MILLIMETER AND RADIO OBSERVATIONS OF $z \sim 6$ QUASARS

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ABSTRACT

We present millimeter and radio observations of 13 SDSS quasars at redshifts $z \sim 6$. We observed 11 of them with the Max Planck Millimeter Bolometer Array (MAMBO-2) at the IRAM 30 m telescope at 250 GHz and all of them with the Very Large Array (VLA) at 1.4 GHz. Four sources are detected by MAMBO-2 and six are detected by the VLA at the $k$-level. These sources, together with another six published in previous papers, yield a submillimeter/millimeter- and radio-observed SDSS quasar sample at $z \sim 6$. We use this sample to investigate the far-infrared (FIR) and radio properties of optically bright quasars in the early universe. We compare this sample to lower redshift samples of quasars observed in the submillimeter and millimeter [(sub)mm] and find that the distribution of the FIR to $B$-band optical luminosity ratio ($L_{\text{FIR}}/L_B$) is similar from $z \sim 2$ to 6. We find a weak correlation between the FIR luminosity ($L_{\text{FIR}}$) and $B$-band optical luminosity ($L_B$) by including the (sub)mm observed samples at all redshifts. Some strong (sub)mm detections in the $z \sim 6$ sample have radio-to-FIR ratios within the range defined by star-forming galaxies, which suggests possible coeval star-forming activity with the powerful AGN in these sources. We calculate the rest-frame radio-to-optical ratios ($R_{1.4} = L_{\nu, 1.4 \text{ GHz}}/L_{\nu, 4400 \text{ Å}}$) for all of the VLA-observed sources in the $z \sim 6$ quasar sample. Only one radio detection in this sample, J083643.85+005453.3, has $R_{1.4}$ of 40 and can be considered radio-loud. There are no strong radio sources ($R_{1.4} \geq 100$) among these SDSS quasars at $z \sim 6$. These data are consistent with, although do not set strong constraints on, a decreasing radio-loud quasar fraction with increasing redshift.

Key words: galaxies: high-redshift — galaxies: starburst — infrared: galaxies — quasars: general — radio continuum: galaxies

1. INTRODUCTION

The tight correlation between the mass of supermassive black holes (SMBHs) in the centers of galaxies and the bulge mass-velocity dispersion is well documented in the local universe (Magorrian et al. 1998; Marconi & Hunt 2003; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) and suggests that the evolution of SMBHs and spheroidal galaxies is coupled even at high redshift. Due to the negative $K$-correction, submillimeter and millimeter [(sub)mm] observations become an efficient way to study the host galaxies of high-redshift quasars (Blain & Longair 1993). Such observations probe the rest-frame far-infrared (FIR) emission from the dust components in the interstellar medium (ISM) of these objects and thus provide a
unique chance to test coeval black hole and bulge formation by searching for massive starbursts in the host galaxies of high-redshift optically bright quasars.

The (sub)mm and radio properties of some optically bright quasar samples are discussed in a number of papers. Observations of large samples of optically selected quasars from \( z \sim 1.5 \) to 5 (Omont et al. 2001, 2003; Carilli et al. 2001; Isaak et al. 2002; Priddey et al. 2003a; Beelen et al. 2006) result in a (sub)mm detection rate of about 30% at mJy sensitivity. The derived FIR luminosities of the (sub)mm detections are typically \( \sim 10^3 L_\odot \) and imply dust masses \( \sim 10^8 M_\odot \). Comparing samples observed with the Max Planck Millimeter Bolometer Array (MAMBO) at the 30 m IRAM telescope at redshifts 2 and 4, Omont et al. (2003) found that the FIR luminosities of the optically bright quasars in these samples do not evolve with redshift. Statistical tests for these (sub)mm-observed quasars show a weak correlation between the optical and FIR luminosities (Omont et al. 2003; Beelen et al. 2004; Cox et al. 2005), which is argued as evidence for FIR emission from warm dust heated by star formation. The inferred star formation rate is \( \sim 10^2 M_\odot \) yr\(^{-1} \) when assuming a normal initial mass function. This interpretation is supported by the fact that the radio-to-FIR ratios for the FIR-luminous sources are consistent with the range spanned by star-forming galaxies (Carilli et al. 2001; Pietric et al. 2006).

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has identified 19 bright quasars at \( z \sim 6 \) (Fan et al. 2000, 2001, 2003, 2004, 2006b). These quasars are unique in that they are undergoing rapid accretion onto SMBHs with masses \( \sim 10^9 M_\odot \) within 1 Gyr of the big bang, an epoch approaching cosmic reionization (Fan et al. 2006a). These quasars are under-luminous in the optical and FIR to radio imply a warm dust component with a temperature of \( T_d = 47 \) K (Priddey et al. 2003b; Robson et al. 2004, 2006; Pentericci et al. 2003b; Shemmer et al. 2006; Jiang et al. 2006; Carilli et al. 2004), (2) the huge amount of molecular gas in its host galaxy can provide the required fuel for massive star formation, and (3) the star formation rates indicated by both FIR luminosity and [C II] 158 \( \mu m \) line luminosity are \( \sim 10^3 M_\odot \) yr\(^{-1} \) (Bertoldi et al. 2003a; Maiolino et al. 2005).

