A 250 GHz SURVEY OF HIGH-REDSHIFT QUASARS FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We present observations at 250 GHz (1.2 mm), 43 GHz, and 1.4 GHz of a sample of 41 QSOs at \( z > 3.7 \) found in the Sloan Digital Sky Survey. We detect 16 sources with a 250 GHz flux density greater than 1.4 mJy. The combination of centimeter and millimeter wavelength observations indicates that the 250 GHz emission is most likely thermal dust emission. Assuming a dust temperature of 50 K, the implied dust masses for the 16 detected sources are in the range 1.5–5.9 \( \times 10^{8} \) \( M_{\odot} \), and the dust emitting regions are likely to be larger than 1 kpc in extent. The radio-through-optical spectral energy distributions for these sources are within the broad range defined by lower redshift, lower optical luminosity QSOs. We consider possible dust heating mechanisms, including UV emission from the active galactic nucleus (AGN) and a starburst concurrent with the AGN, with implied star formation rates between 500 and 2000 \( M_{\odot} \) yr\(^{-1}\).

Subject headings: dust, extinction — galaxies: active — galaxies: evolution — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

On-line material: machine-readable table

1. INTRODUCTION

The existence of massive black holes at the centers of galaxies has long been predicated on consideration of the energetics of active galactic nuclei (AGNs): accretion of matter onto a massive black hole is an order of magnitude more efficient at converting mass into energy than is stellar nucleosynthesis (Begelman, Blandford, & Rees 1984). The last few years have seen an explosion of dynamical evidence for massive black holes at the center of galaxies, and in the direct measurement of black hole masses from the dynamics of circumnuclear regions (Richstone et al. 1998; Miyoshi et al. 1995; Ghez et al. 1998; Genzel et al. 2000; Tanaka et al. 1995). These observations indicate that the overwhelming majority of spheroidal galaxies in the nearby universe contain massive black holes (Kormendy 2000). Moreover, a clear correlation has been found between the black hole mass and the velocity dispersion of the stars in the spheroid (Gebhardt et al. 2000; Ferrarese & Merritt 2000). This correlation suggests a “causal connection between the formation and evolution of the black hole and the bulge” (Gebhardt et al. 2000; Kormendy 2000; Richstone et al. 1998).

Support for this general idea comes from: (i) the observed space density of high-redshift quasi-stellar objects (QSOs), which would require a massive black hole in most low-z spheroidal galaxies (Kormendy & Ho 2000), (ii) the observation of similar rapid increases in the space densities of AGNs and starburst galaxies from \( z = 0 \) to \( z = 2 \) (Boyle & Terlevich 1998; Blain et al. 1999), and (iii) the observation of coeval AGNs and star formation activity in some nearby nuclear starburst galaxies (Rigopoulou et al. 1999; Carilli, Wrobel, & Ulvestad 1999b). On the other hand, the QSO population shows an abrupt turn-over in the comoving number density at \( z \geq 3 \) (Schmidt, Schneider, & Gunn 1995a; Kennefick, Djogovski, & de Carvahlo 1995; Fan et al. 2001b). It is unclear whether such a turnover exists in the starburst population (Blain et al. 1999; Dunlop 2000). Also, questions remain about the relative timescales for the commencement and duration of the starburst and AGN processes (Sanders & Mirabel 1996), and the origin at very high redshift of the “seed” black hole (Richstone et al. 1998).

A particularly intriguing observation that has fueled the debate over coeval starbursts and AGNs at high redshift is the recent detection at 250 GHz of copious thermal dust emission from high-redshift QSOs by Omont et al. (1996a). Omont et al. observed a sample of \( z > 4 \) QSOs from the Automatic Plate Measuring (APM) survey and found that six of 16 sources show dust emission with 250 GHz flux densities of 3 mJy or greater, with implied far-infrared (FIR) luminosities, \( L_{\text{FIR}} > 10^{12} L_{\odot} \), and dust masses \( \geq 10^{8} M_{\odot} \). Follow-up observations of three of these dust-emitting QSOs revealed CO emission as well, with implied molecular gas masses \( \approx 10^{10} M_{\odot} \) (Guilloteau et al. 1997, 1999; Ohta et al. 1996; Omont et al. 1996b; Carilli, Menten, & Yun 1999a).

