SENSITIVE OBSERVATIONS AT 1.4 AND 250 GHz OF $z > 5$ QSOs

A. O. Petric
Department of Astronomy, Columbia University, 550 West 120th Street, 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
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Xiaohui Fan
Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721

P. Cox
Institut d' Astrophysique Spatiale, Université de Paris XI, F-91405 Orsay, France

Michael A. Strauss
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544

A. Omont
Institut d’Astrophysique de Paris, CNRS, 98 bis, Boulevard Arago, F-75014 Paris, France

AND

Donald P. Schneider
Department of Astronomy, 525 Davey Laboratory, Pennsylvania State University, University Park, PA 16802

Received 2003 January 16; accepted 2003 April 1

ABSTRACT

We present 1.4 and 5 GHz observations taken with the Very Large Array, and observations at 250 GHz obtained with the Max Planck Millimeter Bolometer Array at the IRAM 30 m telescope, of 10 optically selected quasi-stellar objects (QSOs) at 5.0 $\leq z \leq 6.28$. Four sources are detected at 1.4 GHz. Two of the sources have rest-frame 1.4 GHz luminosity densities greater than $5.0 \times 10^{26}$ WHz$^{-1}$, placing them in the regime of radio-loud QSOs. Both of these sources are also detected at 5 GHz. These results are roughly consistent with there being no evolution of the radio-loud QSO fraction out to $z \sim 6$. Three sources have been detected at 250 or 350 GHz by these, and previous, observations. The (sub-) millimeter flux densities for these three sources are much larger than their 1.4 GHz flux densities. The rapidly rising spectra into the (rest-frame) far-IR (FIR) argue that the observed millimeter emission is likely thermal emission from warm dust, although more exotic possibilities cannot be precluded. The implied IR luminosities are between $10^{12}$ and $10^{13}$ L$_{\odot}$. For J0301+0020, the radio continuum emission is clearly above that expected for a star-forming galaxy based on the radio-FIR correlation. In this case, it seems likely that the radio emission relates to the active galactic nucleus. For J0756+4104, the radio emission is within the range expected for a star-forming galaxy, while for J1044−0125 the radio upper limit is at least consistent with a star-forming galaxy. If the dust is heated by star formation, the implied massive star formation rates are between 200 and 1000 M$_{\odot}$ yr$^{-1}$. We do not detect radio emission from the reported X-ray jet associated with J1306+0356. The lack of radio emission implies that the magnetic field is well below typical equipartition values in powerful radio jets or that particle acceleration ceased between 10$^6$ and 10$^7$ yr ago or that the X-ray emission is not inverse Compton emission from a jet related to J1306+0356. The highest redshift source in our sample (J1030+0524 at $z = 6.28$) is not detected at 1.4 or 250 GHz, but four fairly bright radio sources ($S_{14GHz} > 0.2$ mJy) are detected in a 2$'$ field centered on the QSO, including an edge-brightened (“ FR II”) double radio source with an extent of about 1$''$. A similar overdensity of radio sources is seen in the field of the highest redshift QSO J1148+5251. We speculate that these overdensities of radio sources may indicate clusters along the lines of sight, in which case gravitational lensing by the cluster could magnify the QSO emission by a factor 2 or so without giving rise to arcsecond-scale distortions in the optical images of the QSOs.

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

1. INTRODUCTION

Surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) have generated large samples of quasi-stellar objects (QSOs) out to $z \sim 6$. Optical spectroscopy of two of the highest-$z$ QSOs revealed, for the first time, evidence for broad, optically thick absorption regions in the (rest-frame) far-UV, as expected for the neutral intergalactic medium (Gunn & Peterson 1965; Becker et al. 2001; Djorgovski et al. 2001; Pentericci et al. 2002; Fan et al. 2003), suggesting that we are probing into the epoch of reionization, the edge of the “dark ages” when the first stars and massive black holes were formed. Assuming that the intrinsic continuum spectra of the $z > 5$ QSOs are
similar to those of nearby QSOs as compiled by Elvis et al. (1994), and that these QSOs are not lensed, Eddington limit arguments result in lower limits of several times $10^9 M_\odot$ for the masses of the black holes in these high-redshift objects.

Study of the dynamics of stars and gas in the nuclear regions of nearby galaxies has led to two remarkable discoveries: (1) the overwhelming majority of spheroidal galaxies in the nearby universe contain massive black holes and (2) there is a correlation between the black hole mass and the velocity dispersion of the stars in the spheroid (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). Assuming that these relations also apply in the high-redshift universe (Shields et al. 2003) implies that the highest redshift QSOs are associated with massive galaxies (greater than $10^{11} M_\odot$). Furthermore, strong metal emission lines in these QSOs suggest that their environments have been quickly enriched, possibly through starburst activity (Fan et al. 2001).