Nineteen \( z \sim 6 \) SDSS quasars have been published to date (Fan et al. 2006c). These are an optically selected sample at the highest redshift. We are pursuing a series of (sub)mm through radio studies on this sample in order to (1) find the general dust and gas properties in the host galaxies of these highest redshift quasars and (2) search for star formation activity coeval with the rapid growth of SMBHs in the early universe.

In this paper we present new MAMBO-2 250 GHz observations of 11 and VLA 1.4 GHz observations of 13 \( z \sim 6 \) SDSS quasars. Then, together with previously published results, we discuss the general FIR and radio properties of the optically selected quasars at \( z \sim 6 \), focusing on luminosity correlations and evolution. We also discuss the radio-loud fraction of quasars. We will present further analysis of the FIR-to-radio SEDs and discuss possible star-forming activity in a second paper. The sample and observations are described in §2, and results are presented in §3. In §§4 and 5 we analyze and discuss the general properties of FIR and radio luminosities for the entire sample, and we give the conclusion in §6. We adopt a concordance cosmology with \( H_0 = 71 \) km s\(^{-1} \) Mpc\(^{-1} \), \( \Omega_m = 0.27 \), and \( \Omega_L = 0.73 \) throughout this paper.

2. SAMPLE AND OBSERVATION

The sample of \( z \sim 6 \) quasars is selected from about 6600 deg\(^2 \) of imaging data from the SDSS (Fan et al. 2006c). Fan et al. (2000, 2001, 2003, 2004, 2006b) selected sources with very red \( i - z \) colors as \( z > 5.7 \) quasar candidates. These candidate sources were followed up with high-quality spectroscopy. Nineteen \( z \sim 6 \) quasars have been published by the SDSS survey (Fan et al. 2000, 2001, 2003, 2004, 2006b) with redshifts ranging from 5.74 to 6.42 and rest-frame B-band optical luminosities\(^1 \) from \( 10^{12.5} \) to \( 10^{13.3} L_\odot \). Most of the 13 objects we observed in this work were discovered in the past 2 years (Fan et al. 2004, 2006a) and have not been observed in the (sub)mm or radio bands before.

We compare the (sub)mm properties of the \( z \sim 6 \) objects with luminous \( L_\text{MB} \geq 10^{12.5} L_\odot \) quasars at lower redshifts from the literature. We define a low-redshift group, \( 1.5 \leq z \leq 3.0 \), using a sample from Omont et al. (2003) containing radio-quiet quasars with B-band absolute magnitude \( -29.5 \leq M_B \leq -27.0 \) and redshift \( 1.8 \leq z \leq 2.8 \) observed by MAMBO at 250 GHz and a sample from Priddey et al. (2003a) of radio-quiet quasars with \( -29.2 \leq M_B \leq -27.5 \) and \( 1.5 \leq z \leq 3.0 \). Our higher redshift group \( 3.6 \leq z \leq 5.0 \) is drawn from the Palomar Sky Survey–selected sample of Omont et al. (2001; \( M_B \leq -27.0, 3.9 \leq z \leq 4.6 \)) and the SDSS sample of Carilli et al. (2001; \( -28.8 \leq M_B \leq -26.1, 3.6 \leq z \leq 5.0 \)), both observed with MAMBO at 250 GHz. The \( 3 \sigma \) detection limits of the MAMBO observations by Omont et al. (2001, 2003) are \( \sim 1.5–4 \) mJy and by Carilli et al. (2001) \( \sim 1.4 \) mJy. The typical \( 3 \sigma \) detection limit of SCUBA observations reported by Priddey et al. (2003a) is \( \sim 10 \) mJy at 350 GHz, which corresponds to an upper limit of \( \sim 4 \) mJy at 250 GHz (assuming a warm dust SED with temperature \( T_d = 47 \) K and emissivity index \( \beta = 1.6 \)).

A total of 13 \( z \sim 6 \) SDSS quasars were observed in the course of the work presented here, all with the VLA at 1.4 GHz and 11 (all but J000552.34–000655.8 and J104845.05+463718.3) with

\( \footnote{1} L_\text{MB} = \nu L_{\nu, 4400} \text{A} = L_{\nu, 4400} \text{A} \text{ is the luminosity density at rest frame 4400 A. We calculate } L_{\nu, 4400} \text{ and } L_\text{MB} \text{ from the AB magnitude at rest frame 1450 A in the discovering papers (Fan et al. 2000, 2001, 2003, 2004, 2006b), assuming an optical spectral index of } -0.5.} \)
MAMBO-2 at 250 GHz (see Table 1 for the source list). J104845.05+463718.3 was a published detection by MAMBO-2 at the IRAM 30 m telescope is a 117 channel bolometer array. The half-power beamwidth of each pixel is 11′, and the spacing between horns is about 20′. The effective sensitivity is about 40 mJy s\(^{-1}\). The new observations were made in the winters of 2004–2005 and 2005–2006 during pooled observations using the on-off mode, wobbling by 32′–46′ in azimuth and at a rate of 2 Hz. The target sources were positioned on the most sensitive bolometer, and the correlated sky noise was determined from the other bolometers and subtracted from the source bolometer. The median rms is ~0.8 mJy (Table 1). We reduced the data with the MOPSIC software package (Zylińska 1998) and standard scripts for on-off observation data.

