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Radio Observations of the Highest Redshift QSOs

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Abstract

We present 1.4, 5, and 250 GHz observations of ten optically selected Quasi Stellar Objects (QSOs) at z $\geq$ 5.0 taken with the Very Large Array (VLA) and the Max-Planck bolometer array (MAMBO) at the IRAM 30 m telescope. Four sources are detected at 1.4 GHz and three at 250 GHz. All three sources detected at 250 GHz have $S_{250} \gg S_{1.4}$, implying that the 250 GHz emission is likely thermal emission from warm dust. Two of these sources have 250-to-1.4 spectral indices below the value expected from the FIR-radio correlation for nearby star forming systems suggesting that at least the 1.4 GHz emission relates to the AGN activity. 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 ($S_{1.4} > 0.2$mJy) are detected in a $2'$ field centered on the QSO, including an edge-brightened ('FRII') double radio source with an extent of about $1'$.

1.1 Introduction

We have undertaken an extensive observational program from radio through submillimeter wavelengths of high-redshift quasi-stellar objects (QSOs) in order to address the interesting possibility of coeval black hole and spheroidal galaxy formation in the earliest epochs (Carilli et a. 2001a, 2001b, 2002; Omont et al. 2001, 2002; Cox et al. 2002). Millimeter-continuum observations of high redshift QSO's show that 30% of the sources are detected in surveys with flux density limits of 1 to 2 mJy at 250 GHz, corresponding to infrared luminosities of order 10^{13} $L_\odot$. Radio continuum studies of the mm-detected sources show that the mm-to-cm spectral energy distributions of many of the sources are consistent with the dust (seen as thermal emission at 250 GHz) being heated by star formation. 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 ($\sim 10^{11} M_\odot$) (Omont et al. 2001, Carilli et al. 2002a,b) leading some authors to conclude that active star formation is inevitable (Omont et al. 2001). A similar conclusion has been reached for lower redshift QSOs by Andreani et al. (2002).

Here we extend our radio study of distant QSOs to the highest redshifts ($z > 5$). These observations are an order of magnitude, or more, more sensitive than previous studies of these sources at cm and mm wavelengths. We assume a Λ dominated cosmology (Ω_m = 0.3, Ω_Λ = 0.7) and H_0 = 65 km sec^{-1} Mpc^{-1} throughout. A more detailed analysis is presented in Petric et al. 2004 (in prep).

1.2 Results

We detect 40% of the high redshift sources sources at 1.4 GHz at the $>$ 50 μJy level. Two of the sources SDSS J0836+0054 ($z = 5.82$) and SDSS J0913+5919 ($z = 5.11$), are considerably brighter than this (1.5 mJy and 18.8 mJy, respectively). The radio spectral index is about –0.75 in both cases. From these data we derive rest-frame 1.4 GHz luminosity densities of 5.0×10^{26} and 4.9×10^{27} W Hz^{-1}, respectively, making these two sources radio-loud according to the definition of Gregg et al. (2002). The percentage of radio-loud sources in this sample is roughly consistent with no evolution in the radio-loud QSO fraction out to $z \sim 6$.

Three sources (J0756+4104 at $z = 5.09$, J0301+0020 at $z = 5.50$, and J1044-0125 at $z = 5.73$) are detected at 250 GHz with flux densities of 4.1$\pm$1.0, 0.87$\pm$0.2, 2.0$\pm$0.8 mJy, respectively. These 250 GHz flux densities are at least ten times above their 1.4 GHz flux densities. The rapidly rising spectrum from cm to mm wavelengths is strong evidence that the millimeter signal is thermal emission from warm dust heated by the AGN or a co-eval starburst, or both. One 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 the FIR luminosity (Condon 1992; Condon & Yin 1990; Miller & Owen 2001; Yun, Reddy, & Condon 2001). If this correlation holds to high redshift (Carilli& Yun 1999; 2000; Yun & Carilli 2002; Garrett 2001) then comparing centimeter and mm continuum luminosities is a possible diagnostic of star formation. However, an important caveat is that lower luminosity, radio quiet QSOs at lower redshift also follow the standard radio–FIR correlation for star forming galaxies (Sopp & Alexander 1991). Whether the sources in the Sopp & Alexander sample also host active star formation remains an open question. Given this uncertainty, we consider the radio-FIR correlation as a consistency check for star formation, but certainly not conclusive.