These fundamental results allow us to investigate the nature of these earliest objects, and in particular to probe the relationship between massive black hole and spheroidal galaxy formation. To address this and other related questions, and in general, to study the cosmic evolution of the radio-to-optical spectra of QSOs, we have undertaken an extensive observational program from radio through millimeter wavelengths of high-redshift QSOs that includes searches for emission from warm dust at millimeter wavelengths from a large sample of $z > 1.8$ QSOs (Carilli et al. 2001a; Omont et al. 2001, 2003), high-resolution imaging at centimeter wavelengths of the nonthermal radio continuum emission from these sources (Carilli et al. 2001a, 2001b), and observations of the CO line emission from selected sources with large infrared luminosities (Carilli, Menten, & Yun 1999; Carilli et al. 1999, 2002b, 2002a; Cox et al. 2002; Beelen et al. 2003).

Millimeter-continuum observations of high-redshift QSOs show that about 30% of the sources are detected in surveys with flux density limits of 1–2 mJy at 250 GHz (Omont et al. 2001; Carilli et al. 2001b; Isaak et al. 2002). Multifrequency studies of the rest-frame radio through far-IR (FIR) spectral energy distributions (SEDs) of these sources reveal that the millimeter emission is thermal emission from warm dust (Benford et al. 1999), and in many of the sources the centimeter-to-millimeter flux density ratios are consistent with the radio-to-FIR correlation for star-forming galaxies (Carilli et al. 2001b). Furthermore, searches for CO line emission from FIR luminous QSOs have resulted in the detection of molecular line emission, indicating the presence of large gas reservoirs ($\sim 10^{11} M_\odot$; Cox et al. 2002). These detections lead some authors to conclude that active star formation is inevitable (Omont et al. 2001) in these FIR luminous, CO-rich quasars. Andreani et al. (2003) reached a similar conclusion for lower redshift QSOs, although for both low- and high-redshift samples the case for star formation is by no means proven.

In this paper, we extend our radio study of distant QSOs to the highest redshifts ($z > 5$). We present observations at 1.4, 5, and 250 GHz. These observations are an order of magnitude, or more, more sensitive than survey observations, such as FIRST and NVSS (Becker, White, & Helfand 1995; Condon et al. 1998). We assume a concordance cosmology ($\Omega_m = 0.3$, $\Omega_L = 0.7$) and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ throughout.

### TABLE 1
Properties of Observed QSOs

| QSO       | $z$    | $M_B$ | R. A. | Decl. | $S_{1.4}$ | $S_{250}$ |
|-----------|--------|-------|-------|-------|-----------|-----------|
| J0231−0729  | 5.41   | −27.37 | 02 31 37.65 | −07 28 54.5 | <50       | <3.5      |
| J0301+0020  | 5.50   | −24.00 | 03 01 17.01 | 00 20 26.0 | 73 ± 18   | 0.87 ± 0.2|
| J0756+4104  | 5.09   | −26.50 | 07 56 18.14 | 41 04 08.6 | 55 ± 17   | 5.5 ± 0.5 |
| J0836+0054  | 5.82   | −28.10 | 08 36 43.83 | 59 23 33.3 | 750 ± 40  | <2.9      |
| J0913+5919  | 5.11   | −26.20 | 09 13 16.56 | 59 19 21.5 | 18950 ± 380 | <2.8     |
| J1030+0524  | 6.28   | −27.37 | 10 30 27.10 | 05 24 55.0 | <61       | <3.4      |
| J1044−0125   | 5.73   | −27.63 | 10 44 33.04 | −01 21 49.6 | <79       | 3.4 ± 1.1 |
| J1204+0202   | 5.03   | −27.64 | 12 04 41.73 | −00 21 49.6 | <87       | N/A       |
| J1208+0010  | 5.27   | −26.30 | 12 08 23.82 | 00 10 27.7 | <60       | <3.1      |
| J1306+0356  | 5.59   | −27.41 | 13 06 08.26 | 03 56 26.3 | <53       | <3.1      |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* From Anderson et al. 2001.
* From Stern et al. 2000a.
* From Fan et al. 2001.
* Extrapolated from 350 GHz ($\lesssim 3$).
* From Fan et al. 2000a.
* From Zheng et al. 2000.
bandwidth of 100 MHz and two polarizations. Each source was observed for about 2 hr. In addition, J0756+4104 was observed for 2 hr at 1.4 GHz in B configuration (maximum baseline of 10 km). Standard phase and amplitude calibration was 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 AIPS task IMAGR. The theoretical rms noise (σ) value corresponding to 2 hr of observing in continuum mode at 1.4 GHz is 16 μJy, and in most of the maps presented here this sensitivity is roughly achieved. The noise level in one source (J1204–0021) was higher (35 μJy), possibly due to some low-level terrestrial interference. We also include a 2% uncertainty in absolute flux density scale determination. The Gaussian restoring CLEAN beam full width at half-maximum (FWHM) was typically ~1.5 for the A configuration observations.

Two of the sources, J0836+0054 and J0913+5919, were observed at 5 GHz on 2002 August 17 in B configuration for about 20 minutes, achieving an rms sensitivity of about 60 μJy. The Gaussian restoring CLEAN beam (FWHM) was ~1.5, matching the resolution of the 1.4 GHz observations.