The VLA observations were made with the A configuration, of which the maximum baseline is 30 km. The sources were observed at 1.4 GHz with two intermediate frequency bands (IFs) and 50 MHz bandwidth per IF. The corresponding full width at half-maximum (FWHM) resolution is about 1.4′. We observed each source for 2–4 hr to a typical rms noise level of ~16 µJy beam\(^{-1}\) (Table 1). The data were reduced and images were made using the standard VLA wide-field data reduction software AIPS.

3. RESULTS

We present our MAMBO-2 results of 11 sources and the VLA results of 13 sources in Table 1. The optical properties are taken from Fan et al. (2006c) and presented as follows: column (1), SDSS name; column (2), redshift; and column (3), AB magnitude at 1450 Å. Column (4) lists the radio 1.4 GHz surface brightness at the optical position. Columns (5)–(7) list the nearest radio peak position and peak surface brightness for detected sources. Column (8) presents the 250 GHz flux densities in mJy. We mark detections with an asterisk. For the source J000552.34–000655.8, there is a strong (~Jy) radio source in the field which precludes deep VLA radio imaging. The rms on the 1.4 GHz map is 130 µJy, which is an order of magnitude higher than the others, yielding an extremely high upper limit of ~390 µJy. Thus, we exclude this source in all of our analyses in this paper.

We show the radio 1.4 GHz continuum images of the 12 remaining sources in Figure 1. We searched for ≥3 σ peaks within a 0.6″ radius from the optical quasar position in the radio map. This is a combination of the positional uncertainty of 0.3″ between the radio and optical reference frames (Deutsch 1999) and the radio-observation uncertainty of σ\(_{\text{pos}}\) ~ FWHM/SNR ~ 0.5″. Six sources are detected at the ≥3 σ level. According to the 1.4 GHz radio source counts (Fomalont et al. 2006), we expect 0.003 detections with S\(_{1.4\text{GHz}}\) ≥ 50 µJy by chance within the total search area around the 12 quasars.

We obtain four detections among the 11 sources with MAMBO. Three of the detections, J084035.09+562419.9, J092721.82+001237.7, and J133550.81+353315.8, are detected at ~4 mJy (Greve et al. 2004; Voss et al. 2006), which is within a 0.6″ radius from the optical quasar position in the radio map. This is a combination of the positional uncertainty of 0.3″ between the radio and optical reference frames (Deutsch 1999) and the radio-observation uncertainty of σ\(_{\text{pos}}\) ~ FWHM/SNR ~ 0.5″. Six sources are detected at the ≥3 σ level. According to the 1.4 GHz radio source counts (Fomalont et al. 2006), we expect 0.003 detections with S\(_{1.4\text{GHz}}\) ≥ 50 µJy by chance within the total search area around the 12 quasars.

We summarize the (sub)mm and radio observations of the six previously observed quasars in the z ~ 6 SDSS sample (Petric et al. 2003; Priddey et al. 2003b; Bertoldi et al. 2003a; Robson et al. 2004; Carilli et al. 2004) in Table 2. Columns (1)–(3) give the name, redshift, and 1450 Å AB magnitude, and columns (4)–(7) give the flux densities at 250, 350, 667, and 1.4 GHz.

Combining Tables 1 and 2, there are 17 z ~ 6 quasars that have been observed with MAMBO. Together with the results from SCUBA at 850 µm, there are 18 z ~ 6 SDSS quasars that have (sub)mm observations at the 1 mJy sensitivity level, and 8 of them are detected at ≥3 σ. The detection rate is 44% ± 16%. The detection rate of optically bright quasar samples at redshifts 2 and

\(\text{Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.}\)

\(a\) Surface brightness at the optical quasar position plus the 1 σ rms on the radio map.

\(b\) Position and surface brightness of the detected radio peak.

\(c\) The detections are marked with an asterisk.

\(d\) Result taken from Bertoldi et al. (2003a).
is \( \sim 30\% \) in Omont et al. (2001, 2003) with an rms level of \( \sim 1.5 \) mJy and \( \sim 39\% \) in Carilli et al. (2001) with a lower rms level of \( \sim 1.4 \) mJy. Thus, our detection rate at \( z \sim 6 \) is slightly higher compared to these observations at lower redshifts but is consistent within the errors.

Seventeen sources in the \( z \sim 6 \) SDSS quasar sample have deep observations with the VLA at 1.4 GHz, and eight are detected at the \( \sim 3 \sigma \) level. J083643.85+005453.3 is the only \( > 1 \) mJy radio source at 1.4 GHz among them. It was detected by Petric et al. (2003), as well as in the FIRST survey (White et al. 1997), leading to a weighted average flux density of 1.74 mJy. Another source, J114816.64+525150.3, has not been observed with the VLA yet, and the FIRST catalog yields an upper limit of 0.44 mJy at the optical position (Bertoldi et al. 2003a). We thus exclude this source in the analysis of radio properties in the next section.

