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Dust emission from the most distant quasars

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Abstract. We report observations of three SDSS $z > 6$ QSOs at 250 GHz (1.2 mm) using the 117-channel Max-Planck Millimeter Bolometer (MAMBO-2) array at the IRAM 30-meter telescope. J1148+5251 ($z = 6.42$) and J1048+4637 ($z = 6.23$) were detected with 250 GHz flux densities of 5.0 ± 0.6 mJy and 3.0 ± 0.4 mJy, respectively. J1630+4012 ($z = 6.05$) was not detected with a 3 σ upper limit of 1.8 mJy. Upper flux density limits from VLA observations at 43 GHz for J1148+5251 and J1048+4637 imply steeply rising spectra, indicative of thermal infrared emission from warm dust. The far-infrared luminosities are estimated to be $\approx 10^{13}\,L_\odot$, and the dust masses $\approx 10^{8}\,M_\odot$, assuming Galactic dust properties. The presence of large amounts of dust in the highest redshift QSOs indicates that dust formation must be rapid during the early evolution of QSO host galaxies. Dust absorption may hinder the escape of ionizing photons which reionize the intergalactic medium at this early epoch.

Key words. galaxies: formation – galaxies: starburst – galaxies: high-redshift – quasars: general – cosmology: observations – submillimeter

1. Introduction

The search for the most distant and early galaxies has become a rapidly evolving field in extragalactic astronomy. Optical imaging and spectroscopic surveys (Palomar Sky Survey, PSS; Sloan Digital Sky Survey, SDSS, York et al. 2000) have revealed a large number of QSOs up to redshifts of 6.4 (Fan et al. 2001, 2003). About 150 high-redshift QSOs selected from these surveys were recently observed at millimeter wavelengths, detecting thermal emission from one third of them (Omont et al. 2001, 2003; Carilli et al. 2001a) up to a redshift of 5.5 (Bertoldi & Cox 2002). Although these optically bright QSOs give a somewhat biased view on the relation between the formation of stars, massive black holes, and galaxies in the early Universe, especially at the highest redshifts they well complement the blank field submillimeter imaging surveys, which have uncovered a population of $z > 2$ dust-obscured starburst galaxies which are likely to be spheroidal galaxies in their formation stages (Smail et al. 1997; Hughes et al. 1998).

Recently, Fan et al. (2003) discovered three QSOs at $z > 6$ in the SDSS, including J1148+5251 at $z = 6.42$, the QSO with the highest known redshift. The spectra of these QSOs show the Gunn-Peterson quenching of continuum emission blueward of Lyα, thus probing the end of the reionization epoch of the Universe (White et al. 2003). These sources provide an opportunity to study the growth of massive black holes and their associated stellar populations at the end of the "dark ages", in the earliest epochs of luminous cosmic structure formation.

In this Letter, we report the detection of 250 GHz (1.2 mm) continuum emission from two of the SDSS $z > 6$ QSOs and upper limits to their 43 GHz continuum emission which confirm that the emission is thermal dust radiation, thus enabling us to estimate far-infrared luminosities and dust masses. Throughout this paper, we adopt $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$ (Spergel et al. 2003).

2. Observations

The millimeter continuum measurements were made in January and February 2003 using the 117-channel MAMBO-2 array (Kreysa et al. 1999) at the IRAM 30 m telescope on Pico Veleta (Spain). MAMBO-2 has a half power spectral bandwidth between 210 and 290 GHz with an effective frequency of 250 GHz. The beam size on the sky is 10.7 arcsec. The sources were observed with a single channel using the standard on-off mode with the telescope secondary chopping in azimuth by 32″ at a rate of 2 Hz. For flux calibration a number of calibration

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sources were observed, resulting in an estimated absolute flux uncertainty of 15%. The total on plus off target observing time was 51, 128, and 68 min, for J1148, J1048, and J1630, respectively. The data were analyzed using the MOPSI software package. Correlated noise was subtracted from each channel using the weighted average signals from the surrounding channels.

J1148+5251 was imaged with MAMBO-2 using the on-the-fly mapping technique with chopping in azimuth by 42 arcsec. Skynoise was subtracted and the double beam maps were combined through shift-and-add. Five maps of one hour duration each were combined for the final image, which is displayed as signal/noise contours in Fig. 1.

Continuum observations at 43 GHz of J1148+5251 and J1048+4637 were done using the VLA in the D configuration (max. baseline = 1 km). The sources were observed for 4 hours and 0.7 hour, respectively. Standard amplitude calibration was performed using 3C 286. Fast switching phase calibration was employed using celestial calibrators within 3° of the target sources. The calibration cycle time was 200 seconds, and the phase stability was excellent, with typical changes in antenna-based phase solutions between calibration scans $<10°$ on the longest baselines. Images were generated using the deconvolution task IMAGR in AIPS, and CLEANed to residuals of 1.5 σ. The Gaussian restoring CLEAN beam was $\sim 1''$ (FWHM). The rms noise level in the final image for J1048+4637 is 0.37 mJy/beam, and 0.11 mJy/beam for J1148+5251.

