RADIO AND MILLIMETER OBSERVATIONS OF $z \sim 2$ LUMINOUS QSOs

A. O. PETRIC
Astronomy Department, Columbia University, New York, NY 10027; andreea@astro.columbia.edu

C. L. CARILLI
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801; ccarilli@nrao.edu

F. BERTOLDI
Argelander Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany

A. BEELEN
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

P. COX
Institut de Radioastronomie Millimétrique, Domaine Universitaire, 38406 Saint Martin d’Hères, France

AND

A. OMONT
Institute d’Astrophysique de Paris, CNRS, 98 bis Boulevard Arago, 75014 Paris, France

Received 2004 December 27; accepted 2006 April 30

ABSTRACT

We present Very Large Array observations at 1.4 and 5 GHz of a sample of 16 quasi-stellar objects (QSOs) at $z = 1.78–2.71$. Half of the chosen quasars are bright at millimeter wavelengths (250 or 350 GHz), while the other half were not detected at millimeter wavelengths; the former QSOs were detected at 1.4 GHz, in most cases at high significance (signal-to-noise ratio $S/N \geq 7$), but only three of the latter sources were detected at radio frequencies, and only at lower significance ($S/N \sim 3$). The data are consistent with a correlation between the millimeter and radio fluxes, indicating a physical connection between the mechanisms responsible for the radio and millimeter emission. However, this conclusion is based on data including many upper limits, and deeper data are clearly needed to verify this correlation. All eight millimeter-detected QSOs are detected in the radio continuum, with radio flux densities consistent with the radio-to-far-IR correlation for low-$z$ star-forming galaxies. However, four of these have flatter spectral indices than is typical for star-forming galaxies (i.e., greater than $-0.5$), suggesting that radiation from the central active galactic nucleus (AGN) dominates the observed radio emission. All the sources detected at 1.4 GHz are spatially unresolved, with size limits typically $<1^\prime = 6$ kpc. High star formation rate galaxies at low redshift are typically nuclear starbursts, with sizes $<1$ kpc. Hence, the current radio size limits are insufficient to constrain the emission model (AGN or starburst).

Key words: dust, extinction — galaxies: active — galaxies: evolution — galaxies: ISM — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

Studies of the dynamics of stars and gas in the nuclear regions of nearby galaxies suggest that the vast majority of spheroidal galaxies in the nearby universe contain massive black holes and that the mass of the central black holes correlates with the velocity dispersion in the spheroid (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). These findings suggest a fundamental relationship between the formation of massive black holes and the stellar content of galaxies. Radio–millimeter studies of ($z > 2$) QSOs indicate that about 20%–30% of the sources are detected in surveys with 3 $\sigma$ flux density limits of 1.5–4 mJy at 250 GHz (Omont et al. 2001, 2003; Carilli et al. 2001a, 2001b; Isaak et al. 2002; Bertoldi et al. 2003a, 2003b; Petric et al. 2003; Beelen et al. 2006). The millimeter-to-centimeter spectral indices of these sources imply that the millimeter radiation is thermal emission from warm dust and that in many of the sources the spectra are consistent with the dust being heated by star formation (Carilli et al. 2001b). Detections of CO line emission from far-IR (FIR)-luminous QSOs indicate the presence of large gas reservoirs ($\sim 10^{11} M_\odot$; Cox et al. 2002; Walter et al. 2003), leading some authors to conclude that active star formation is inevitable (Omont et al. 2001).