4. ANALYSIS

4.1. The FIR Emission

To estimate the FIR luminosity of our \( z \sim 6 \) quasars, we model the FIR continuum with an optically thin graybody (eq. [1]), adopting a dust temperature of \( T_d = 47 \) K and emissivity index of \( \beta = 1.6 \), which is derived from the mean SED of high-redshift quasars (Beelen et al. 2006). We normalize the SED to the (sub)mm data and integrate the model SED from rest-frame 42.5 to 122.5 \( \mu m \) to get the total FIR flux:

\[
\text{FIR} \propto \int_{\nu} \frac{1}{\exp(h\nu/kT_d) - 1} \ d\nu.
\]

This estimation of FIR emission is sensitive to the assumed dust temperature (\( T_d \)). A higher temperature, e.g., \( T_d = 55 \) K,
will increase the estimated FIR flux by a factor of $\sim 1.5$. For nondetections ($< 3 \sigma$), we adopt as upper limits the larger value of either (1) the 2 $\sigma$ rms or (2) the measured value at the optical position plus 1 $\sigma$ rms for all the following calculations and plots. The FIR luminosities ($L_{\text{FIR}}$) are given in Table 3; most of the (sub)mm-detected sources are very luminous in the FIR band, with implied $L_{\text{FIR}} \sim 10^{13} L_\odot$ (see Table 3). We estimate the FIR luminosities for all the low-redshift comparison samples in the same way.

We plot the FIR luminosity ($L_{\text{FIR}}$) versus redshift in Figure 2, including the $z \sim 6$ SDSS sample and all the comparison samples. In Figure 3 we present the histograms of the $L_{\text{FIR}}$ and $L_{\text{FIR}}/L_B$ distributions separately for different redshift intervals. For the (sub)mm detections at all redshifts, the $L_{\text{FIR}}$ values lie between $10^{12.5}$ and $10^{13.8} L_\odot$. The $1.5 \leq z \leq 3$ group covers an even narrower range, with most of the detected sources distributed at $L_{\text{FIR}} \geq 10^{13} L_\odot$. These ranges are partially a result of the detection thresholds, i.e., a detection limit of 1.5 mJy at 250 GHz corresponds to FIR luminosities of $\sim 10^{12.5} L_\odot$ for redshifts from 4 to 6 and $\sim 10^{13} L_\odot$ at $z \sim 2$. However, the $L_{\text{FIR}}/L_B$ distributions are similar for the (sub)mm detections at all redshifts (see Fig. 3b). A similar conclusion was obtained by Omont et al. (2003) and Beelen (2004), but we are extending it to the quasar sample at $z \sim 6$. This fact suggests the optical-to-FIR SEDs of the luminous quasars in both the optical and FIR bands do not evolve much from $z \sim 2$ to 6.

Figure 4 plots $L_{\text{FIR}}$ versus $L_B$ for quasars at all redshifts. We present correlation tests for (1) the $z \sim 6$ sample only ($z \sim 6$), (2) samples at all redshifts (total), and (3) (sub)mm detections in all samples (detection). We apply the general Kendall’s $\tau$ test (Isobe et al. 1986), taking $L_B$ as the independent variable and $L_{\text{FIR}}$ as the dependent variable. The results are listed in Table 4; column (1) gives the sample used, column (2) gives the sample size, and column (3) gives the Kendall’s $\tau$ value. The probabilities ($P_{\text{null}}$) that no correlation exists between $L_B$ and $L_{\text{FIR}}$ (the null hypothesis) are given in column (4). We take $P_{\text{null}} = 5\%$ as
the significance level below which the null hypothesis can be rejected.

There is no correlation between $L_B$ and $L_{\text{FIR}}$ for the $z \sim 6$ sample only ($P_{\text{null}} \sim 44\%$). However, the $P_{\text{null}}$ value is 6% when all the samples are included, which suggests a marginal correlation. These results indicate that the FIR and optical emission of these (sub)mm-observed quasars are correlated, but the scatter is large enough that the correlation is not seen over a narrow luminosity range. This correlation is even more significant when we do the test with only the (sub)mm detections at all redshifts ($P_{\text{null}} \sim 0.02\%$). But one should be careful with this result, as there may be a number of observational or selection biases in the sample of detections. For example, given the similar observational sensitivity level, the FIR luminosity threshold for the (sub)mm detections is decreasing with redshifts at $z > 2$ (see Fig. 1).

We apply linear regression to all of the (sub)mm-observed samples (total) and the subsample of detections (detection) using the expectation-maximization method, which can deal with data including upper limits (Isobe et al. 1986). The best-fitting results are

$$\text{total: } \log \left( \frac{L_{\text{FIR}}}{L_\odot} \right) = (0.21 \pm 0.15) \log \left( \frac{L_B}{L_\odot} \right) + (9.67 \pm 2.03),$$

(2)

$$\text{detection: } \log \left( \frac{L_{\text{FIR}}}{L_\odot} \right) = (0.40 \pm 0.09) \log \left( \frac{L_B}{L_\odot} \right) + (7.82 \pm 1.20).$$

(3)