Two different mechanisms have been proposed for heating the dust in high-redshift QSOs. Given the large dust and gas masses, Omont et al. (1996a) make the circumstantial argument that star formation is inevitable, and hence that the dominant dust heating mechanism may be star formation. Supporting evidence comes from deep radio observations at 1.4 GHz, which show that the ratio of the radio continuum to submillimeter continuum luminosity from some of these sources is consistent with the well-established radio-to-far-IR correlation for low-redshift star-forming galaxies (Yun et al. 2000). And Omont et al. (2001) make the simple point that copious star formation is required in order to produce the dust. The implied star formation rates are so extreme, \( \geq 10^{8} M_{\odot} \) year\(^{-1}\), that a significant fraction of the stars in the QSO host galaxy can be formed in less than 10\(^{9}\) yr.
the dust is distributed in a kiloparsec-scale warped disk, dust heating on kpc scales is accomplished by assuming that on parsec scales, the rest-frame FIR emission must be due to dust which is thought to arise in a hot (10^6 K) and dense (10^2 cm^-3) region. Hence, while the optical “big blue bump” emission is thought to arise in a hot (10^4 K) accretion disk on parsec scales, the rest-frame FIR emission must be due to warm dust on kiloparsec scales. In the Sanders et al. (1989) model for AGN-powered IR emission from QSOs, dust heating on kpc scales is accomplished by assuming that the dust is distributed in a kiloparsec-scale warped disk, thereby allowing UV radiation from the AGN to illuminate the outer regions of the disk. An alternate mechanism for large-scale dust heating has been proposed by Maloney, Hollenbach, & Tielens (1996) in which hard X-rays penetrate the very high column density gas in the vicinity of the AGN.

In this paper we present extensive observations at centimeter and millimeter wavelengths of a sample of high-redshift QSOs from the Sloan Digital Sky Survey (SDSS; York et al. 2000). Our observations include sensitive radio continuum imaging at 1.4 and 43 GHz with the Very Large Array (VLA), and photometry at 250 GHz using the Max-Planck Millimeter Bolometer array (MAMBO) at the IRAM 30 m telescope. These observations are a factor 3 more sensitive than previous studies of high-redshift QSOs at these frequencies (Schmidt et al. 1995b; Omont et al. 1999).

Alternatively, the dust may be heated by radiation from the AGN. Sanders et al. (1989) argue that radiation from the AGN is the dominant dust heating mechanism, since in most cases it requires the absorption of only a small fraction (≤ 20%) of the AGN UV luminosity by dust, even for the high-redshift sources (Carilli et al. 2000). An important constraint on AGN dust heating models is provided by the minimum size of about 1 kpc for the dust emission region one derives from the observed luminosity and dust temperature (see § 3). Hence, while the optical “big blue bump” emission is thought to arise in a hot (10^4 K) accretion disk on parsec scales, the rest-frame FIR emission must be due to warm dust on kiloparsec scales. In the Sanders et al. (1989) model for AGN-powered IR emission from QSOs, dust heating on kpc scales is accomplished by assuming that the dust is distributed in a kiloparsec-scale warped disk, thereby allowing UV radiation from the AGN to illuminate the outer regions of the disk. An alternate mechanism for large-scale dust heating has been proposed by Maloney, Hollenbach, & Tielens (1996) in which hard X-rays penetrate the very high column density gas in the vicinity of the AGN.

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1996a; Stern et al. 2000). Details of the multifrequency radio continuum imaging will be given elsewhere (Rupen et al. 2001, in preparation). In this paper we present the radio results that are relevant to the analysis and interpretation of the dust continuum emission. We compare the dust emission properties of these sources with their optical and radio continuum and spectral properties, and with those of lower redshift sources. We assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$, $\Lambda = 0$, and we define the spectral index, $\alpha$, as a function of frequency, $\nu$, as: $S_\nu \propto \nu^\alpha$.

2. THE SAMPLE

The QSO sample is the result of optical spectroscopy of objects of unusual color from the northern Galactic Cap and the Southern Equatorial Stripe of the SDSS. The survey has yielded over 100 QSOs with $z \geq 3.6$, including eight of the 10 highest redshift QSOs known (Fan et al. 1999, 2000, 2001a, 2001b; Schneider et al. 2000a, 2000b, 2001; Zheng et al. 2000).