Observations at 250 GHz were made using the Max-Planck Millimeter Bolometer Array (MAMBO; Kreyss et al. 1998) at the IRAM 30 m Telescope on Pico Veleta in Spain, during the winter of 2001–2002 within dynamically scheduled, pooled observations, except for J0301+0020, which was reported on by Bertoldi & Cox (2002). MAMBO is a 37-element bolometer array with an effective central frequency of 250 GHz for thermal sources. The beam for the feed horn of each bolometer is matched to the telescope beam of 0.6. Observations were made in standard on-off mode, with 2 Hz chopping of the secondary by 50° in azimuth. The data were reduced using the MOPSI software package (Zylka 1998). Pointing was monitored every hour and was found to be repeatable to within 2°. The sky opacity was monitored every hour. Zenith optical depths were lower than 0.3 at all times. Gain calibration was performed using observations of Mars, Uranus, and Ceres. We estimate a 20% uncertainty in absolute flux density calibration based on these observations.

The target sources were centered on the central bolometer in the array, and the temporally correlated variations of the sky signal (sky noise) detected in the surrounding six bolometers were subtracted from the central bolometer signal. The total sky plus source observing time for each source was about 1 hour, leading to rms sensitivities of 0.5–1.0 mJy, depending on the weather.

3. RESULTS

The results from the 1.4 and 250 GHz observations are listed in Table 1. The abbreviated source names (col. [1]), the redshifts (col. [2]), the absolute blue magnitude (MB) obtained by assuming a flat Λ-dominated cosmology (col. [3]), and the optical position (cols. [4] and [5]) is compiled from the optical discovery papers. Columns (6) and (7) give the 1.4 and 250 GHz flux densities with 1 σ error bars, and 3 σ upper limits are given for nondetections.

The 1.4 GHz images of these sources are shown in Figure 1. The positional uncertainty for the radio observations is given by σr = FWHM/(S/N) (Fomalont 1999), where FWHM corresponds to the Gaussian restoring beam, and S/N is signal-to-noise ratio of the detection. For a 3 σ detection this corresponds to 0.5 for most of our sources. To this must be added the typical astrometric uncertainty 0.1 (Pier et al. 2003) of the optical data, and the uncertainty in the relationship between radio and optical reference frame, which is about 0.25 (Deutsch 1999). Thus, we only consider emission within 0.6 of the optical position to be associated with the QSO.

Fomalont et al. (2003) show that the sub-millijansky source counts follow the relation N(>S1.4) = 0.026S−1.1
darbmin−2, with 1.4 GHz flux density, S1.4, in millijanskys. Hence, within 0.6 of a given source, we expect 1.5 × 10−4 sources with S1.4 ≥ 70 μJy by chance. Blain et al. (2002) show that there are about 2000 sources deg−2 with S250 > 1 mJy. At this flux density level, we then expect 0.01 sources by chance within the beam of the 30 m telescope (i.e., within 5° of the target source).

3.1. Notes on Individual Sources

J0231–0728 (z = 5.41): There is a 3 σ unresolved source at 1.4 GHz situated 1° away from the optical position of the QSO. This is farther than the 0.6 positional accuracy of our measurements, so J0231–0728 is considered a nondetection at 1.4 GHz. This source is also not detected at 250 GHz.

J0301+0020 (z = 5.50): A radio continuum source with S1.4 = 73 ± 17 μJy is detected within 0.5 of the optical QSO position. The radio source is not resolved, and Gaussian fitting sets an upper limit to its size at 1.4 GHz of 1°. Bertoldi & Cox (2002) detect this QSO at 250 GHz with a flux density of 0.87 ± 0.20 mJy.

J0756+4104 (z = 5.09): The combined A and B configuration observations show a 1.4 GHz source with S1.4 = 65 ± 17 μJy within 0.2 of the optical QSO position. Gaussian fitting to the radio emission sets an upper limit to its size of 2° south of the QSO. This QSO is also detected with MAMBO with S250 = 5.5 ± 0.5 mJy.

J0836+0054 (z = 5.82): This source is clearly detected at 1.4 GHz with a flux density of 1.75 ± 0.04 mJy. Gaussian fitting sets an upper limit to the source size of 0.65 at 1.4 GHz. J0836+0054 is also detected at 5 GHz with a flux density of S5 = 580 ± 57 μJy. The implied radio spectral index is −0.8. A second radio source with S1.4 = 0.44 mJy is detected 10° south of the QSO. Deep optical and near-IR imaging of this field suggests that this second source is associated with a lower redshift galaxy, and unrelated to the QSO (Rusin et al. 2003). J0836+0054 is not detected at 250 GHz with a 3 σ upper limit of 2.9 mJy.

J0836+0054 was also detected in the FIRST radio survey (Becker et al. 1995) at 1.4 GHz with a flux density of 1.1 ± 0.15 mJy. The difference in flux density between the FIRST measurement and our more recent measurement is significant at the 4 σ level, such that the radio source appears to be variable on yearly timescales.

J0913+5919 (z = 5.11): This source is clearly detected at 1.4 GHz with S1.4 = 18.95 ± 0.4 mJy. Gaussian fitting to

---

1 D. Rusin and collaborators also observed J0836+0054 on May 5 at 5 GHz. Their flux densities are equal to ours within the errors.
the radio emission sets an upper limit to the source size of 0"2 at 1.4 GHz. J0913+5919 is also clearly detected at 5 GHz with $S_5 = 8.1 \pm 0.2$ mJy, implying a spectral index for this source of $\sim 0.7$. This source is not detected at 250 GHz with a 3 $\sigma$ upper limit of 2.8 mJy.