The regression results show a nonlinear relationship between the FIR emission and the quasars’ optical emission with slopes much smaller than unity. We plot the fitting results in Figure 4. As a comparison, we calculate the typical FIR–to–$B$-band luminosity ratios for local optical quasars based on the radio-quiet and radio-loud quasar templates in Elvis et al. (1994). The FIR
luminosities are integrated directly from the template SEDs. The derived FIR—to—B-band luminosity ratios \( \left( L_{\text{FIR}}/L_{\text{B}} \right) \) are 0.29 and 0.38 for the radio-quiet and radio-loud templates, respectively, and are plotted as \( L_{\text{FIR}} = 0.29 L_{\text{B}} \) (solid line) and \( L_{\text{FIR}} = 0.38 L_{\text{B}} \) (long-dashed line) in Figure 4. According to Figure 4, most of the (sub)mm detections have larger \( L_{\text{FIR}}/L_{\text{B}} \) values than those of the local optical quasar templates. Of the eight (sub)mm-detected quasars at \( z \sim 6 \), six have FIR emission stronger than that predicted from the radio-quiet template (by factors from \( \sim1.5 \) to \( \geq5 \)), and only one source, J081827.40+172251.8, is consistent with the template within the errors.

4.2. The Radio Emission

The rest-frame 1.4 GHz luminosities \( (L_{\odot}) \) for the 17 quasars observed with the VLA in the \( z \sim 6 \) sample are calculated, assuming a power-law \( (f_{\nu} \sim \nu^{\alpha}) \) radio SED and a radio spectral index of \( \alpha = -0.75 \) (Condon 1992). Since all the sources are unresolved on the radio maps (Fig. 2), we adopt the peak surface brightness in Table 1 as the 1.4 GHz flux density for our VLA detections and take the larger value of either the 2 \( \sigma \) rms on the radio map or the measured value at the optical position plus 1 \( \sigma \) rms as the upper limits for nondetections. The rest-frame radio—to—B-band optical luminosity density ratios \( R_{14} = L_{\nu,1.4 GHz}/L_{\nu,4400 \AA} \) (Cirasuolo et al. 2003, 2006) are calculated and listed in Table 3; \( L_{\nu,4400 \AA} \) is the luminosity density at rest frame 4400 \( \AA \) (see footnote 1). We adopt \( R = L_{\nu,5 GHz}/L_{\nu,4400 \AA} = 10 \) (Kellermann et al. 1989) to separate radio-loud and radio-quiet sources. This corresponds to \( R_{14} \sim 30 \) by assuming the above radio spectral index and converting the rest-frame 5 GHz flux density to 1.4 GHz.

We plot the rest-frame 1.4 GHz radio luminosity \( (L_{\odot}) \) versus B-band luminosity \( (L_{\text{B}}) \) in Figure 5. The typical 3 \( \sigma \) detection limit of the VLA observation is \( \sim50 \mu \text{Jy (dotted line)} \), which is roughly 10 times deeper than that of the FIRST survey (solid line). Thus, our VLA observations are sensitive enough to detect any radio-loud source with B-band luminosity \( >10^{12} L_{\odot} \) at \( z \sim 6 \) for...
all of the 17 sources. We plot the $R_{\text{1.4GHz}}/C3$ distribution of the 17 $z \sim 6$ quasars in Figure 6. None of the 13 sources with new radio data reported in this paper is radio-loud. For the whole sample of 17 $z \sim 6$ quasars, there is one marginally radio-loud object, J083643.85+005453.3, with $R_{\text{1.4GHz}}/C3 \sim 40$.

The deep VLA observations also enable us to investigate the correlation between radio and FIR emission of the $z \sim 6$ quasars. Yun et al. (2001) employ a $q$-parameter to quantify the ratio of the FIR and radio luminosities,

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

Yun et al. (2001) studied the infrared-selected galaxies in the IRAS 2 Jy sample and found a $q$-value of 2.34 for typical star-forming galaxies. We calculate the $q$-values for the 12 $z \sim 6$ quasars that are detected at either radio or (sub)mm wavelengths. We also plot $L_{\text{FIR}}$ versus the rest-frame 1.4 GHz radio luminosity density ($L_{\text{1.4GHz}}$) in Figure 6, comparing the $z \sim 6$ quasar sample to typical star-forming galaxies in the local universe (Yun et al. 2001). The dashed line in Figure 6 corresponds to the typical $q$-value of 2.34 in star-forming galaxies, and the dotted lines denote excesses that are 5 times above and below this typical correlation (Yun et al. 2001).

There are four sources in the $z \sim 6$ quasar sample that are detected in both the radio and (sub)mm regimes. One of them, J081827.40+172251.8, has a small $q$-value that falls beyond the range defined by typical star-forming galaxies, indicating the dominance of AGN power in the FIR-to-radio SED of this quasar.
source. However, the FIR-to-radio ratios of the other three sources, although slightly above the mean value of $q = 2.34$, are consistent with star-forming galaxies (Fig. 6 and Table 3).