We observed 41 of these high-redshift QSOs, taken from Fan et al. (1999), Fan et al. (2000), and Schneider et al. (2000a). The QSO properties are listed in Table 1. The observed sources span a range of $M_B = -26.1$ to $-28.8$, and a redshift range of $z = 3.6$ to 5.0. Comparative numbers for the APM sample of 16 QSOs observed by Omont et al. (1996a) are $M_B = -26.8$ to $-28.5$, and $z = 4.0$ to 4.7.

The sources in Table 1 have a mean optical spectral power law index, $\alpha = -0.67$, with a dispersion of 0.29, a mean redshift, $z = 4.20$, with a dispersion of 0.44, and a mean absolute blue magnitude, $M_B = -27.07$, with a dispersion of 0.57. We can compare these values to those of the 39 QSOs at $z > 3.6$ from the SDSS Fall Equatorial stripe presented in Fan et al. (2001b). The Fall Equatorial stripe sample is a statistically complete sample of high-$z$ QSOs selected according to the same criteria as the sources listed in Table 1. The Fall Equatorial stripe sample has a mean optical spectral power law index, $\alpha = -0.79$, with a dispersion of 0.34, a mean redshift, $z = 4.06$, with a dispersion of 0.39, and a mean absolute blue magnitude, $M_B = -26.82$, with a dispersion of 0.58. Hence, within the scatter of the distributions, the sources in Table 1 can be considered representative of the complete high-$z$ QSO sample from the Fall Equatorial stripe.

3. OBSERVATIONS

Observations were made using MAMBO (Kreysa et al. 1999) at the IRAM 30 m telescope on Pico Veleta in Spain, in 1999 December and 2000 February. MAMBO is a 37 element bolometer array sensitive between 190 and 315 GHz. The half-power sensitivity range is 210–290 GHz, but the overall profile is asymmetric, with a sharp rise in sensitivity at low frequency, then a gradual decrease in sensitivity to higher frequency. Convolving the frequency response of the bolometer array with the atmospheric transmission curve (which also decreases with increasing frequency), and with the rising spectrum of a typical dust emitting source at high redshift, leads to an effective central frequency of 250 GHz. The beam for the feed horn of each bolometer is matched to the telescope beam of 10′.6, and the bolometers are arranged in a hexagonal pattern with a beam separation of 22′′. 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 MOPSIS software package of the Max-Planck-Institut für Radioastronomie (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 ranged between 0.23 and 0.36. 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 remaining bolometers were subtracted from all the bolometer signals. The total on-target plus off-target observing times for the sources are listed in Table 1. The typical rms sensitivity in 1 hour was 0.5 mJy for the on-source bolometer beam.

The 1.4 GHz VLA observations were made in the A (30 km) and BnA (mixed 30 km and 10 km) configurations on 1999 July 8, August 14, September 30, and October 8 using a total bandwidth of 100 MHz with two orthogonal polarizations. Each source was observed for a total of 2 hours, with short scans made over a large range in hour angle to improve Fourier spacing coverage. Standard phase and amplitude calibration were applied, as well as self-calibration using background sources in the telescope beam. The absolute flux density scale was set using observations of 3C 48. The final images were generated using the wide field imaging and deconvolution capabilities of the AIPS task IMAGR. The theoretical rms noise value is between 20 and 30 µJy beam$^{-1}$, depending on the range of telescope elevations over which the source was observed, and for about half the sources the measured noise values are in this range. For the remaining sources, the noise levels are significantly higher due to side-lobe confusion by bright sources. The Gaussian restoring CLEAN beams were between 1.5′ and 3′ FWHM.

Some of the sources had previous VLA detections as part of the FIRST survey (SDSS J1053–0016, SDSS J1235–0003, SDSS J1412–0101; Becker, White, & Helfand 1995). We reobserved these sources, and obtained the same flux densities to within 15% of the FIRST values in all cases.

We chose four of the dust emitting sources (SDSS J0150+0041, SDSS J0255+0048, SDSS J0338+0021, SDSS J1112+0050) as a subsample for 43 GHz observations, in order to search for high-frequency, flat-spectrum emission that might be synchrotron self-absorbed at 1.4 GHz. Observations were made on 2000 February 20 using the VLA in the B (10 km) configuration in standard continuum mode. Fast switching phase calibration was employed (Carilli & Holdaway 1999), and observing times were 0.5 hr at 43 GHz, resulting in a rms noise of 0.35 mJy beam$^{-1}$.