J0913+5919 was also detected in the NVSS radio survey (Condon et al. 1998) with a total flux density of 18.5 $\pm$ 0.5 mJy, implying that the source is not variable on yearly timescales.

J1030+0524 ($z = 6.28$): This source was the highest redshift QSO published at the time of observation. The source is not detected at 1.4 or 250 GHz. However, four fairly bright sources ($S_1 \gtrsim 200 \mu$Jy) are detected at 1.4 GHz in a 2' field centered on the QSO (Fig. 2), including an edge-brightened double radio source (FR II; Fanaroff & Riley 1974) with an extent of about 1' and a total flux density of 29 mJy.

J1044−0125 ($z = 5.73$): This source is not detected at 1.4 GHz with a 3 $\sigma$ upper limit of $S_{1.4} < 79$ mJy. We did not observe this source with MAMBO. Iwata et al. (2001) report a flux density at 350 GHz for J1044−0125 of 6.2 $\pm$ 2.0 mJy. Assuming a thermal IR spectrum typical for ultraluminous IR galaxies leads to an expected 250 GHz flux density of 3.4 $\pm$ 1.1 mJy for a source at $z = 5.73$. Near-IR spectroscopic observations of this source reveal a prominent C $^{iv}$ absorption feature whose shape suggests that this is a broad absorption line QSO (Maiolino et al. 2001; Goodrich et al. 2001).
4. ANALYSIS

4.1. Fraction of Radio-Loud Objects

Questions regarding both the bimodality of the radio luminosity function of QSOs and its evolution, have been investigated by numerous workers (e.g., Peacock, Miller, & Longair 1986; Miller, Peacock, & Mead 1990; Schmidt et al. 1995; Stern et al. 2000a; Lacy et al. 2001; Ivezic et al. 2002). Two definitions are generally used to demarcate radio-quiet and radio-loud QSOs. One criterion is based on the radio-optical ratio, $R_{\text{ro}}$, of the specific fluxes at rest-frame 5 GHz and 4400 Å (Kellerman et al. 1989), where typical radio-loud sources have $R_{\text{ro}}$ in the range 10–1000, while radio-quiet sources have $R_{\text{ro}} < 1$. Peacock et al. (1986) point out that $R_{\text{ro}}$ can be used as a discriminating parameter only if the radio and optical luminosities are linearly correlated, which does not seem to be the case (Stocke et al. 1992). The second definition divides the sources at the 1.4 GHz luminosity density of $3 \times 10^{25}$ W Hz$^{-1}$ (Gregg et al. 1996). Ivezic et al. (2002) find that for optically selected QSOs the two definitions are consistent as a consequence of selection effects in flux-limited samples, so far for the remainder of this paper we will use the Gregg et al. (1996) definition to classify a source as radio-loud.

Having the radio spectral indexes of the two bright radio sources, J0836+0054 and J0913+5919 ($-0.8$ and $-0.7$, respectively), allows us to estimate their luminosity densities at a rest-frame frequency of 1.4 GHz. For J0836+0054, the value is $5.0 \times 10^{25}$ W Hz$^{-1}$, while that for J0913+5919 is $4.9 \times 10^{27}$ W Hz$^{-1}$. Both these sources are radio-loud by any definition.

The radio spectral indexes for J0756+4104 and J0301+0020 are unknown, so we calculate luminosity densities using the spectral index of $-0.5$ adopted in previous studies (e.g., Stern et al. 2000a; Ivezic et al. 2002). The 1.4 GHz rest-frame luminosities for these two sources are $1.2 \times 10^{25}$ and $1.6 \times 10^{25}$ W Hz$^{-1}$ respectively, placing them below the radio-loud demarcation.

Three sources (J0756+4104, J0301+0020, and J1044–0125) are detected at (sub-)millimeter wavelengths at levels at least 10 times above their 1.4 GHz flux densities, implying rapidly rising spectra from centimeter to millimeter wavelengths. Note that an observing frequency of 250 GHz corresponds to a rest frequency of 1600 GHz (=188 μm) for a source at $z = 5.5$, such that the MAMBO observations sample the rest-frame FIR part of the spectra. Benford et al. (1999) have performed multiwavelength observations of a number of millimeter-loud high-redshift QSOs, and in every case they find that the rest-frame FIR SEDs are consistent with a graybody spectrum characteristic of thermal emission from warm dust. In the analysis below, we will assume that the rapidly rising centimeter-to-millimeter spectra of the three millimeter-loud sources in our sample imply thermal emission from warm dust. However, we cannot preclude more exotic explanations for the rapidly rising spectra, such as synchrotron self-absorption at rest-frame FIR wavelengths.