5. DISCUSSION

The heating sources of the FIR-emitting dust in quasars are studied and the contributions from host galaxy star formation are discussed in a number of papers (e.g., Haas et al. 2003; Omont et al. 2003; Schweitzer et al. 2006). Star formation is believed to be the dominant dust-heating resource in the local infrared-luminous quasars that are located in ultraluminous infrared galaxies (ULIRGs) (Hao et al. 2005). Schweitzer et al. (2006) studied the connection between FIR emission and PAH/low-excitation fine-structure emission lines of the local Palomar-Green quasars. Their results suggest that star formation is responsible for at least 30% of the average local quasar FIR emission and that this contribution tends to increase with FIR luminosity. The $z \sim 6$ SDSS quasars we discuss in this paper belong to the population of the brightest quasars in the optical. About one-third of them are detected at (sub)mm wavelengths. According to Figure 4, most of these detections have FIR luminosities stronger than the predictions from local quasar templates, indicating extra emission from warm dust in these sources compared to the typical optical quasar emission. Moreover, the relationship between the FIR and $B$-band optical emission is nonlinear and significantly scattered, only manifesting itself when a larger luminosity range is considered (see §4.1). Beelen (2004) studied a number of optically bright quasar samples at $z > 1.5$ that had (sub)mm observations and first reported this weak correlation between FIR and $B$-band optical emission, namely, $\log L_{\text{FIR}} = (8.36 \pm 0.90) + (0.33 \pm 0.07) \log L_{B}$ (see also Cox et al. 2005). The results are consistent when we include our new observations at $z \sim 6$. In addition, most of the (sub)mm detections at $z \sim 6$ have FIR-to-radio ratios or upper limits within the range occupied by star-forming galaxies (see Table 3 and Fig. 6).

One possible explanation for all of these facts is that star formation is happening on a massive scale in the host galaxies of these FIR-luminous $z \sim 6$ quasars and dominating the heating process of the FIR-emitting warm dust. The implied star formation rate is $\sim 10^{5} M_{\odot} \text{yr}^{-1}$. This idea is supported by the detection of CO in the high-redshift quasars that have strong FIR emission ($L_{\text{FIR}} \gtrsim 10^{13} L_{\odot}$). CO line emission was detected in several FIR-luminous quasars at $z \gtrsim 4$, including the highest redshift quasar, J114816.64+525150.2 (e.g., Riechers et al. 2006; Bertoldi et al. 2003b; Walter et al. 2003, 2004). The CO detections indicate a huge amount of molecular gas in the host galaxies of these FIR-luminous quasars, which is the requisite fuel for star formation. Moreover, Riechers et al. (2006) found that the FIR-to-CO relation of the high-redshift FIR-luminous quasars is consistent with that defined by ULIRGs, star-forming galaxies, and submillimeter galaxies.

One may argue that the strong FIR emission can also be processed by AGN power, since the dust torus geometry of these sources is still unknown. This possibility cannot be ruled out given the limited data we have for these sources, but detailed dust models are required to explain the results we list above. One fact is that the hot dust emission of the SDSS $z \sim 6$ quasars probed by recent Spitzer observations is similar to that of the local quasar templates, as mentioned in §1 (Jiang et al. 2006). Four (sub)mm detections are included in this Spitzer-observed sample, and no different properties are found in the optical-to-NIR SEDs of these sources. This may not support the idea of a very different geometry of the dust torus.

However, we should mention that there are still large uncertainties in the estimations of the FIR luminosities for these (sub)mm-detected $z \sim 6$ quasars. The FIR luminosities for some of the sources can be overestimated given the poor data at (sub)mm wavelengths. Thus, further studies on these (sub)mm-detected $z \sim 6$ quasars are required, including observations of the submillimeter continuum at higher frequencies and emission lines of CO and other molecules, such as HCN, as well as the C and C$^{+}$ fine-structure lines.

Another interesting question is how the current radio observations constrain the radio-loud fraction (RLF) at $z \sim 6$. The RLF of optically selected quasar samples is $\sim 10\%$, as quoted in many papers (Kellermann et al. 1989; Ivezić et al. 2002, 2004; Cirasuolo et al. 2003, 2006). Jiang et al. (2007) studied the FIRST data (Becker et al. 1995) for SDSS quasars with redshifts up to 5 and suggested that the quasar RLF increases with optical luminosity and decreases with redshift, namely, $\log(\text{RLF})/(1 - \text{RLF}) = (-0.112 \pm 0.109) + (-2.196 \pm 0.269) \log (1 + z) + (-0.203 \pm 0.026)(M_{5000} + 26)$. This result gives an RLF of $\sim 37\%$ at $z = 0.5$, $\sim 11\%$ at $z = 2$, and $\sim 2\%$ at $z = 6$, given the rest-frame 2500 Å absolute AB magnitude $M_{2500} = -27.3$—the typical value of the $z \sim 6$ SDSS quasar sample.$^{6}$

There is one marginally radio-loud source in this $z \sim 6$ sample of 17 sources. This result argues against a high RLF, i.e., $>20\%$, for the current SDSS quasar sample at $z \sim 6$. Thus, it is roughly consistent with the result of Jiang et al. (2007). However, the sample size is still too small to set a strict constraint, i.e., to differentiate an RLF between different geometry of the dust torus.