4. RESULTS AND ANALYSIS

The results of our 250 GHz survey of high-redshift QSOs are given in Table 1. These include: (i) flux densities at 250 GHz ($S_{250}$; col. [3]), (ii) flux densities at 1450 Å ($S_{1450}$; col. [4]), (iii) flux densities at 1.4 GHz at the position of the optical QSO ($S_\lambda$; col. [5]), (iv) absolute blue magnitudes (col. [6]; Fan et al. 1999, 2000), (v) observing time at 250 GHz, and (vi) notes on source properties (col. [8]). In the following analysis we consider a source with a measured flux density 3 times greater than the rms noise (3 $\sigma$) to be a valid detection. Such sources are marked with an asterisk (*) in Table 1. We should also point out that the millimeter, centimeter, and optical observations were not simultaneous.
We detect 16 of the 41 sources at \( S_{250} \geq 1.4 \) mJy. Only four of the sources have \( S_{250} \geq 3 \) mJy. A higher detection rate at the limit of \( S_{250} \geq 3 \) mJy was found in the survey of the APM QSO sample by Omont et al. (1996a, 1996b), in which they detected six of 16 sources. This difference in detection rates appears to be statistically significant: if there were a true universal fraction of 10% of high-\( z \) QSOs with \( S_{250} \geq 3 \) mJy, then there is about a 1% chance that in 16 objects six or more would meet this criterion. The optical/near-IR color selection criteria for the APM sample are similar to those of the SDSS sample. The one significant difference is that the rest frame blue luminosities for the APM are somewhat higher on average (by about 0.5 mag), than those of the SDSS sources in Table 1 (see § 2). However, given the lack of a strong correlation between \( M_B \) and \( S_{250} \) (see Fig. 2 below), the cause for the possibly higher detection rate at high \( S_{250} \) for the APM sample relative to the SDSS sample remains unknown. Further observations of the millimeter properties of high-\( z \) QSOs that are in progress may clarify this issue (Omont et al. 2001).

Considering the radio properties of the sources in Table 1, nine sources in Table 1 are detected at 1.4 GHz at \( z \geq 3 \). For the nine radio-detected sources in Table 1, eight are unresolved, with size limits (FWHM) of about 1″, while SDSS J0232—0000 is possibly extended, with a size \( \sim 1.3″ \). Miller, Peacock, & Mead (1990) suggested a division between radio-loud and radio-quiet QSOs at a rest frame 5 GHz spectral luminosity of \( 10^{33} \) erg s\(^{-1}\) Hz\(^{-1}\). This corresponds to a flux density of \( S_{1.4} = 1 \) mJy for a source at \( z = 4.2 \) assuming a radio spectral index of \( -0.8 \). According to this criterion, two of 16 SDSS QSOs detected at 250 GHz can be considered radio-loud (SDSS J1235—0003 and SDSS J1412—0101), while two of 25 sources not detected at 250 GHz can be considered radio-quiet (SDSS J0153—0011 and SDSS J1053—0016). Both fractions are consistent with the value of 10% of optically selected high-redshift QSOs being radio loud according to this criterion (Schmidt et al. 1995b; Stern et al. 2000).

4.1. Evidence for Thermal Dust Emission at 250 GHz

We first address the question of whether the 250 GHz emission is thermal dust emission or nonthermal synchrotron radiation. For most of the sources detected at 250 GHz, the 1.4 GHz flux density (or upper limit) is an order of magnitude or more below the 250 GHz flux density. Two of the sources have 1.4 GHz flux densities comparable to, or larger than, the 250 GHz flux density. The source SDSS J1412—0101 has \( S_{1.4} = 3.9 \) mJy and \( S_{250} = 4.5 \) mJy. Observations of this source at 8.4 GHz revealed a 1.1 mJy source (Rupen et al. 2001, in preparation), such that the centimeter source has a falling spectrum of index \( -0.7 \), making it unlikely that the millimeter continuum is a continuation of the synchrotron emission spectrum from the AGN. The source SDSS J1235—0003 has \( S_{250} = 1.6 \) mJy, and \( S_{1.4} = 4.5 \) mJy. Observations on the same day as those at 1.4 GHz found a 5 GHz flux density of \( S_5 = 17 \) mJy, and a 15 GHz flux density of \( S_5 = 7 \) mJy. The source was unresolved at all frequencies. In this case, it remains possible that the 250 GHz emission is nonthermal.