3. Results

The results from the MAMBO and VLA observations are summarized in Table 1. Two of the QSOs, J1148+5251 and J1048+4737, are detected above 5 σ significance at 250 GHz (rest frame 165 μm). These QSOs are not detected at 43 GHz (rest frame 970 μm), with upper limit flux densities below 1 mJy. The steep rest-frame submillimeter spectral index suggests that the emission is thermal dust radiation and not synchrotron radiation.

J1148+5251. The highest redshift source yet discovered ($z = 6.42$), J1148+5251 is an extremely luminous QSO powered by a massive black hole of $3 \times 10^9\, M_\odot$ accreting close to its Eddington limit (Willott et al. 2003). In a K'-band Keck image (Fan et al. 2003), the source ($K' = 16.9$) is unresolved and no other optical source with $K' > 21$ is present within $10''$ of the QSO, thereby ruling out strong gravitational lensing on arcsecond scales. J1148+5251 is detected at 250 GHz in the pointed measurements at 4.8 ± 0.8 mJy, and in the map at 5.3 ± 1.0 mJy. It was not detected at 43 GHz with the VLA to a 3 σ limit of 0.33 mJy, implying a lower limit to the spectral index between 43 and 250 GHz of +1.6.

J1148+5251 was not detected at 1.4 GHz in the VLA FIRST survey (Becker et al. 1995). However, the survey shows two bright radio sources within $1'$ of J1148+5251 (Fig. 1 and Table 1). The one located north-east of the QSO, FIRST-NE, is also detected (unresolved) at 43 GHz, implying a falling spectrum between 1.4 and 43 GHz of index −1.2. The other FIRST source (FIRST-SW) is located south-west of J1148+5251, coincident with a large elliptical galaxy at redshift 0.05 (Fan et al. 2003), and is not detected at 43 GHz. The lower resolution VLA 1.4 GHz NVSS and Westerbork 327 MHz Northern Sky Survey (WENSS) show that FIRST-SW is located at the center of extended radio emission reaching about 4 arcmin SE-NW (Fig. 1). For a $1'$ field one expects only 0.003 sources by chance with $S_{1.4} > 8$ mJy (Fomalont et al. 2003), so the presence of several such objects in the vicinity of the QSO is remarkable.

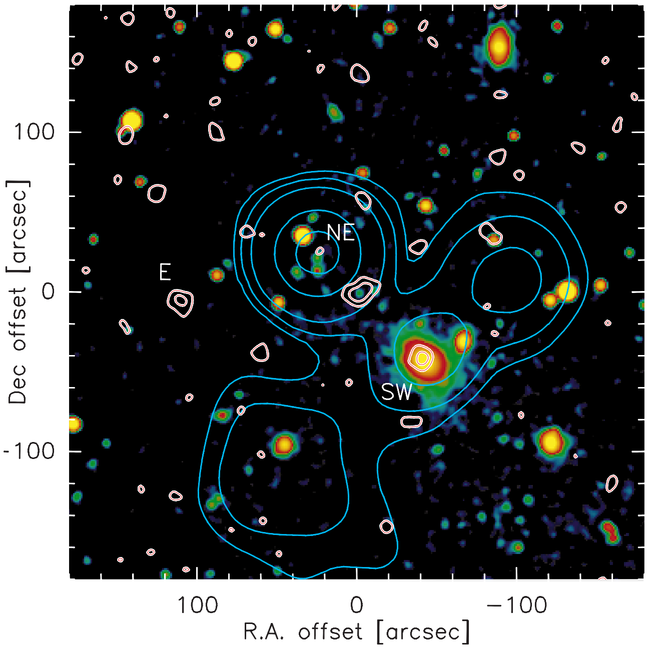

Fig. 1. The 6 arcmin field surrounding the QSO SDSS J114816.64+525150.3. Coordinates are offsets from the optical QSO, which is visible as a faint blue dot. *Color image*: SDSS z band image, smoothed to $4''$ and logarithmically scaled. *Red-white contours*: MAMBO-2 250 GHz signal to noise map smoothed to $13''$. The contours correspond to 2 and 4 σ. The rms noise level, σ, in the proper map is 0.9 mJy in the central $100''$ and rises to $\sim$1.7 mJy at a radius $200''$. *Blue contours*: VLA NVSS 1.4 GHz image. The beam size is $45''$, and contour values are 2, 4, 8, 32, 64 mJy/beam.