We should also mention the recent discovery of a radio-loud quasar at $z > 6$, FIRST J1427385+331241 (McGreer et al. 2006), with a FIRST flux density of 1.73 mJy. This source is the most radio-luminous quasar known at $z \sim 6$, with $R_{600} > 100$. However, it cannot be included in our radio-loud analysis at $z \sim 6$, as the selection criteria of this source are quite different.

$^{6}$ $M_{2500}$ is estimated from the absolute AB magnitude at rest frame 1450 Å ($M_{1450}$; Fan et al. 2006c). For the current sample of 19 $z \sim 6$ SDSS quasars with $M_{1450}$ from $-26.2$ to $-27.9$, we adopt a typical value of $M_{1450} = -27.0$ and an optical spectral power-law index of $-0.5$. 

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**Fig. 6.** Logarithm of the rest-frame 1.4 GHz radio luminosity density ($\log L_{\text{1.4 GHz}}$) vs. the logarithm of the FIR luminosity ($\log L_{\text{FIR}}$). The filled squares represent the detections in both radio and (sub)mm bands, and the open squares with arrows represent the upper limits of the nondetections in either radio or (sub)mm. The upper limits are calculated as in Fig. 2. The crosses represent the IRAS 2 Jy sample of galaxies in Yun et al. (2001), and the dashed line indicates the typical radio-to-FIR correlation in star-forming galaxies with correlation parameter $q = 2.34$ (Yun et al. 2001). The dotted lines represent excesses 5 times above and below the typical $q$-value.
from those of the SDSS quasars and its UV/optical emission is just beyond the SDSS detection limits (McGreer et al. 2006).

6. CONCLUSION

In this paper we present new results of millimeter and radio observations of a sample of $z \sim 6$ quasars. These quasars are selected from the SDSS survey and observed with MAMBO-2 at 250 GHz and the VLA at 1.4 GHz. We obtain three $>4 \sigma$ detections and one $\sim 3 \sigma$ detection out of 11 sources observed by MAMBO-2 and six radio detections out of 13 sources observed by the VLA.

We combine our new millimeter and radio results of the SDSS $z \sim 6$ quasars with results from the literature and discuss the FIR and radio properties of the optically selected quasars at $z \sim 6$. Our conclusions are as follows:

1. Eight out of 18 $z \sim 6$ optically selected quasars are detected in the (sub)mm regime. This indicates a (sub)mm detection rate of $44\%$ at $z \sim 6$ in mJy sensitivity. Within the errors, this is consistent with the $\sim 30\%$ (sub)mm detection rate at lower redshift (e.g., Carilli et al. 2001; Omont et al. 2001, 2003). The observational data imply FIR luminosities of $\sim 10^{13} L_\odot$ in the (sub)mm-detected sources.

2. We compare the distribution of FIR luminosities and FIR-to-optical ratios between the $z \sim 6$ SDSS sample and (sub)mm-observed optically bright quasars ($L_F \geq 10^{12.5} L_\odot$) at lower redshifts. The distributions of the FIR-to-optical ratio are similar for different redshift groups, which suggests that the average optical-to-FIR SED of optically bright quasars is independent of redshift.

3. We extend the quasar FIR-to-optical correlation study to the $z \sim 6$ SDSS sample. No correlation is found with the $z \sim 6$ sample only. However, a correlation (albeit with large scatter) can be seen when all the samples extending from $z = 1.5$ to 6.42 are included.

4. We also discussed the FIR-to-radio ratios of the $z \sim 6$ quasars by comparing them to the typical correlation defined by star-forming galaxies. Three of the four sources that are detected in both the millimeter and radio bands have FIR-to-radio ratios within the range defined by star-forming galaxies.

5. We found no strong radio sources with $R_{14} > 30$ among the new SDSS sources of bright $z \sim 6$ quasars. In the whole $z \sim 6$ sample, only one radio detection has a radio-to-optical ratio of $R_{14} \sim 40$ and no source has $R_{14} > 100$. These data are consistent with, but do not set strong constraints on, the recent conclusion of a decreasing radio-loud quasar fraction with increasing redshift (Jiang et al. 2007).

These results give a view of the general FIR through radio properties of the $z \sim 6$ SDSS quasars. The data are consistent with the idea that massive starbursts may exist in the host galaxies of the strong (sub)mm detections at $z \sim 6$ and contribute to the FIR and radio emission.

These strong (sub)mm sources provide the only candidates to search for CO and C$^+$ into the epoch of reionization and to test the idea of coeval SMBH and host galaxy formation. We may expect to go an order of magnitude deeper in a few years’ time with the coming instruments of the Expanded Very Large Array and the Atacama Large Millimeter Array.

