S_{850}/2.5$. Contrary to initial expectations, we find no trend between $S_{1.1}$ and Lyα/HeII. The possible origin of this result is discussed in §6.

5 ANALYSIS OF THE MID-IR SPECTRAL ENERGY DISTRIBUTION

In Fig. 8 we show the Spitzer IRAC [3.6]-[4.5] versus [5.8]-8.0 colour-diagram, adapted from Stern et al. (2005), for all HzRGs in our sample that are detected in all 4 IRAC channels. Most of our target HzRGs, as well as those studied by Seymour et al. (2007), are found within the region of red rest-frame optical and near-IR color characteristic of hot dust, overlapping with the distribution of the Spitzer-selected power-law QSOs of Lacy et al. (2004) and Martínez-Sansigre et al. (2008). While the colours of our target HzRGs are marginally consistent with colours expected for active galaxies, those detected by AzTEC (filled squares) appear near the edges of the distribution, along the model tracks of young dust obscured stellar clusters modeled by Efstathiou et al. (2000). This is also the area where the majority of submillimetre-bright sources are clustered (Yun et al. 2008, 2011), and these AzTEC detected HzRGs display rest-frame near-IR properties more like SMGs than other HzRGs.

The diagram shown in Fig. 9 aims to distinguish active galaxies from starburst systems using two different diagnostic criteria proposed recently by different groups: (1) $S_{24}/S_R > 1000$ (Dark Optical Galaxies, or DOGs: Dey et al. 2008; Fiore et al. 2008); and (2) $S_{8.0}/S_{1.3} > 2$ (Ivison et al. 2004; Pope et al. 2008). The DOGs were first identified in the study of a population of $z \sim 2$ infrared bright galaxies that are extremely faint in the optical bands, and Fiore et al. (2008) concluded based on their X-ray analysis that as many as 80% of these dust-obscured galaxies host a Compton-thick AGN. The latter criterion was initially developed to exploit the presence of PAH features and a power-law AGN spectral shape in the rest-frame near-IR, similar to the information used in Fig. 8.

In this diagram, the majority of the HzRGs detected in MIPS 24 μm by Seymour et al. (2007) appear above the DOGs line of $S_{24}/S_R > 1000$ (dotted line), suggesting warm dust and a heavily obscured AGN are present in these HzRGs. All six of our target HzRGs detected in the MIPS 24 μm bands are below the dotted line and are on average bluer than the others. In fact, the three AzTEC-detected HzRGs are among the bluest HzRGs. The AzTEC detected HzRGs also show a flatter $S_{8.0}/S_{1.3}$ flux ratio than the rest of the HzRGs. Taken together, these rest-frame opti-
Table 3. Radio and optical properties of the radio galaxies. A dash (–) indicates that a quantity has not yet been measured, or is not available in the literature. Columns are as follows. (1) Source name. (2) Source redshift. (3) The 1.1 mm flux density of the millimetre counterpart, measured from our AzTEC data. (4) The spectroscopic Lyα luminosity in units of 10^{44} erg s^{-1}. (5) Lyα luminosity in units of 10^{44} erg s^{-1} measured from narrow-band images. (6) The flux ratio Lyα/HeII. (7) Ratio of the Lyα luminosity to the far-infrared luminosity; the theoretically expected value is ~0.03; Lyα luminosities measured from narrow band images are used where available, otherwise luminosities measured from long-slit spectra are used. (8) Projected size of the radio source (D_{radio}). (9) References for the size of the radio source, and for the luminosities of the Lyα and HeII emission lines; references have been abbreviated to the first two letters of the first author’s surname and the last two digits of the publication year, and the abbreviations are appended to the full bibliographic references at the end of this paper.