It is possible that emission from a compact AGN could be synchrotron self-absorbed at low frequency. To check this idea, we performed 43 GHz observations of four of the 250 GHz detected sources, as listed in § 3; none of the sources were detected. Assuming a 2 \( \sigma \) upper limit of 0.7 mJy at 43 GHz implies a rising spectrum between 43 and 250 GHz of index \( \alpha > 0.5 \). While this limit is well below the index expected for thermal dust emission (\( \alpha_{250} \approx 3 \) for a source at \( z = 4.2 \)), it does argue against compact, synchrotron self-absorbed sources as the origin of the 250 GHz emission, as such sources typically show millimeter spectral indices \( \alpha_{\text{mm}} \approx 0 \pm 0.3 \) (Sanders et al. 1989). In the following discussion we will assume that the 250 GHz emission from the sources in Table 1 is thermal dust emission, with the possible exception of SDSS J1235—0003. These data imply that in millimeter surveys of high-redshift QSOs, the fraction of flat-spectrum, radio-loud AGNs with synchrotron emission extending into the millimeter regime is at most a few percent. Studies of lower redshift QSOs show that the fraction of flat-spectrum radio-loud sources in optically selected samples is also only a few percent (Hopkins et al. 1998).

A source with \( S_{250} = 1 \) mJy at \( z = 4.2 \) and a dust spectrum of the type seen in the low-redshift starburst galaxy Arp 220 (corresponding roughly to a modified blackbody spectrum of dust emissivity index \( = 1 \) and temperature \( = 50 \) K) has an FIR luminosity, \( L_{\text{FIR}} \), of \( 1.1 \times 10^{12} L_\odot \), where \( L_{\text{FIR}} \) corresponds to the integrated luminosity between 42 and 122 \( \mu \)m (Condon 1992). If we assume that star formation is the mechanism giving rise to the dust emission, we can use the relations in Omont et al. (2001) and Carilli et al. 2001, in preparation, to derive the dust mass, \( M_D \), and total star formation rate, \( \dot{S}_F \), from \( S_{250} \). The relations are \( M_D = 1.1 \times 10^8 \times S_{250} \ M_\odot \) and \( \dot{S}_F = 360 \times S_{250} \ M_\odot \) yr\(^{-1}\), with \( S_{250} \) in mJy. This again assumes \( T_D = 50 \) K.

A conservative lower limit to the solid angle, \( \Omega_D \), of a dust emitting source can be derived from the observed flux density making the extreme assumption of optically thick emission (Downes et al. 1999). Assuming \( T_D \approx 50 \) K (Benford et al. 1999) and \( z = 4 \), leads to: \( \Omega_D > 0.0043 S_{250} \) arcsec\(^2\), where \( S_{250} \) is the 250 GHz flux density in mJy. This implies absolute lower limits to the angular diameters of the sources in Table 1 between 0.08 and 0.15, corresponding to physical sizes of 0.5 to 1 kpc. Given the likelihood that the observed 250 GHz emission is from an optically thin graybody, it is almost certain that the sources are larger than these lower limits. Also, this size corresponds to the total emitting area. Multiple smaller regions within the 10′6 telescope beam are certainly possible (see § 5). Observations at millimeter wavelengths with subarcsecond resolution are required to constrain the source sizes.

4.2. Trends with Redshift and \( M_B \)

Figure 1 shows values of \( S_{250} \) versus redshift for the 41 QSOs in Table 1. The solid line is the expected flux density of Arp 220. This curve shows clearly the effect of the large “inverse \( K \)” correction for thermal dust emission at millimeter and submillimeter wavelengths, with the observed flux density of a source such as Arp 220 remaining roughly constant over the observed redshift range (Blain & Longair 1993). There is an interesting trend for a lower detection rate for the SDSS QSOs with increasing redshift: for \( z < 4.4 \) we detect 14 of 28 sources while for \( z > 4.4 \) we detect two of 13 sources. A larger sample of sources, over a larger redshift range, is required to verify this trend.