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REFERENCES

Bechtold, J., et al. 2003, ApJ, 588, 119
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Beelen, A. 2004, Ph.D. thesis, Obs. Paris
Beelen, A., Cox, P., Benford, D. J., Dowell, C. D., Kovács, A., Bertoldi, F., Omont, A., & Carilli, C. L. 2006, ApJ, 642, 694
Bertoldi, F., Carilli, C. L., Cox, P., Fan, X., Strauss, M. A., Beelen, A., Omont, A., & Zyłka, R. 2003a, A&A, 406, L55
Bertoldi, F., et al. 2003b, A&A, 409, L47
Blain, A. W., & Longair, M. S. 1993, MNRAS, 264, 509
Carilli, C. L., et al. 2001, ApJ, 555, 625
———. 2004, AJ, 128, 997
Cirasuolo, M., Celotti, A., & Magliocchetti, M. 2003, MNRAS, 346, 447
Cirasuolo, M., Magliocchetti, M., Gentile, G., Celotti, A., Cristiani, S., & Danese, L. 2006, MNRAS, 371, 695
Condon, J. J. 1992, ARA&A, 30, 557
Cox, P., Beelen, A., Bertoldi, F., Omont, A., Carilli, C. L., & Walter, F. 2005, in The Dusty and Molecular Universe, ed. A. Wilson (ESA SP-577; Noordwijk: ESA), 115
Deutsch, E. W. 1999, AJ, 118, 1882
Elvis, M., et al. 1994, ApJS, 95, 1
Fan, X., Carilli, C. L., & Keating, B. 2006a, ARA&A, 44, 415
Fan, X., et al. 2000, AJ, 120, 1167
———. 2001, AJ, 122, 2833
———. 2003, AJ, 125, 1649
———. 2004, AJ, 128, 515
———. 2006b, AJ, 131, 1203
———. 2006c, AJ, 132, 117
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Fomalont, E. B., Kellermann, K. I., Cowie, L. L., Capak, P., Barger, A. J., Partridge, R. B., Windhorst, R. A., & Richards, E. A. 2006, ApJS, 167, 103
Gebhardt, K., Bender, R., & Bower, G. 2000, ApJ, 539, L13
Greve, T. R., Ivison, R. J., Bertoldi, F., Stevens, J. A., Dunlop, J. S., Lutz, D., & Carilli, C. L. 2004, MNRAS, 354, 779
Haas, M., et al. 2003, A&A, 402, 87
Hao, C. N., Xia, Y. M., Mao, S., Wu, H., & Deng, Z. G. 2005, ApJ, 625, 78
Isaak, K. G., Pridey, R. S., McMahon, R. G., Omont, A., Peroux, C., Sharp, R. G., & Withington, S. 2002, MNRAS, 329, 149
Isoye, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Ivezić, Z., et al. 2002, AJ, 124, 2364
———. 2004, in ASP Conf. Ser. 311, AGN Physics with the Sloan Digital Sky Survey, ed. G. T. Richards & P. B. Hall (San Francisco: ASP), 347
Iwamuro, F., Kimmura, M., Eto, S., Mailara, T., Motohara, K., Yoshii, Y., & Doi, M. 2004, ApJ, 614, 69
Jiang, L., Fan, X., Ivezic, Z., Richards, G. T., Schneider, D. P., Strauss, M. A., & Kelly, B. C. 2007, ApJ, 656, 680
Jiang, L., et al. 2006, AJ, 132, 2127
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Magorrian, J., et al. 1998, AJ, 115, 2285
Maiolino, R., et al. 2005, A&A, 440, L51
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21
McGreer, I. D., Becker, R. H., Helfand, D. J., & White, R. L. 2006, ApJ, 652, 157
Omont, A., Beelen, A., Bertoldi, F., Cox, P., Carilli, C. L., Pridey, R. S., McMahon, R. G., & Isaak, K. G. 2003, A&A, 398, 857
Omont, A., Cox, P., Bertoldi, F., McMahon, R. C., Carilli, C. L., & Isaak, K. G. 2001, A&A, 374, 371
Pentericci, L., et al. 2003, A&A, 410, 75
Petric, A. O., Carilli, C. L., Bertoldi, F., Beelen, A., Cox, P., & Omont, A. 2006, AJ, 132, 1307
Petric, A. O., Carilli, C. L., Bertoldi, F., Fan, X., Cox, P., Strauss, M. A., Omont, A., & Schneider, D. P. 2003, AJ, 126, 15

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Priddey, R. S., Isaak, K. G., McMahon, R. G., & Omont, A. 2003a, MNRAS, 339, 1183
Priddey, R. S., Isaak, K. G., McMahon, R. G., Robson, E. I., & Pearson, C. P. 2003b, MNRAS, 344, L74
Riechers, D. A., et al. 2006, ApJ, 650, 604
Robson, I., Priddey, R. S., Isaak, K. G., & McMahon, R. G. 2004, MNRAS, 351, L29
Schweitzer, M., et al. 2006, ApJ, 649, 79
Shemmer, O., et al. 2006, ApJ, 644, 86
Tremaine, S., et al. 2002, ApJ, 574, 740
Voss, H., Bertoldi, F., Carilli, C., Owen, F. N., Lutz, D., Holdaway, M., Ledlow, M., & Menten, K. M. 2006, A&A, 448, 823
Walter, F., Carilli, C. L., Bertoldi, F., Menten, K., Cox, P., Lo, K. Y., Fan, X., & Strauss, M. A. 2004, ApJ, 615, L17
Walter, F., et al. 2003, Nature, 424, 406
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
Willott, C. J., McLure, R. J., & Jarvis, M. J. 2003, ApJ, 587, L15
York, D. G., et al. 2000, AJ, 120, 1579
Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803
Zylka, R. 1998, MOPSI User’s Manual (Grenoble: IRAM)