However, the issue of what heats the dust in dusty IR-bright QSOs has not been settled. Chini et al. (1989) found that most $z < 0.4$ QSOs show dust emission with dust masses about a few times $10^7 M_\odot$. On the basis of millimeter-to-X-ray spectral indices, these authors argue that the dominant dust heating mechanism is radiation from the active galactic nucleus (AGN). Benford et al. (1999) analyze a sample of 20 mostly radio-quiet quasars with redshifts between 1.8 and 4.7 by combining their measurements at 350 $\mu$m with data from other far-IR and millimeter wavelengths. These authors try to fit the spectral energy distribution (SED) and find that the SEDs are consistent with the FIR luminosity being dominated by emission from a dust component at $\sim 50$ K. This is similar to what is found for ultraluminous IR galaxies; however, for the majority of sources in their sample a large luminosity contribution from higher temperature dust cannot be ruled out. Haas et al. (2000, 2003) obtain IR-to-millimeter SEDs for a random sample of Palomar Green quasars and learn that the SEDs show a variety of shapes (power-law, mid-IR-dominated, and FIR-dominated). This suggests that...
more than one type of source, heating mechanism, or dust is responsible for the observed SEDs.

A detailed FIR photometry study of a sample of optically selected bright quasars done by Andreani et al. (2003) does not find a strong connection between the B luminosity and the warm dust color temperature and thus suggests that there is no strong relation between the energy emitted by the nuclear source and that collected bright quasars done by Andreani et al. (2003) does not find a strong connection between the energy emitted by the nuclear source and the FIR and thus suggests that there is no strong connection between the energy emitted by the nuclear source and that collected bright quasars done by Andreani et al. (2003) does not find a strong connection between the energy emitted by the nuclear source and the FIR and thus suggests that there is no strong connection between the energy emitted by the nuclear source and the FIR.

Notes.—Col. (1): Source name. Col. (2): Redshift. Cols. (3) and (4): Absolute blue magnitude ($M_B$). Cols. (5) and (6): Optical position in J2000.0 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Cols. (7) and (8): Location of the 1.4 GHz radio emission

| QSO (1) | $z$ (2) | $M_B$ (3) | $M_B^{ABS}$ (4) | R.A. (5) | Decl. (6) | S1.4 (7) | S50 (8) | S150 (9) |
|---------|--------|----------|----------------|---------|---------|---------|---------|---------|
| J0018-0220... | 2.56 | -28.4 | -28.3 | 00 21 27.37 | -02 03 33.8 | 00 21 27.24 | <120 | **a** |
| J0035+4405... | 2.71 | -28.5 | -28.4 | 00 37 52.31 | 44 21 32.9 | 00 37 52.33 | 150 ± 16 | <120 | **b** |
| J0812+4028... | 1.78 | -27.0 | -27.0 | 08 12 00.50 | 40 28 14.0 | 08 12 00.50 | 200 ± 60 | <100 | 4.3 ± 0.8 |
| J0937+7301... | 2.52 | -28.6 | -28.5 | 09 37 48.89 | 73 01 58.3 | 09 37 48.89 | 440 ± 20 | 530 ± 36 | 3.8 ± 0.9 |
| J1409+5628... | 2.56 | -28.5 | -28.4 | 14 09 55.60 | 56 28 26.5 | 14 09 55.57 | 940 ± 20 | 310 ± 60 | 10.7 ± 0.6 |
| J1543+5359... | 2.37 | -28.4 | -28.3 | 15 43 59.37 | 53 59 03.3 | 15 43 59.45 | 140 ± 20 | 370 ± 100 | 3.8 ± 0.9 |
| J1611+4719... | 2.35 | -27.8 | -27.7 | 16 11 39.90 | 47 11 58.0 | 16 12 39.91 | 200 ± 20 | <120 | 4.6 ± 0.7 |
| J1649+5303... | 2.26 | -28.2 | -28.2 | 16 49 15.02 | 53 03 16.5 | 16 49 15.00 | 820 ± 20 | 910 ± 80 | 4.6 ± 0.8 |