| Source name | z  | S_{1.1} (mJy) | L_{Lyα}(slit) (10^{44} erg s^{-1}) | L_{Lyα}(image) (10^{44} erg s^{-1}) | Lyα/HeII | L_{Lyα}/L_{FIR} | D_{radio} (kpc) | Refs |
|-------------|----|---------------|------------------------------------|-------------------------------------|---------|-----------------|----------------|-----|
| MRC 2201-555| 0.51 | 6.1±0.8 | – | – | – | – | 22 | Bu06 |
| MRC 2008-068| 0.55 | 8.6±0.9 | – | – | – | – | 0.2 | Je00 |
| MRC 2322-052| 1.19 | <2.0 | – | – | – | – | 64 | Be99 |
| TXS 2322-040| 1.51 | 2.3±0.6 | – | – | – | – | 0.5 | Li07 |
| MRC 2048-272| 2.06 | 2.3±0.8 | – | 0.65 | – | 0.0035 | 70 | Pe00 Ve07 |
| MRC 0355-037| 2.15 | 5.0±0.8 | 0.40 | – | 3.0 | 0.0010 | 101 | Go05 Rö07 |
| PKS 1138-262| 2.16 | <3.4 | 1.7 | 25 | 10.7 | >0.025 | 80 | Ca07 Rö97 Ve07 |
| 4C +23.56   | 2.48 | <1.4 | 0.40 | 2.1 | 5.3 | >0.018 | 390 | Ca07 Ch06 Rö97 C98 Kn97 |
| MRC 2104-242| 2.49 | 3.7±0.9 | 2.9 | – | 13 | 0.010 | 180 | Pe00 V99 Ov01 |
| PKS 0529-549| 2.58 | 6.4±0.7 | 0.41 | – | 12.3 | 0.00084 | 10 | Br07 Rö97 |
| MRC 0316-257| 3.13 | <1.9 | 0.21 | 0.7 | – | >0.0047 | 59 | Ca07 A98 Ve07 |
| TN J2009-3040| 3.16 | 3.3±0.9 | 1.4 | 3.0 | 24.3 | 0.013 | 54 | Bo07 DeBr00 Ve07 |
| 4C +41.17   | 3.79 | 3.5±1.0 | 2.1 | 13 | 26.5 | 0.054 | 145 | Ch09 Ch96 Rö97 Re03 |
| TN J2007-1316| 3.83 | 2.8±0.9 | 0.26 | – | 9.0 | 0.0014 | 26 | Bo07 DeBr00 |
| TN J1338-1942| 4.10 | <1.7 | 1.7 | 4.5 | 18.4 | >0.014 | 80 | Pe00 DeBr99 DeBr01 Ve07 |
| TN J0924-2201| 5.19 | 3.6±0.9 | 0.10 | 0.15 | – | 0.00074 | 8 | vB99 DeBr01 Ve07 |

5.1 24\mu m images

In Fig. 10 we show 160′×160′ postage stamps of the 24\mu m emission, with contours of the 1.1 mm emission overlaid, in order to illustrate interesting morphological features around 3 of the radio galaxies. A detailed analysis of clustering in the full 170-300 arcmin^{2} fields (as opposed to the 7 arcmin^{2} ‘postage stamps’ considered herein) of our sample of 17 high-z active galaxies will be presented in a future paper (Zeballos et al., in preparation).

5.1.1 MRC 2201-555

The 24 \mu m MIPS image shows an arc of emission running through the position of the radio galaxy, with a total spatial extent of ~38′ or 230 kpc. The NW portion of the arc takes the form of a relatively bright source ~16′ (100 kpc) to the NW, which is linked to the radio galaxy by a bridge of lower surface brightness emission. This structure is too compact to resolve at the resolution of our AzTEC/ASTE observation.

5.1.2 MRC 0355-037

The MIPS image shows an arc comprised of several 24 \mu m sources extending ~60′(~500 kpc) to the WSW from the position of the radio galaxy. At or near to the end of this arc, our AzTEC map shows a peak which has S/N~2.6, after correcting for the negative sidelobes of radio galaxy’s AzTEC counterpart.

5.1.3 TN J2007-1318

An arc of several 24 \mu m sources extends ~50′ (~360 kpc) SSE from the radio galaxy. Similarly, in our AzTEC image there is arc of 1.1 mm emission, cospatial with the 24 \mu m arc, with peak S/N~2.4 after correcting for the negative sidelobes of radio galaxy’s 1.1 mm counterpart.