One possible method for addressing the question of dust heating is using the fact that star-forming galaxies at low redshift follow a very tight linear relation between radio continuum and FIR luminosity (Condon & Yin 1990; Condon 1992; Crawford et al. 1996; Miller & Owen 2001; Yun, Reddy, & Condon 2001). This correlation holds over 4 orders of magnitude in luminosity with only a factor of 2 scatter around linearity for galaxy samples selected in the optical, IR, and radio. While a general correlation is expected, since the synchrotron radiation at centimeter wavelengths and thermal dust emission at IR wavelengths both relate to massive star formation, the tightness and linearity of the correlation remain puzzling. A further uncertainty in using the FIR-radio correlation to assess the significance of star formation in heating the dust is that lower luminosity radio-quiet QSOs at lower redshift also follow the standard radio-FIR correlation for star-forming galaxies (Sopp & Alexander 1991). Whether the sources in the Sopp & Alexander sample also host active star formation remains unknown. In addition, there is the question of whether the radio-FIR correlation holds in star-forming galaxies. A point located below the curve (plus scatter) on this diagram indicates a source that is radio-loud relative to a star-forming galaxy. In such an object, it is likely that the radio emission is due to the active galactic nucleus (AGN) and not star formation (Yun et al. 2001).

Figure 3 shows the relationship between redshift and the 250-to-1.4 GHz spectral index ($\alpha_{1.4}^{250}$) for a star-forming galaxy taken from the study of Carilli & Yun (2000). This model consists of the mean SED (plus scatter) of 17 low-redshift, star-forming galaxies. The FIR part of this model SED corresponds roughly to a modified blackbody spectrum with a dust temperature of 50 K and emissivity index of 1.5, and the centimeter part of the spectrum is constrained to follow the radio-to-FIR correlation for star-forming galaxies. A point located below the curve (plus scatter) on this diagram indicates a source that is radio-loud relative to a star-forming galaxy. In such an object, it is likely that the radio emission is due to the active galactic nucleus (AGN) and not star formation (Yun et al. 2001).

For J0301+0020, we find $\alpha_{1.4}^{250} = 0.5 \pm 0.1$, well below the region defined by star-forming galaxies. For J0756+4104, we find $\alpha_{1.4}^{250} = 0.86 \pm 0.08$, which is consistent (within the

---

Fig. 2.—Wider field image of J1030+0524 at 1.4 GHz. The FWHM of the Gaussian restoring beam is 3′′ × 3′′. Contour levels are a geometric progression in the square root two starting at 0.13 mJy beam$^{-1}$. Three negative contours (dashed lines) are included. The cross shows the position of the optical QSO.
Fig. 3.—Relationship between redshift and the observed spectral index between 250 and 1.4 GHz for star-forming galaxies (solid curve), as derived from the models presented in Carilli & Yun (2000). The dashed lines show the rms scatter in the distribution. The 250- to 1.4 GHz spectral indexes for QSOs detected at 250 GHz are shown with 1σ error bars.

with the low end of the range for star-forming galaxies. For J1044−0125, we extrapolate to 250 GHz from the measured 350 GHz flux density (§3). This source was not detected at 1.4 GHz, implying $\alpha_{1.4} > 0.7$, which is at least consistent with star formation. A factor of 2 deeper radio observations are required to test whether this source follows the radio-FIR relationship defined by low-redshift galaxies.

4.3. Inverse Compton Emission from J1306+0356?

X-ray observations of the source J1306+0356 (Brandt et al. 2002) suggest a possible jetlike feature 23″ from the QSO position (Schwartz 2003). Schwartz (2003) argues that the emission may be due to inverse Compton (IC) scattering of the cosmic background by relativistic electrons in a jet emanating from the QSO. These same relativistic electrons would emit radio synchrotron radiation in the presence of a magnetic field, hence we have searched for radio emission from the location of the jetlike X-ray feature.

We have not detected radio emission from the possible X-ray jet in J1306+0356 to a 3σ limit of 150 $\mu$Jy at 1.4 GHz (after convolving to the $5″ \times 2″$ resolution corresponding to the box containing the X-ray “jet”). The flux density of the X-ray feature at 1 keV ($2.4 \times 10^{17}$ Hz) is $8.3 \times 10^{-4}$ $\mu$Jy, assuming a spectral index of $-1$.

A long-standing and well-documented technique for deriving magnetic fields in extragalactic radio sources is by comparing the radio synchrotron and X-ray IC flux densities (Harris & Grindlay 1979). The constraint on the magnetic field strength comes from the fact that the IC X-ray emissivity is a function of the relativistic electron density and the energy density in the dominant ambient photon field (presumably the microwave background), and the synchrotron radio emissivity is a function of the relativistic electron density and the magnetic energy density. A recent simple parameterization of this calculation can be found in equation (4) from Carilli & Taylor (2002). In the case of the jetlike X-ray feature in J1306+0356, only a radio upper limit is available, such that we can only derive an upper limit to the magnetic field strength. Using equation (4) from Carilli & Taylor (2002), and the X-ray flux density and radio upper limits given above, we derive an upper limit of 3 $\mu$G to the magnetic field in the jetlike feature in J1306+0356. Note that this limit assumes the X-ray emission is IC, and that the relativistic electrons have a power-law energy distribution of index $-3$ over a wide range in energy (see §5.3 for more details).