Properties of Sources with mm/sub-mm Upper Limits

| Properties of Sources Detected in mm/sub-mm
|-----------------|-----------------|-----------------|-----------------|
| QSO (1) | $z$ (2) | $M_B$ (3) | $M_B^{ABS}$ (4) | R.A. (5) | Decl. (6) | S1.4 (7) | S50 (8) | S150 (9) |
|---------|--------|----------|----------------|---------|---------|---------|---------|---------|
| J0837+145... | 2.51 | -28.2 | -28.1 | 08 37 12.60 | 14 59 17.0 | ... | <81 | <1.8 |
| J0958+470... | 2.48 | -27.8 | -27.7 | 09 58 45.50 | 47 03 24.0 | ... | <81 | <2.1 |
| J0941+582... | 1.95 | -27.1 | -27.1 | 09 41 25.80 | 58 25 19.0 | 09 41 25.74 | 58 25 19.4 | 120 ± 31 | <1.8 |
| J1210+3939... | 2.40 | -27.8 | -27.7 | 12 10 10.20 | 39 39 36.0 | 12 10 10.22 | 39 39 35.7 | 74 ± 24 | <2.4 |
| J1304+2953... | 2.85 | -28.1 | -28.0 | 13 04 12.00 | 29 53 49.0 | 13 04 11.97 | 29 53 49.1 | 88 ± 22 | <3.0 |
| J1309+2814... | 2.21 | -27.9 | -27.9 | 13 09 17.20 | 28 14 04.0 | ... | <66 | <3.6 |
| J1401+5438... | 2.37 | -27.4 | -27.3 | 14 01 48.40 | 54 38 59.0 | ... | <72 | <2.7 |
| J1837+5105... | 1.98 | -29.3 | -29.3 | 18 37 25.30 | 51 05 59.0 | ... | <60 | <2.4 |

Notes.—Col. (1): Source name. Col. (2): Redshift. Cols. (3) and (4): Absolute blue magnitude ($M_B$). Cols. (5) and (6): Optical position in J2000.0 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Cols. (7) and (8): Location of the 1.4 GHz radio emission peaks as derived from the Gaussian fitting. Cols. (9)–(11): Flux densities at 1.4, 5, and 250, with 1σ error bars. In cases of nondetections, 3σ upper limits to the flux densities are listed.

a Priddey et al. (2003) detect this source at 350 GHz at 17.2 ± 2.9 mJy. At the time of submitting this paper no observations at 250 GHz had been made of this source.

b Priddey et al. (2003) detect this source at 350 GHz at 9.4 ± 2.8 mJy. At the time of submitting this paper no observations at 250 GHz had been made of this source.

c Omont et al. (2003).

d Position derived from the Digital Sky Survey using the AIPS program JMFIT.

This paper presents the radio (1.4 and 5 GHz) continuum properties of a sample of 16 QSOs at $z \sim 2$. These sources were chosen to (1) have similar optical properties ($M_B$, spectra) to those of quasar samples with redshifts greater than 3.7, for which we have comparable (sub)millimeter and centimeter observations, and (2) be radio-quiet, that is, not detected in the Faint Images of the Radio Sky at 20 cm survey, which has a typical sensitivity limit of $\sigma = 0.15$ mJy (Becker et al. 1995). Half of the observed quasars are bright at 250 GHz ($S_{250} \approx 4$ mJy; Omont et al. 2003) or 350 GHz ($S_{350} \approx 10$ mJy; Priddey et al. 2003) (Table 1), which implies $L_{\text{FIR}} > 10^{13} L_\odot$, and the other half have not been detected at either of these frequencies. These data help constrain the evolution with redshift of the radio-to-optical SEDs of luminous QSOs. We also look for systematic differences between the radio properties of FIR-bright and FIR-faint quasars and examine evidence for star formation in these systems. We use $\Omega_M = 0.3$, $\Omega_L = 0.7$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$. For comparison with previous work (e.g., Omont et al. 2003) we...
also give the alternative $M_B$ magnitudes in an Einstein–de Sitter cosmology, $\Omega_M = 1.0$, $\Omega_\Lambda = 0$, and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$.