6 DISCUSSION

In the process of this study, we have identified a statistically significant anti-correlation between the size of the radio source and the brightness of the millimetre continuum emission (or SFR). This is by no means the first investigation into the possible relationships between the size of a radio source and the other properties of radio galaxies; numerous relationships have been found previously between the observed size of powerful radio sources and various UV, optical and infrared properties. Best, Longair & Röttgering (1996)
found a morphological evolution with radio size in their sample of eight 3CR radio galaxies at 1<z<1.3. For galaxies with relatively smaller radio sources, their HST images reveal a string of bright knots tightly aligned with the radio emission. The galaxies with relatively larger radio sources, while still showing the alignment effect (e.g. Chambers, Miley & van Breugel 1987; McCarthy et al. 1987), are generally more compact and contain fewer bright optical knots. Furthermore, galaxies with smaller radio sources, the extended emission line region (EELR) tend to have a relatively smaller observed spatial extent, as measured with Lyα (van Ojik et al. 1997). The EELR of these galaxies also show more extreme emission line kinematics, have brighter UV-optical emission lines, and ratios between emission lines that imply they have lower ionization states (Best, Röttgering & Longair 2000; Inskip et al. 2002; Humphrey et al. 2006). In addition, the polarization of the rest-frame UV continuum emission is correlated with radio source size (Solórzano-Fiárrrea et al. 2004), suggesting that the ratio between scattered light and starlight is relatively higher in radio galaxies with larger radio sources. The anticorrelation between 850 µm luminosity and UV continuum polarization found by Reuland et al. (2004) appears to confirm that the UV continuum polarization is indeed strongly dependent on the rate of star formation. Furthermore, HzRGs showing anomalously high values of Lyα/HeII (≥15), likely due to the presence of a powerful starburst (~100 M⊙ yr⁻¹) tend to have smaller radio sources than those with ‘normal’ or ‘low’ values (Villar-Martín et al. 2007). These radio-optical trends are commonly supposed to be the result of (a) interaction between the radio source and the host galaxy, (b) slowing of radio source expansion in radio galaxies that are in relatively denser environments, or (c) age effects of the radio source. A previously unanswered question was whether the star formation rate is intrinsically higher in HzRGs with smaller radio sources, or whether instead the UV-optically derived SFR merely appears higher due to some difference in dustiness, geometry, etc. Observations in the millimetre/sub-mm regime give us a new perspective from which we may address this question, since the observations are sensitive to UV-
optically obscured (rather than unobscured) star forming regions. Assuming that the millimetre/sub-mm continuum is dominated by thermal emission from starburst-heated dust, as we believe to be the case, then our anticorrelation between $S_{1.1}$ and radio size leads us to conclude that HzRGs with relatively smaller radio sources do indeed tend to have intrinsically higher SFR.

In light of this conclusion, it seems natural to now question whether the increase in the mm/sub-mm detectability of HzRGs at $z \geq 2.5$ is due to a genuine redshift evolution in the rate or mode of star formation in the host galaxies, as has commonly been supposed (Archibald et al. 2001; Reuland et al. 2004). Indeed, we propose an alternative hypothesis: that there is a bias towards identifying HzRGs with smaller radio sources at higher $z$ (Fig. 12) because these sources are associated with more luminous narrow emission line regions (e.g. Best, Röttgering & Longair 2000). And since smaller radio sources typically have more luminous mm/sub-mm emission (Figs. 5 & 6), we propose that this translates into a bias in favour of identifying HzRGs with significantly more luminous mm/sub-mm emission at higher $z$. Identifying and studying the ‘missing’, line-weak HzRGs will be crucial for testing this hypothesis (see Reuland et al. 2003b; Reuland 2005; Miley & De Breuck 2008).

It is not known whether the observed size of the radio source is determined primarily by the density of the interstellar/intergalactic medium through which the source propogates, or whether the size instead determined primarily by the age of the radio source. If we were to assume the latter, then we would be able to gauge the lifetime of luminous, dusty star formation episodes ($S_{1.1} > 2.5$ mJy; SFR $> 500 M_\odot$ yr$^{-1}$) closely associated with HzRGs. In Fig. 5, all of the luminous millimetre counterparts are associated with HzRGs that have radio source diameters of $d < 200$ kpc: we adopt $d \sim 200$ kpc as the approximate stage in the growth of the radio source at which the luminous millimetre counterparts fade to $S_{1.1} < 2.5$ mJy (SFR $< 500 M_\odot$ yr$^{-1}$). Assuming a conservative expansion speed of $\sim 0.01 c$ for the radio source (e.g. Best et al. 1995), this diameter implies an age of $\sim 30$ Myr. A similar age was estimated by Willett et al. (2002) for a smaller sample of high-$z$, radio-loud quasars. However,
we must be cautious about generalising this to obscured star formation in non-active galaxies (i.e., to sub-mm galaxies in general): HzRGs contain two powerful sources of feedback, the radio source and the accretion disc, both of which are able to quench star formation and, perhaps, to ignite it. Conceivably, feedback of this kind could either lengthen or shorten the lifetimes of star formation activity in HzRGs, and could mean that lifetimes of obscured star formation activity determined for HzRGs are not necessarily representative of those for millimetre/sub-millimetre galaxies in general.