5. DISCUSSION

5.1. Radio-Loud QSOs at High Redshift

There has been considerable debate in the literature about the redshift evolution of the radio-loud fraction of QSOs (e.g., Visnovsky et al. 1992; Schneider et al. 1992; Schmidt et al. 1995; Hooper et al. 1995; Goldschmidt et al. 1999; Stern et al. 2000a). Most recently, Ivezić et al. (2002) have investigated this question using large samples of QSOs out to $z > 2.2$ from the SDSS. They conclude that about 8% of QSOs are radio-loud, independent of redshift. Two out of the 10 QSOs at $z > 5$ observed in our study are radio-loud, which is roughly consistent (given the small number statistics) with the fraction seen at lower redshift, e.g., the Poisson probability of seeing two radio-loud quasars when the expectation value is 0.8 is 14%. As emphasized by Ivezić et al. (2002), larger QSO samples at high redshift are required to separate effects related to redshift-luminosity biases in flux-limited samples.

The radio-loud sources J0836+0054 and J0913+5919 are compact (less than 1″) and have steep spectra (−0.8 and −0.7), classifying them as compact steep-spectrum (CSS) objects. CSS objects are a mixed bag of source types, ranging from steep-spectrum core jets (size is less than or equal to a few parsecs), to small (size is ~1 kpc), double-lobed radio galaxies, i.e., compact symmetric objects (CSOs). The CSOs are particularly intriguing, since they are thought to be very young radio sources, and their ages can be measured through VLBI observations of the proper motions of the radio hot spots, with typical measured ages between $10^4$ and $10^5$ yr (Polatidis & Conway 2002). Recent VLBI imaging of J0836+0054 by Frey et al. (2003) at 1.6 GHz shows a marginally resolved source at 10 mas resolution, suggesting that this source is a steep spectrum core-jet and not a CSO. Similar VLBI imaging has not been performed for J0913+5919, but the lack of variability of this source (§3) makes it a prime candidate for a high-redshift CSO.

In either case, the fact that the radio-loud fraction of QSOs appears to be relatively constant out to very high redshift, and that the two radio-loud QSOs at $z > 5$ discovered thus far have steep radio spectra, is encouraging from the perspective of studying the neutral intergalactic medium (IGM) during the epoch of reionization through observation of $\text{H} \text{I}$ $21$ cm absorption (the “21 cm Forest”). Calculations by Carilli, Gnedin, & Owen (2002) and Furlanetto & Loeb (2002) show that the next generation of low-frequency, large-area radio telescopes, such as the LOFAR and the Square Kilometer Array, will be able to study the neutral IGM beyond the epoch of reionization (EOR) in $\text{H} \text{I}$
21 cm absorption toward discrete radio sources as faint as a few millijanskys at frequencies below 200 MHz. Both J0836+0054 and J0913+5919 would be easily adequate for such studies if they were placed beyond the EOR.

5.2. Thermal Emission from Warm Dust and Star Formation

Three of the 10 sources in our study (J0301+0020, J0756+4104, and J1044–0125) have been detected at (sub-)millimeter wavelengths with flux densities much larger than their 1.4 GHz flux densities. Again, such steeply rising spectra provide strong evidence that the (sub-)millimeter emission is thermal emission from warm dust.

We have considered these sources in the context of the radio-to-FIR correlation for star-forming galaxies, as quantified in the 1.4-to-250 GHz spectral index, $\alpha_{250}^{1.4}$ (Fig. 3). For J0301+0020, the $\alpha_{250}^1$ value is clearly below that expected for a star-forming galaxy. In this case, it seems likely that the radio emission relates to the AGN activity. For J0756+4104, the $\alpha_{250}^1$ value is within the range defined by star-forming galaxies, while for J1044–0125 the lower limit to $\alpha_{250}^1$ is at least consistent with a star-forming galaxy.

Given the interest in coeval massive black hole–spherical galaxy formation, it is instructive to consider what the properties of these sources would be if the 250 GHz emission were a result of dust heated by a starburst. Using the relations between 250 GHz flux density, FIR luminosity, and star formation rates in Omont et al. (2003), based on typical spectra of low-redshift ultraluminous infrared galaxies (i.e., Arp 220), leads to $L_{\text{FIR}} = 2.8 \times 10^{12} L_\odot$ for J0301+0020, $1.4 \times 10^{13} L_\odot$ for J0756+4104, and $7 \times 10^{12} L_\odot$ for J1044–0125, as well as as massive (greater than $5 M_\odot$) star formation rates of 200, 1000, and 500 $M_\odot$ yr$^{-1}$, respectively. At these extreme star formation rates, most of the stars in a large spherical galaxy could form in a dynamical time of $10^8$ yr. However, it should again be stressed that these rates assume the dust is heated by star formation, as opposed to being heated by the AGN itself.

5.3. X-Ray–Loud, Radio-Quiet Jets at High Redshift?

We have not detected radio emission from the reported X-ray “jet” in J1306+0336 (Schwartz 2003). The implied upper limit to the magnetic field (3 $\mu$G) is more than an order of magnitude below typical magnetic field values in powerful radio jets. Perhaps the simplest conclusion from these results is that the X-ray feature is not IC emission from a jet emanating from J1306+0336.