2. OBSERVATIONS

Very Large Array observations at 1.4 GHz were made on 2002 April, in the A configuration (maximum baseline of 30 km), with a total bandwidth of 100 MHz and two orthogonal polarizations. Each source was observed for about 1 hr at 1.4 GHz. Standard phase and amplitude calibration were applied, and all sources were self-calibrated using field sources. The absolute flux density scale was set with observations of either 3C 48 or 3C 286.

The final images were generated using the wide-field imaging (Cotton 1999; Bridle & Schwab 1999) and deconvolution capabilities of the Astronomical Image Processing System (AIPS) task IMAGR. The theoretical rms noise ($\sigma$) value corresponding to 1 hr of observing in continuum mode at 1.4 GHz is $23 \mu$Jy, and in most of the maps presented here this sensitivity is roughly achieved. The Gaussian-restoring CLEAN beam full width at half-maximum (FWHM) was typically $\sim 1.5$ for the A-configuration observations.

The eight FIR-bright sources were observed at 5 GHz in 2002 October in the C configuration for $\sim 20$ minutes, achieving an rms sensitivity of order 45 $\mu$Jy. The Gaussian restoring CLEAN beam FWHM was typically of order 4$^\prime$ for the C-configuration observations. The lower quality of the 5 GHz data did not permit an appropriate fit to determine the source size. When determining the spectral indices we used the integrated 5 GHz fluxes and their respective errors.

The 250 GHz data used in the analysis for this paper were obtained with the Max-Planck Millimeter Bolometer array (Kreysa et al. 1998) at the IRAM 30 m telescope on Pico Veleta in Spain with 1 $\sigma$ flux density sensitivities ranging between 0.6 and 1.3 mJy, and are described in detail in Omont et al. (2003).

3. RESULTS AND ANALYSIS

The results for the millimeter-detected quasars are presented in the upper half of Table 1, while those for the millimeter-nondetected sources are given in the lower half. The 250 GHz data are described by Omont et al. (2003), while the 350 GHz properties of J0018–0220 and J0035+4405 are detailed by Priddey et al. (2003).

When considering radio emission from the target sources, an important issue is astrometry and source confusion. The positional uncertainty for the radio observations is given by $\sigma_0 \sim \text{FWHM}/(S/N)$ (Fomalont 1999), where FWHM corresponds to that of the Gaussian restoring beam and S/N is the signal-to-noise ratio of the detection. For a $3 \sigma$ detection this corresponds to $0.75$ for most of our sources. To this must be added the typical astrometric uncertainty of the optical data and the uncertainty in the relationship between the radio and optical reference frames, which is about $0.75$ (Deutsch 1999). Considering confusion, E. B. Fomalont (2006, in preparation) shows that the sub-millijansky source counts follow the relation $N(>S_{1.4}) = 0.026 S_{1.4}^{-1.1}$ arcmin$^{-2}$, with 1.4 GHz flux density, $S_{1.4}$, in millijanskys. Hence, within $1.5'$ of a given source we expect $6 \times 10^{-4}$ sources with $S_{1.4} \geq 70 \mu$Jy by chance. A deep survey of 357 arcmin$^2$ by Greve et al. (2004) finds that there are 15 sources in the region surveyed with $S_{30} > 3.75$ mJy. At this flux density level we expect about 0.003 sources by chance within the beam of the 30 m telescope (i.e., within $5^\prime$ of the target source). Overall, we only consider radio emission as associated with the QSO if it is $>3 \sigma$ and located within $1.5'$ of its given optical position.

Using these criteria, all of the millimeter-detected sources are also detected at 1.4 GHz with flux densities between 0.14 and 0.94 mJy. Moreover, in all but one case the sources are detected at high significance ($>7 \sigma$). Conversely, only three of the millimeter-nondetected sources are detected at 1.4 GHz, and all of these are fainter than 0.17 mJy.