Figure 2 shows values of \( L_{\text{FIR}} \) versus \( M_B \) for the 41 QSOs in Table 1. At the limit of \( L_{\text{FIR}} > 1.8 \times 10^{12} L_\odot \), we detect...
nine of 23 sources with $M_B > -27$, and seven of 17 sources with $M_B < -27$. This is consistent with the lack of a strong correlation between $M_B$ and $L_{FIR}$ in the lower redshift, lower optical luminosity sample of Palomar-Green (PG) QSOs presented by Sanders et al. (1989; see also Chini, Kreysa, & Biermann 1989), and it is indicative of the large scatter in the dust properties of QSOs in general (see Fig. 4 below), and the relatively narrow range in $M_B$ in Figure 2.

4.3. Comparison to the Radio-to-FIR Correlation for Star-Forming Galaxies

Figure 3 shows the relationship between redshift and the 250 to 1.4 GHz spectral index for a star-forming galaxy taken from the model of Carilli & Yun (2000) based on 17 low-redshift galaxies (roughly equivalent to a modified blackbody spectrum with $T_B = 50$ K and dust emissivity index $= 1.5$). The relationship relies on the tight radio-to-FIR correlation seen for star-forming galaxies in the nearby universe (Condon 1992). The dotted curve gives the rms scatter for the 17 galaxies. The solid symbols are the results for the SDSS QSOs detected at 250 GHz, while the open symbols are for the APM QSO sample from Omont et al. (1996a) and Yun et al. (2000). The arrows indicate nondetections in the radio, and hence lower limits to the spectral index. On this diagram, a point located below the curve would indicate a source that is radio-loud relative to the standard radio-to-FIR correlation for star-forming galaxies, while a point located above the curve would indicate a source which is radio-quiet relative to this relationship (Condon 1992). The lower limits are below the curve, and hence they are consistent with a star-forming galaxy spectrum, although a factor 2 better sensitivity at 1.4 GHz is required to provide more stringent constraints in this regard.

The radio-detected QSOs fall below the star-forming galaxy curve in Figure 3. Two of the sources (SDSS J1235−0003 and SDSS J1412−0101) are clearly radio-loud AGNs (see § 4). The fainter radio detections may indicate radio emission from the AGNs, but at a level below that required for the source to be defined as radio loud according to Miller et al. (1990). An alternative explanation
4.4. Spectral Energy Distributions

Figure 4 shows the mean radio-through-optical spectral energy distributions (SEDs) for radio-loud and radio-quiet QSOs derived from observations of a large sample of PG QSOs by Sanders et al. (1989). The solid curve shows the SED for radio-loud QSOs, while the dashed curve shows the SED for radio-quiet QSOs. The hatched regions indicate the scatter in the measured values for the PG sample. Note that the QSOs in the PG sample are typically an order of magnitude less luminous in the rest-frame UV than the high-redshift sources, with most of the PG sources in the range $M_B = -23$ to $-27$.

The data points in Figure 4 show the results for the millimeter detections in the SDSS and APM QSO samples, normalized by their blue spectral luminosities. The normalized millimeter detections all fall within the range defined by the PG sample. The upper limits for the nondetected sources at 250 GHz would fall at the low end of the range defined by the Sanders et al. (1989) SEDs.

The two radio-loud SDSS QSOs according to the Miller et al. (1990) definition detected at 250 GHz are clearly evident in the normalized SEDs in Figure 4, while the normalized upper limits for the nondetected sources at 1.4 GHz are consistent with the Sanders et al. (1989) radio-quiet QSO SED. The remaining three radio-detected SDSS QSOs in Figure 4 fall in-between the radio-loud and radio-quiet SEDs, as do the QSOs from the APM sample. The large gap between the radio-loud and radio-quiet SEDs from Sanders et al. (1989), as reproduced in Figure 4, represents the possible bimodality of the radio properties of QSOs, as suggested by Stocke et al. (1992). The reality of this bimodality has been called into question recently by White et al. (2000), and Stocke et al. (1992) show that the bimodality is less clearly delineated for high blue luminosity QSOs relative to lower luminosity sources. Further analysis of the radio detections within this sample, including studies of radio spectra and spatial structure, will be given in Rupen et al. (2001, in preparation).

4.5. Broad Absorption Lines

Omont et al. (1996a) suggest a possible correlation between the broad absorption line (BAL) phenomenon and thermal dust emission in QSOs. In the APM sample of Omont et al. (1996a), two of six sources detected at 250 GHz have BAL features. The BAL fraction for high-$z$ QSOs in general is about 10% (Fan et al. 2001a).