The MAMBO image of J1148+5251 reveals at least two other sources (Fig. 1): the $z = 0.05$ elliptical galaxy (FIRST-SW) south-west of J1148+5251, and a source toward the east (mm-E), with no optical counterpart in the SDSS images. We also notice a 2 σ peak which coincides with FIRST-NE, which may correspond to the fainter part of a double compact optical galaxy. Several potential millimeter sources at the 3 σ level are found in the 1.2 mm map, but considering the size of the map they are not very significant.

It is peculiar that the QSO is surrounded by two strong millimeter sources. The MAMBO deep field surveys (Bertoldi et al. 2000a,b; Carilli et al. 2001b) show an average surface density of sources with flux density >4 mJy of 0.02 arcmin^{-2}. The probability to find two such millimeter sources within a 2 arcmin radius from the QSO is only 6%. The optical images show that the QSO falls into a region with an overdensity of foreground galaxies surrounding the $z = 0.05$ elliptical galaxy. That the central cD galaxy of a cluster can show noticeable submillimeter emission was pointed out by, e.g., Edge et al. (1999). The association of the QSO with a millimeter-bright

Table 1. Properties of the observed QSOs and of field sources near J1148+5251.

Source	z	M_{1450} [mag]	RA (J2000)	Dec (J2000)	$S_{1.4}$ [mJy]	S_{43} [mJy]	S_{250} [mJy]	$L_{\rm FIR}$ [$L_\odot$]	$M_{\rm dust}$ [$M_\odot$]
J1630+4012	6.05	−26.1	16 30 33.90	+40 12 09.6	<0.44	–	0.8 ± 0.6	$<5\times10^{12}$	$<2\times10^{8}$
J1048+4637	6.23	−27.6	10 48 45.05	+46 37 18.3	<0.43	<1.11	3.0 ± 0.4	7.5×10^{12}	4×10^{8}
J1148+5251	6.42	−27.8	11 48 16.64	+52 51 50.3	<0.33	<0.33	5.0 ± 0.6†	1.2×10^{13}	7×10^{8}
mm-SW			11 48 12.17	+52 51 09	<0.33	<0.33	5.1 ± 1.0		
FIRST-SW	0.05		11 48 12.16	+52 51 08	8.0 ± 0.2††	<0.33			
mm-NE			11 48 19.30	+52 52 14	<0.33	<0.33	2.2 ± 1.0		
FIRST-NE			11 48 19.58	+52 52 13	75 ± 1	1.2 ± 0.11			
mm-E			11 48 28.79	+52 51 44	<0.33	<0.33	5.8 ± 1.1		

NOTE – The optical properties are from Fan et al. (2003) and the 1.4 GHz data from the VLA FIRST survey. Upper limits are given at the 3 σ level. † Average of on-off and map measurements. †† Source may be over-resolved in the FIRST survey.
To estimate the far-infrared luminosities, $L_{\rm FIR}$, we adopt a dust temperature of 45 K and an emissivity index $\beta = 1.5$, which is typical for the spectrum of an infrared-luminous galaxy. Increasing β to 2 would raise the luminosities by ∼20%, whereas varying the dust temperature by ±10 K would change the luminosities by about a factor 2 down or up, respectively.

cD could thus be interpreted as due in part to a lens amplification of the QSO by the cluster or the dark matter halo associated with the elliptical. However, the low redshift of the cD or cluster would not produce a strong amplification. The presence of an intervening CIV absorption system at $z = 4.95$ (White et al. 2003) hints at the possible existence of another possible lens, but a high-redshift lens would not produce a large amplification either.

It remains unclear whether the eastern millimeter source mm-E or the strong radio source FIRST-NE are associated with the QSO or with the foreground cluster.

If we assume that the source mm-E is lens amplified by a factor 2, then the chance probability to find such a source within 2′ of the QSO is of order unity. Although the statistical evidence is weak, the optical, millimeter, and radio data hint at a mild lens amplification toward J1148+5251, which would lower its implied luminosity and dust mass. Alternatively, they hint at a possible overdensity of objects near the $z = 6.4$ QSO.

J1048+4637. At $z = 6.23$, this optically very luminous BAL QSO is the third most distant quasar identified to date. There is no evidence for arcsecond scale gravitational lensing of this source (Fan et al. 2003). J1048+4637 is detected at 250 GHz, but not at 43 GHz (Table 1), and we find a lower limit to the spectral index between 43 and 250 GHz of +0.6. This QSO was not detected at 1.4 GHz in the FIRST survey to a 3 σ upper limit of 0.43 mJy/beam. There is, however, a possible detection of a faint, 0.46 mJy radio source 20″ west of the QSO.