The 1.4 GHz images of the detected sources are shown in Figure 1. The optical positions are indicated by crosses. From Gaussian-fitting we find no clear evidence that any of the sources are extended at the 1.4 GHz resolution of $\sim 1.5', with typical upper limits to source sizes of $\sim 1'.7$. The 4.8 GHz images of the detected sources are shown in Figure 2.

4. THE RADIO-FIR CORRELATION

In the local universe star-forming galaxies from optical-, IR-, or radio-selected samples follow a very tight linear relation between their radio continuum and FIR luminosities, with only a factor of 2 scatter around linearity over 4 orders of magnitude in luminosity (Condon 1992; Condon & Yin 1990; Miller & Owen 2001; Yun et al. 2001). If this correlation holds at high redshift (Carilli & Yun 1999, 2000; Yun & Carilli 2002; Elbaz et al. 2002; Appleton et al. 2004), then the ratio of radio to FIR fluxes can be used to constrain the star formation properties of high-$z$ QSOs. Recent work by Chapman et al. (2005) suggests that the radio-FIR correlation also holds in the case of submillimeter galaxies with redshifts between 1.7 and 3.6. These authors use the 850 $\mu$m and radio data with the spectroscopic redshfits to estimate dust temperatures for the sources in their sample. This is done by assuming an SED like that of an object that would fall on the radio-FIR correlation. Chapman et al. (2005) also observe a subset of these galaxies at 450 $\mu$m to confirm the determined temperatures and SEDs, and so vindicate the assumption that the radio-FIR correlation can be used to estimate star formation rates in their sample.

However, an important caveat is that lower luminosity, radio-quiet QSOs at lower redshift also follow the standard radio-FIR correlation for star-forming galaxies (Sopp & Alexander 1991). This can also be seen in the Haas et al. (2003) sample of Palomar Green QSOs. It is unclear whether the sources in the Sopp & Alexander sample also host significant active star formation. Overall, whether or not an object is on the radio-FIR trend is only a consistency check that the source is actively forming stars, but certainly not conclusive proof thereof. Therefore, it ought to be used in conjunction with at least one other star formation diagnostic such as radio spectral index, variability, or source size.

The radio-FIR correlation is typically quantified through the parameter $q$, defined as

$$q = \log \left( \frac{L_{\text{FIR}}}{3.75 \times 10^{12} \text{ W m}^{-2}} \right) - \log \left( \frac{F_{1.4}}{1 \text{ W m}^{-2} \text{ Hz}^{-1}} \right),$$

where $L_{\text{FIR}}$ corresponds to the FIR luminosity between 40 and 120 $\mu$m and $F_{1.4}$ is the radio flux at 1.4 GHz in W m$^{-2}$ Hz$^{-1}$. In their extensive study of 2000 IRAS-selected galaxies, Yun et al. (2001) find a mean $q$-value of 2.34 and that 98% of these sources are within $\pm \log 5$ of the mean. They conclude that this range ($q = 1.64 - 3$) corresponds to star-forming galaxies, while significantly lower $q$-values imply a contribution from a radio-loud AGN.

A second star formation diagnostic is the radio spectral index, with a typical value of $\alpha \sim -0.75 \pm 0.25$ for star-forming galaxies (Condon 1992). The spectrum of subarcsecond-scale radio
emission from high-$z$ AGNs is typically flat ($\alpha \sim 0$); however, there are exceptions, namely, the steep spectra exhibited by sources known as “compact symmetric objects” (CSOs; O’Dea 1998). Given the existence of CSOs, we consider the radio spectral index an additional consistency check for star formation.