Our data on the SDSS sample provide only marginal support for this idea, with four of the 16 sources detected at 250 GHz showing evidence for BAL features, as compared to three sources with BALs out of the 25 nondetected sources at 250 GHz.

5. DISCUSSION

We detect 16 of 41 high-redshift QSOs from the SDSS survey with $S_{250} \geq 1.4$ mJy. Assuming $T_D = 50$ K, we show that the 250 GHz emission is most likely thermal emission from warm dust on a scale of more than 1 kpc in the host galaxy of the QSO. The implied dust masses for the sources are in the range of $1.5 - 5.9 \times 10^8 M_\odot$. If the dust is heated by star formation, the star formation rates are in the range 500 to 2000 $M_\odot$ yr$^{-1}$. Sensitive radio observations show a radio-loud fraction (according to the definition of Miller et al. 1990) for the sample as a whole of 10%, consistent with previous observations of high-redshift QSOs, with no clear relationship between dust emission and radio-loud QSOs.

The blue-normalized optical-through-radio SEDs for these sources are within the broad range delineated by the PG sample of lower redshift, lower luminosity QSOs (Fig. 4). This result suggests that for the sources detected at 250 GHz, we are not seeing a major new broadband spectral emission “feature” in high-redshift QSOs relative to the SEDs of lower redshift QSOs. Conversely, the blue-normalized limits for the nondetections at 250 GHz in the SDSS high-$z$ QSO sample are at the low end of the distribution defined by low-$z$ QSOs, leaving open the possibility of a population of high-$z$ sources which are underluminous in the rest frame submillimeter relative to the SED of low-$z$ QSOs. While this result could be used to argue against models involving a major burst of star formation in the host galaxies of high-redshift QSOs, the large scatter in the millimeter SEDs could effectively mask such a phenomenon. Also, Sanders et al. (1989) point out that from centimeter to submillimeter wavelengths, the radio-quiet SED model based on the PG QSO sample is consistent with the observed SEDs for star-forming galaxies.

A number of studies have addressed the question of the
dust heating mechanism in high-z AGNs by SED modeling, with mixed results. Radiative transfer models by Rowan- Robinson (2000) suggest that the observed SEDs at rest frame wavelengths greater than 50 μm are consistent with an extreme starburst model for most high-redshift dust emitting QSOs. On the other hand, models by Andreani, Francescini, & Granato (1999) and Willott, Rawlings, & Jarvis (1999) suggest that the dust emission spectra from 3 to 30 μm can be explained by dust heated by the AGN. The centimeter-to-millimeter SEDs may also indicate star formation in a few sources (Yun et al. 2000); however, the radio limits in most sources are inadequate to constrain such a model (Fig. 3). Mid-infrared spectroscopy using the Space Infrared Telescope Facility of the PAH features and other spectral lines may provide a star formation versus AGN diagnostic (Genzel et al. 1998). Spatially resolved observations may be critical in addressing this issue, since a dust emitting region spatially distinct from the optical QSO can be used to argue for at least some dust heating by star formation. Such an argument has been used convincingly in the case of CO and dust emission in the vicinity of a number of high-redshift radio galaxies and AGNs (Papadopoulos et al. 2000, 2001; Ivison et al. 2000). To date, the only high-redshift QSO in which such a spatial segregation has been observed is the z = 4.7 QSO BR1202−0725, in which the centimeter and millimeter continuum, and the CO line emission, show two sources of roughly equal strength separated by 4″, while the optical line and continuum emission is restricted to a single source (Hu, McMahon, & Egami 1996; Omont et al. 1996b; Ohta et al. 1996; Yun et al. 2000; Kohno et al. 2000, in preparation).

The question of the dominant dust heating mechanism, i.e., AGN versus star formation, is difficult to answer for low-redshift sources (Rigopoulou et al. 1999). Addressing the question at high redshift is just that much more difficult. The sources detected at 250 GHz in Table 1 present an ideal opportunity for addressing this issue in detail. A number of follow-up observations of these sources are required to properly address this question, including: (i) more sensitive radio continuum observations to better characterize the centimeter-to-millimeter SEDs, (ii) submillimeter observations to determine the dust temperature, (iii) high-resolution (sub) millimeter observations to determine the spatial distribution of the dust, and (iv) CO observations to better constrain the gas mass and kinematics. Such observations are at the limit of what is possible with current instrumentation but will become routine with the expanded VLA and the Atacama Large Millimeter Array.

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