J1630+4012. This $z = 6.05$ QSO is the optically faintest $z > 5.7$ QSO found in the SDSS (Fan et al. 2003). J1630+4012 is neither detected at 250 GHz nor at 1.4 GHz, and no radio sources are found within 1′ from the QSO to this limit.

4. Discussion

All five QSOs known to date at $z \geq 6$ (Fan et al. 2001, 2003) were observed at 250 GHz to rms sensitivities ∼1 mJy (Petric et al. [2003] place upper limits for J1030+0524 and J1306+0356 at $z = 6.28$ and 5.99, respectively). The detection of two quasars reported in this Letter is consistent with the 30% detection fraction of QSOs in the redshift range $z \approx 2$ to 6 surveyed at 250 GHz to mJy sensitivities (Omont et al. 2001, 2003; Carilli et al. 2001a). The fraction of optically luminous QSOs that are also infrared luminous is therefore roughly constant with redshift, out to the highest redshifts explored. If the dominant dust heating mechanism is radiation from young stars, the implied star formation rates in J1048 + 4637 and J1148 + 5251 are 2000 $M_\odot\,{\rm yr}^{-1}$ and 3000 $M_\odot\,{\rm yr}^{-1}$, respectively, comparable to what was derived for the $1.5 < z < 5.5$ QSOs detected at millimeter wavelengths.

In the optical spectra of the two $z > 6$ QSOs detected at 250 GHz, the Lyα+[NV] emission lines are relatively weak, in contrast to the three non-detected QSOs, which show stronger and sharper lines (Fan et al. 2001, 2003). This trend agrees with the results of Omont et al. (1996) that luminous high redshift QSOs with weak broad emission or broad absorption optical lines tend to have stronger millimeter emission.

From the infrared luminosities, we derive dust masses of 4×10^{8} and 7×10^{8} $M_\odot$ for J1048+4637 and J1148+5251, respectively. Following Omont et al. (2001) we here adopted a dust absorption coefficient at 230 μm of $\kappa_{230} = 7.5\,{\rm cm}^2\,{\rm g}^{-1}$, a value that applies to a galactic dust composition and is unknown for high redshift sources. The implied dust mass is affected also by the assumed temperature of the warm dust component and by the possible presence of an additional cold dust component (see the discussion in Omont et al. 2001). Despite these large uncertainties, the estimated dust masses are huge, implying a high abundance of heavy elements at $z \approx 6$. This is consistent with the super-solar metallicities found in the three QSOs discussed here (Fan et al. in preparation), and with the Fe/Mg abundance ratios near or above the solar value measured in three other QSOs at $5.7 < z < 6.3$ (Freudling et al. 2003).

The presence of large amounts of dust at redshift 6.4 implies that efficient dust formation took place between the corresponding cosmic time and the epoch of early reionization

($z_\mathrm{r} \approx 17$, Kogut et al. 2003), a time span of $\approx$0.7 Gyr. At a constant formation rate this implies a net dust production rate of $\approx 1\,M_\odot\,\mathrm{yr}^{-1}$ in these starburst QSOs.

A time span of 0.7 Gyr is short by at least a factor 2 to efficiently produce refractory grains in the quiescent winds of low-mass ($M \leq 8\,M_\odot$) stars. If the observed dust were the product of stellar processes, the initial refractory dust enrichment might have occurred primarily through dust condensation in supernova remnants, and perhaps in the winds of high-mass ($M \geq 40\,M_\odot$) stars, which are thought to have dominated the early phases of star formation (e.g., Bromm & Loeb 2003). The dust in the early Universe must then be composed of silicates and perhaps oxides, since carbon dust is primarily formed from stars of mass 2–5 $M_\odot$ (Dwek 1998) – except if dust production in the winds of high-mass stars was important (Todini & Ferrara 2001). For silicate and iron oxide dust the mass absorption coefficient may take a higher value (Henning & Muschke 1997) than the one we adopted to compute the dust mass, which may therefore be overestimated.

Elvis et al. (2002) proposed that dust may be produced in outflows from the broad line region of an AGN. The dust content of QSOs should then be roughly independent of redshift, which is consistent with the similar FIR properties of QSOs from redshift 2 to beyond 6. A difficulty with this model is that it requires pre-existing heavy elements in the interstellar medium, and hence prior star formation may be required regardless. This mechanism can produce up to $10^7\,M_\odot$ of dust fairly readily, but the production of the much larger amounts may be problematic.

Although the quasars we observed are extreme and rare objects hardly representative of the dominant star forming galaxies in the early Universe, they do show that early star formation lead to a rapid metal and dust enrichment of the interstellar medium. Therefore absorption by dust could have significantly reduced the escape fraction of ionizing radiation from galaxies during the epoch of reionization.

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