Table 2 presents some of the estimated parameters for these sources (names in col. [1]) that were detected in FIR. Their bolometric luminosities (col. [2]) were estimated from the absolute blue magnitudes given by Omont et al. (2003), using the concordance cosmology. Omont et al. (2003) used the standard Einstein-de Sitter cosmology with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ to estimate the rest-frame absolute $B$-band magnitudes, and so we scaled the blue magnitudes to the concordance cosmology by scaling the luminosity distances accordingly. To convert the blue luminosity $L_B$ to a bolometric measurement $L_{bol}$ we assumed a bolometric correction from the $B$ band of $L_{bol}/L_B = 12$ (Elvis et al. 1994). The radio properties such as the rest-frame luminosity at 1.4 and 5 GHz and the $5–1.4$ GHz radio spectral...
indices are shown in columns (3) and (4). For consistency with earlier treatments (Omont et al. 2001, 2003) the FIR luminosity (col. [5]) was derived assuming a dust temperature and dust emissivity of 45 K and an emissivity index $\beta = 1.5$, which in this redshift range translates to the following scaling:

$$L_{\text{FIR}} = 4.7 \times 10^{12} \left( \frac{D_{\text{LH}0=65}}{D_{\text{LH}0=71}} \right)^2 S_{250} \text{ mJy} L_{\odot},$$

where $D_{\text{LH}0=65}$ and $D_{\text{LH}0=71}$ are the luminosity distances for the cosmologies used in Omont et al. (2003) and this paper. The $q$-parameter is given in column (6).

5. DISCUSSION

We find a very clear relationship between the millimeter and radio emission properties for the quasars in our sample. Although all the millimeter-detected sources are also detected at 1.4 GHz, in all cases the 1.4 GHz flux density is much less than the 250 GHz flux density, typically by an order of magnitude or more. Such a sharply rising spectrum from the radio through the (rest-frame) FIR is good evidence for the FIR emission being thermal emission from warm dust (Carilli et al. 2002), as has been confirmed through multifrequency (rest-frame) FIR observations of selected sources, including some of the sources in the current sample (Benford et al. 1999; Beelen et al. 2006).

An important issue concerning the millimeter fluxes of high-$z$ QSOs is whether there is a continuum of millimeter luminosities or whether there are two physically distinct types of QSOs: millimeter-loud and millimeter-quiet. The flux limits on the
nondetections in current millimeter and submillimeter studies allow for either possibility. However, F. Bertoldi et al. (2006, in preparation) suggest that the average of nondetections yields a clear detection and that the distribution of flux densities can be fitted by an exponential. On the other hand, submillimeter observations of a sample of X-ray-absorbed and nonabsorbed AGNs find that strong submillimeter emission is found only in X-ray-absorbed sources (Page 2001; Page et al. 2001, 2004).

The radio observations presented herein are interesting in this regard. All eight millimeter-loud sources in our study were detected at 1.4 GHz, and all but one of these at high significance \((>0.2 \pm 0.02 \, \text{mJy})\). Only three of the eight millimeter-quiet QSOs were detected at 1.4 GHz, and these at lower flux densities \((<0.17 \, \text{mJy})\), and the rest were not detected in images with rms values \(~0.02 \, \text{mJy}\). Recall that all the sources were selected to have similar optical magnitudes, such that the radio and millimeter differences are unlikely to relate to differences in bolometric luminosity or magnification by gravitational lensing. We performed a statistical study based on methods that take upper limits formally into account, using the statistics package ASURV (Feigelson & Nelson 1985; Isobe et al. 1986). The statistical tests used indicate that the two populations are different to a high significance level;

Fig. 1i

Fig. 1j

Fig. 1k

Fig. 1.—Continued
that is, based on their radio properties at 1.4 GHz, the probability that the two samples of submillimeter-detected and nondetected quasars are drawn from the same population is very low ($\lesssim 10^{-4}$).

Figure 3 shows that a simple explanation for the different 1.4 GHz flux density distributions for the submillimeter-detected versus nondetected sources may be a correlation between the 1.4 GHz and FIR luminosities for QSO host galaxies. In Figure 3 we show that the 1.4 GHz and FIR luminosities of the sources (including limits) are consistent with a correlation between the two bands. This suggests a connection between the mechanisms producing the emission in each band. Such a connection would be a natural consequence of star formation. We note that flux density is not proportional to redshift, so this tentative correlation cannot result from a mutual correlation with distance.