We have also investigated whether there might be a correlation between the millimetre flux density and the $\text{Ly}_\alpha$/HeII ratio, which is expected to be sensitive to SFR also. While $\text{Ly}_\alpha$ can originate from stellar photoionized HII regions and from AGN-ionized nebulae, the HeII line is expected to come predominantly from nebulae that are ionized by the AGN. Though both $\text{Ly}_\alpha$/HeII and the millimetre flux density are expected to be correlated with SFR, and therefore with each other, no significant trend was found between them. Furthermore, the luminosity of the Lyo emission is often more than an order of magnitude lower than one would have expected given the SFR derived from the 1.1 millimetre flux density (we estimate $L_{\text{Ly} \alpha}/L_{\text{HeII}} \sim 0.0007-0.054$, while the expected value is $\sim 0.03$). This may mean that one (or both) of the millimetre and $\text{Ly}_\alpha$ emission is an inaccurate tracer of the SFR in HzRGs. This could be due to destruction of $\text{Ly}_\alpha$ photons by the dust associated with this kind of star formation activity.

Thus far, we have tacitly assumed that the sources we identify as 1.1 mm counterparts are the radio galaxy hosts themselves. However, it is important to be aware that the spatial resolution of our observations, together with the signal to noise ratios of the detections, has resulted in 1σ positional uncertainties of $\sim 2''-16''$ for our 1.1 mm counterparts. This means that the sources we identify as 1.1 mm counterparts could in actual fact be offset by tens or even hundreds of kpc from the galactic nucleus, which would place them in the outskirts or outside of the host galaxy. This may be the case for TN J0924-2201, which is undetected in SCUBA photometry (Reuland et al. 2004), but which according to our criteria has a 1.1 mm counterpart in our AzTEC map ($\S 3.2$) – this suggests that the AzTEC source is not the actual counterpart, but is instead a MMG several tens of kpc from the radio galaxy. Also of relevance in this context are results from a FWHM=2'' spatial resolution SMA study of the $z=3.79$ radio galaxy 4C +60.07 (Ivison et al. 2008): the luminous sub-mm emission, previously assumed to be centred on the active galaxy’s host, was resolved into two discrete sub-mm sources with offsets of 1'' ($\sim 10$ kpc) and 4'' ($\sim 30$ kpc) from the position of the radio core. These two results provide evidence, although anecdotal in nature, that the millimetre/sub-mm emission associated with high-z radio galaxies may not always be spatially coincident with the host galaxy. Unfortunately, with currently available facilities high resolution observations of the kind presented by Ivison et al. (2008) are costly and are sensitive only the very brightest of MMGs. The next generation of millimetre/sub-mm facilities, such as the 50 m Large Millimetre Telescope or the Atacama Large Millimetre Array, will be needed to resolve this issue.

Nevertheless, we can state that all 17 of the active galaxies in our sample are associated with one or more MMG, and thus we conclude that high-z (radio-loud) active galaxies are beacons for finding MMGs.

7 SUMMARY

We have presented 1.1 mm imaging observations of the 7 arcmin² fields around 16 powerful radio galaxies at $0.5<z<5.2$ and a radio quiet quasar at $z=6.3$. With these new observations, we have more than doubled the number of high-z radio galaxies which have been imaged at millimetre/sub-millimetre wavelengths. For all 17 active galaxies, we detect at least one associated millimetric source, which shows that high-z (radio-loud) active galaxies are beacons for finding millimetre/sub-millimetre galaxies at high-z. We identify likely millimetric counterparts for 11 radio galaxies, and these have 1.1 mm flux densities ranging between $<1.4$ mJy ($3\sigma$) and $8.6\pm 0.9$ mJy, with implied star formation rates of $<200$ to $\sim 1300$ $M_\odot$ yr$^{-1}$. After stacking our images at the position of the radio galaxies, including those for which we did not detect the millimetric counterpart, we derive an average flux density of $3.4\pm 0.2$ mJy.

For the high-z radio galaxies, we have identified an anticorrelation between 1.1 mm flux density (or star formation rate) and the projected linear size of the radio source. From this result, we have concluded that smaller radio sources are associated with more powerful (obscured) starbursts.

We have also presented images and photometry from new and archival Spitzer IRAC and MIPS observations. We find that the mid-infrared spectral energy distributions of the radio galaxies tend to be bluer than those of Spitzer-selected high-z active galaxies (Lacy et al. 2004; Martínez-Sansigre et al. 2008). In particular, the radio galaxies which we have detected at 1.1 mm have mid-infrared colours consistent with obscured star formation. We have also identified three $\geq 100$ kpc arcs of $24\mu$m sources of which three radio galaxies appear to be part; for the two arcs at $z\geq 2$, we note a spatial correlation between the 24 $\mu$m and the 1.1 mm emission.

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