It is possible that such a jet could be IC X-ray–loud and still be radio-quiet, even for strong magnetic fields, due to the different radiative lifetimes of the particles involved. The spectral peak of the cosmic microwave background behaves as $1.6 \times 10^{11}(1+z)$ Hz, such that observations at 1 keV are sensitive to electrons with Lorentz factors, $\gamma_e \sim 1000$, independent of redshift. The radiative lifetime of such electrons at $z \sim 6$ is $\sim 1.0 \times 10^7$ yr. For comparison, observations of a $z \sim 6$ jet at 1.4 GHz probe electrons with $\gamma_e \sim 7000$, assuming a 50 $\mu$G magnetic field, corresponding to a radiative lifetime $\sim 1.3 \times 10^6$ yr. If particle acceleration ceased between $10^6$ and $10^7$ yr ago, then the exponential cut-off at high energies in the relativistic particle population might lead to the situation observed, i.e., an X-ray–loud but radio-quiet jet. More sensitive X-ray observations and lower frequency radio observations are required to test this interesting possibility.

5.4. Overdensities of Radio Sources toward the Highest Redshift QSOs

For the highest redshift QSO in our sample, J1030+0524 at $z = 6.28$ (Fig. 2), we find four fairly bright radio sources ($S_{1.4} > 200 \mu$Jy) within 1$'$ of the QSO, one of which is an arcminute-scale powerful double (FR II) radio source. Note that for a 2$'$ field one expects only 0.5 sources by chance with $S_{1.4} > 200 \mu$Jy. It seems unlikely that the sources are at the redshift of the QSO, since an arcminute-scale double radio galaxy has never been detected beyond $z \sim 3$ (Carilli et al. 1997). Interestingly, the highest redshift QSO known, J1148+5251 at $z = 6.4$ (Fan et al. 2003), also has two bright radio sources (8 and 70 mJy at 1.4 GHz) within 1$'$ of the QSO position (Bertoldi et al. 2003).

A possible explanation for the excess radio source density in the fields of the two highest redshift QSOs is that the radio sources are in a group or cluster that happens to lie along the line of sight. If this is the case, then gravitational lensing by the cluster could magnify the QSO emission by a factor 2 or so without giving rise to arcsecond-scale distortions in the optical images of the QSOs.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. M. A. S. acknowledges support of NSF grant AST 00-71091. One of the authors (A.O.P.) thanks Jacqueline van Gorkom and David Helfand for providing comments on earlier versions of this paper, and Mark Dijkstra, Suvi Gezari, Stephen Muchovej, and Pietro Reviglio for many informative conversations about galaxy evolution.

REFERENCES

Anderson, S. F., et al. 2001, AJ, 122, 503
Andreon, P., Cristiani, S., Grazian, A., La Franca, F., & Goldschmidt, P. 2003, AJ, 125, 444
Becker, R. H., et al. 2001, AJ, 122, 2850
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Beelen, A. 2003, in preparation
Benford, D. J., Cox, P., Omont, A., Phillips, T. G., & McMahon, R. G. 1999, ApJ, 518, L65
Bertoldi, F., & Cox, P. 2002, A&A, 384, 11L
Bertoldi, F., et al. 2003, in preparation
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. T. 2002, Phys. Rep., 369, 111
Brandt, W. N., et al. 2002, ApJ, 569, L5
Brázdil, A. H., & Schwab, F. R. 1999, in ASP Conf. Ser. 180, Bandwidth and Time-Average Smearing in Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco: ASP), 371
Carilli, C. L., Bertoldi, F., Omont, A., Cox, P., McMahon, R. G., & Isaak, K. G. 2001a, AJ, 122, 1679
Carilli, C. L., et al. 2001b, ApJ, 555, 625
———. 2002a, ApJ, 575, 145
Carilli, C. L., Gnedin, N. Y., & Owen, F. 2002, ApJ, 577, 22
Carilli, C. L., et al. 2002b, AJ, 123, 1838
Carilli, C. L., Menten, K. M., & Yun, M. S. 1999, ApJ, 521, L25
Carilli, C. L., Rottgering, H., Miley, G., Pentericci, L., & Harris, D. 1997, in The Most Distant Radio Galaxies, ed. H. Rottgering, P. Best, & M. Lehnert (Amsterdam: Royal Dutch Acad.), 123

[1] Shioya et al. (2002) have found a faint optical galaxy located within 1/9 of the quasar. They suggest that the QSO may be gravitationally magnified by this galaxy by a factor of about 2. We have not corrected for this magnification in the calculations above.