However, our samples are very small, so it is difficult to ascertain what factors are responsible for the lower level of activity in the non-FIR-detected sources. Clearly, more sensitive surveys of QSOs at multiple wavelengths are required to properly test the hypothesis that there are two physically distinct populations of millimeter-loud and millimeter-quiet sources and to understand the evolutionary stages of these sources.

As shown in Figure 4, all of the eight millimeter-detected QSOs are detected in the radio continuum, with radio flux densities consistent with the radio-to-FIR correlation for low-$z$ star-forming galaxies. However, four of these have flatter spectral indices than is typical for star-forming galaxies ($\alpha_{1.4} < -0.5$).

The other four millimeter-detected sources either are at the low end of the $q$-range defined for star-forming galaxies or have
flat radio spectral indices (Table 2). It is possible that very early in its evolution ($<10^7$ yr), i.e., before many supernovae have populated the interstellar medium with cosmic-ray electrons, a starburst might show a flat spectral index, corresponding to free-free radio emission. A flat index might be seen if we were observing a very young starburst, in which the thermal free-free emission from O and B stars overwhelms the synchrotron radiation from supernovae. However, this scenario would imply that we are looking at this object during a rapid and massive starburst. It seems more likely that in the sources with flat radio indices, the radiation from the central AGN dominates the observed radio emission.

![Graph](image)

**Fig. 3.**—Radio (in W Hz$^{-1}$) vs. millimeter luminosities (in $L_\odot$) for all our sources. This figure suggests that the mechanisms producing radio and millimeter emission in these quasars are connected. We note that flux density is not proportional to redshift, so this tentative correlation cannot result from a mutual correlation with distance.

![Graph](image)

**Fig. 4.**—Distribution of $q$-values as a function of 60 $\mu$m luminosity. The crosses are for the IRAS 2 Jy sample of Yun et al. (2001). The squares with error bars are for the millimeter-detected QSOs with steep radio spectral indices, and the triangles are millimeter- and radio-detected sources with almost flat or rising spectral indices (Table 2). The solid line marks the average value of $q = 2.34$, while the dotted lines mark the radio-excess (lower) and IR-excess (upper) objects, as discussed in Yun et al. (2001).

TABLE 2

**Estimated Properties**

| QSO   | $L_{bol}/L_\odot$ (1) | $\alpha_{1.4}^5$ (2) | $L_{1.4}/L_\odot$ (4) | $L_{5.0}/L_\odot$ (5) | $L_{FIR}/L_\odot$ (6) | $q$ (7) |
|-------|----------------------|---------------------|----------------------|----------------------|----------------------|--------|
| J0018–0220 | 2.20E+14             | $< -0.61$           | 8.3E+24              | 3.8E+24              | 2.3E+13              | 2.4 ± 0.2 |
| J0035+4405 | 2.42E+14             | $< -0.18$           | 3.1E+24              | 2.5E+24              | 1.3E+13              | 2.3 ± 0.3 |
| J0812+4028 | 6.07E+13             | $< -0.60$           | 2.7E+24              | 1.4E+24              | 1.7E+13              | 2.7 ± 0.4 |
| J0937+7301 | 2.65E+14             | 0.15 ± 0.08         | 5.3E+24              | 6.4E+24              | 1.5E+13              | 2.4 ± 0.2 |
| J1409+5628 | 2.42E+14             | $< -0.90$ ± 0.25    | 4.2E+25              | 1.4E+25              | 4.3E+13              | 2.0 ± 0.1 |
| J1543+5359 | 2.20E+14             | 0.80 ± 0.20         | 7.2E+23              | 1.9E+24              | 1.6E+13              | 3.3 ± 0.3 |
| J1611+4719 | 1.27E+14             | $< -0.40$           | 4.2E+24              | 2.5E+24              | 1.9E+13              | 2.5 ± 0.2 |
| J1649+5303 | 1.83E+14             | 0.10 ± 0.30         | 8.9E+24              | 9.9E+24              | 1.9E+13              | 2.4 ± 0.2 |
| J0837+145 | 1.83E+14             | ...                 | $< 3.0E+24$          | $< 1.1E+24$          | $< 7.3E+12$          | ...    |
| J0958+470 | 1.27E+14             | ...                 | $< 2.9E+24$          | $< 1.1E+24$          | $< 8.5E+12$          | ...    |
| J0914+582 | 6.66E+13             | ...                 | 2.9E+24              | 9.6E+23              | 7.3E+12              | 2.5     |
| J1210+3939 | 1.27E+14             | ...                 | 2.5E+24              | 9.5E+23              | 1.2E+13              | 2.6     |
| J1304+2953 | 1.67E+14             | ...                 | 4.3E+24              | 1.7E+24              | 1.2E+13              | 2.5     |
| J1309+2814 | 1.39E+14             | ...                 | $< 1.8E+24$          | $< 7.0E+23$          | $< 1.2E+13$          | ...    |
| J1401+5438 | 8.77E+13             | ...                 | $< 2.3E+24$          | $< 9.8E+23$          | $< 1.1E+13$          | ...    |
| J1837+5105 | 5.05E+14             | ...                 | $< 1.3E+24$          | $< 5.0E+23$          | $< 9.7E+13$          | ...    |

**Notes.**—Table 2 presents some of the estimated properties for the millimeter-detected sources (col. [1]). Their bolometric luminosities (col. [2]) were estimated from the absolute blue magnitudes given in Omont et al. (2003), using the concordance cosmology. Omont et al. used the standard Einstein–de Sitter cosmology with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and $q_0 = 0.5$ to estimate the rest-frame absolute $B$-band magnitudes, and so we scaled the blue magnitudes to the concordance cosmology by scaling the luminosity distances. To convert the blue luminosity $L_B$ to a bolometric measurement $L_{bol}$ we assumed a bolometric correction from the $B$ band of $L_{bol}/L_B = 12$ (Elvis et al. 1994). The radio properties (1.4 and 5 GHz luminosities and 5–1.4 GHz spectral index, $\alpha_{1.4}^5$) are given in cols. (3)–(5). For the objects observed at both 1.4 and 5 GHz we calculated the rest-frame 1.4 GHz luminosity using the estimated spectral indices, or the upper limits for the indices. For sources observed at only one radio frequency (1.4 GHz) we used a default spectral index of $-0.75$. The FIR luminosity (col. [6]) was derived assuming a dust temperature of 45 K and an emissivity index $\beta = 1.5$. This translates to the following scaling: $L_{FIR} \sim 4.7 \times 10^{-3} (S_{250}/1 \text{ mJy})L_\odot$ over the range of interest. The $q$-parameter is given in col. (7).
one source, J1409+5628, a massive reservoir of molecular gas ($\sim 10^{11} M_\odot$), the required fuel for such a starburst, has recently been detected (Beelen et al. 2004). Similar searches are underway for CO emission from the other QSOs.

All the sources detected at 1.4 GHz are spatially unresolved, with size limits typically $< 1'' = 6$ kpc. High star formation rate galaxies at low redshift are typically nuclear starbursts, with sizes $< 1$ kpc. Hence, the current radio size limits are insufficient to constrain the emission model (AGN or starburst). A potentially powerful test of AGN versus starburst radio emission comes from VLBI observations, to search for extended (on scales of hundreds of parsecs), lower surface brightness radio emission. Recent VLBI observations (Momjian et al. 2004, 2005) of one of the sources

C. C. would like to acknowledge support from the Max-Planck-Forschungspreis. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. We also thank the anonymous referee, who helped improve the structure and content of this paper.

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