[2] Note that for $z = 6.28$ (Fig. 2), we find four fairly bright radio sources within 1$'$ of the QSO, one of which is an arcminute-scale powerful double (FR II) radio source. Note that for a 2$'$ field one expects only 0.5 sources by chance with $S_{1.4} > 200 \mu$Jy. It seems unlikely that the sources are at the redshift of the QSO, since an arcminute-scale double radio galaxy has never been detected beyond $z \sim 3$ (Carilli et al. 1997). Interestingly, the highest redshift QSO known, J1148+5251 at $z = 6.4$ (Fan et al. 2003), also has two bright radio sources (8 and 70 mJy at 1.4 GHz) within 1$'$ of the QSO position (Bertoldi et al. 2003).
No. 1, 2003

OBSERVATIONS OF $z > 5$ QSOs

23

Carilli, C. L., & Taylor, G. B. 2002, ARA&A, 40, 319
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
———. 2000, ApJ, 530, 618
Condon, J. J. 1992, ARA&A, 30, 575
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A.,
Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Condon, J. J., & Yin, Z. F. 1990, ApJ, 357, 97
Cotton, W. D. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio
Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San
Francisco: ASP), 357
Cox, P., et al. 2002, A&A, 387, 406
Crawford, T., Marr, J., Partridge, B., & Strauss, M. A. 1996, ApJ, 460, 225
Deutsch, E. W. 1999, AJ, 118, 1882
Djorgovski, S. G., Castro, S., Stern, D., & Mahabal, A. A. 2000, ApJ, 560,
L5
Elvis, M., et al. 2002, A&A, 387, 406
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Fomalont, E. B. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio
Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San
Francisco: ASP), 301
Fomalont, E. B., et al. 2003, in preparation
Goodrich, R. W., et al. 2001, ApJ, 561, L23
Gregg, M. D., Becker, R. H., White, R. L., Helfand, D. J., McMahon,
R. G., & Hook, I. M. 1996, AJ, 112, 407
Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633
Harris, D. E., & Grindlay, J. E. 1979, MNRAS, 188, 25
Hooper, E. J., Impey, C. D., Foltz, C. B., & Hewett, P. C. 1995, ApJ, 445,
62
Isaak, K., Priddey, R. S., McMahon, R. G., Omont, A., Peroux, C., Sharp,
R. G., & Withington, S. 2002, MNRAS, 329, 149
Ivezic, Z., et al. 2002, AJ, 124, 2364
Iwata, I., Ohta, K., Nakanihki, K., Kohno, K., & McMahon, R. 2001,
PASJ, 53, 871
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R.
1989, AJ, 98, 1195
Kreysa, E., et al. 1998, Proc. SPIE, 3357, 319
Lacy, M., Laurent-Muehleisen, S. A., Ridgway, S. E., Becker, R. H., &
White, R. L. 2001, ApJ, 551, L17
Magorrian, J., et al. 1998, AJ, 115, 2285
Maiolino, R., Mannucci, F., Baia, C., Gennari, S., & Oliva, E. 2001, A&A,
372, L5
Miller, L., Peacock, J. A., & Mead, A. R. G. 1990, MNRAS, 244, 207
Miller, N. A., & Owen, F. N. 2001, AJ, 121, 1903
Maiolino, R., Bertoldi, F., Cox, P., Carilli, C. L., Priddey, R. S.,
McMahon, R. G., & Isaak, K. G. 2003, A&A, 398, 857
Maiolino, R., Cox, P., Bertoldi, F., McMahon, R. G., Carilli, C., & Isaak,
K. G. 2001, A&A, 374, 371
Peacock, J. A., Miller, L., & Longair, M. S. 1986, MNRAS, 218, 265
Pentericci, L., et al. 2002, AJ, 123, 2151
Per, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M.,
Lupton, R. H., & Ivezic, Z. 2005, AJ, 125, 1559
Polatidis, A. G., & Conway, J. E. 2003, Publ. Astron. Soc. Australia, 20, 69
Rusin, M., et al. 2003, in preparation
Schmidt, M., van Gorkom, J. H., Schneider, D. P., & Gunn, J. E. 1995, AJ,
109, 473
Schneider, D. P., van Gorkom, J. H., Schmidt, M., & Gunn, J. E. 1992, AJ,
103, 1451
Schwartz, D. A. 2003, ApJ, 571, L71
Sharp, R. G., McMahon, R. G., Irwin, M. J., & Hodgkin, S. T. 2001,
MNRAS, 326, L45
Shields, G. A., Gebhardt, K., Salviander, S., Wills, B. J., Xie, B.,
Brotherton, M. S., Yuan, J., & Dietrich, M. 2003, ApJ, 583, 124
Shioya, Y., et al. 2002, PASJ, 54, 975
Sopp, H., & Alexander, P. 1991, MNRAS, 251, 14P
Stern, D., Djorgovski, S. G., Perley, R. A., de Carvalho, R. R., & Wall,
J. W. 2000a, AJ, 119, 1526
Stern, D., Spinrad, H., Eisenhard, P., Bunker, A., Dawson, S., Stanford,
S. A., & Elston, R. 2000b, ApJ, 533, L75
Stocke, J., Morris, S. L., Weymann, R. J., & Foltz, C. B. 1992, ApJ, 396,
487
Tremaine, S., et al. 2002, ApJ, 574, 740
Visnovsky, K. L., Impey, C. D., Foltz, C. B., Hewett, P. C., Weymann,
R. J., & Morris, S. L. 1992, ApJ, 391, 560
York, D. G., et al. 2000, AJ, 120, 1579
Yun, M. S., & Carilli, C. L. 2002, ApJ, 568, 88
Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803
Zheng, W., et al. 2000, AJ, 120, 1607
Zylka, R. 1998, MOPSI User’s Manual (Grenoble: IRAM)