Figure 1.1 shows the relationship between redshift and the 250–1.4 GHz spectral index ($\alpha_{1.4}^{250}$) 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_D=50K and a dust emissivity index of 1.5). A point located below the curve on this diagram indicates a source that is radio loud relative to a star-forming galaxy. The 250–to–1.4 GHz spectral index for J0301+0020 is 0.5 ± 0.1, well below the region defined by star forming galaxies. The value for J0756+4104 is 0.8 ± 0.1, which is marginally below the star forming galaxy range. In these two cases it seems likely that the radio emission relates to the AGN activity. J1044-0125 was detected at 250GHz with $S_{250} = 2.0 \pm 0.8$mJy, but not at 1.4 GHz. For this source $\alpha_{1.4}^{250} > 0.6$, and 350 GHz observations (Isaak et al. 2002) both suggest that star formation might be the dominant dust heating source.

The highest redshift QSO currently published, J1030+0524 at $z = 6.28$ (Fan et al. 2001), is not detected at 1.4 or 250 GHz, with 3σ limits of 61μJy and 3.4 mJy, respectively. However, four fairly bright sources ($>$ 200μJy) are detected at 1.4 GHz in a $2'$ field centered on the QSO, including an edge-brightened ('FRII') double radio source with an extent of about $1'$ (Figure 1.2).

1.3 Discussion

Given the interest in co-eval massive black hole–spheroidal galaxy formation, it is instructive to consider what the properties of the sources detected at 250 GHz would be if the emission was a result of dust heated by a starburst. Using the relations between 250

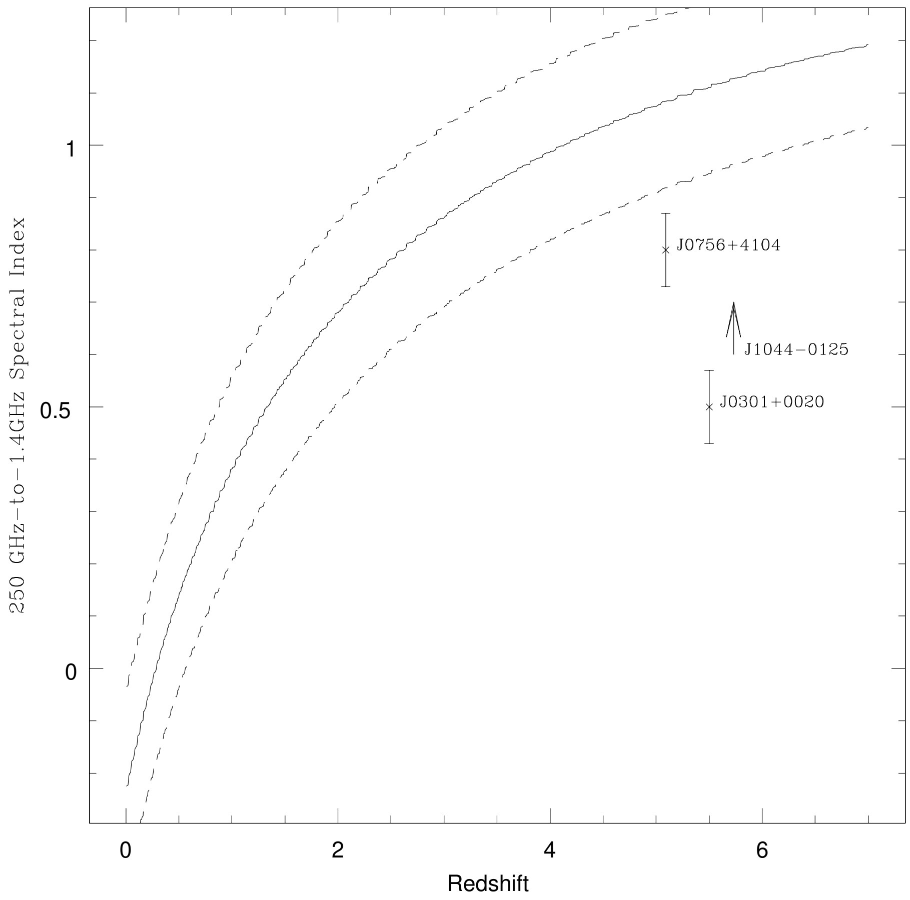

Fig. 1.1. The relationship between redshift and the observed spectral index between 250 and 1.4 GHz for star-forming galaxies (solid curve), as derived from the models presented in Carilli & Yun (2000). The dashed lines show the rms scatter in the distribution. The 250–to–1.4 GHz spectral indexes for QSOs detected at 250 GHz are shown with 1σ error bars.

GHz flux density and FIR luminosity in Omont et al. (2004) based on typical spectra of low redshift ultra-luminous infrared galaxies leads to: $L_{\rm FIR} = 2.8 \times 10^{12}$ $L_\odot$ for J0301+0020, 1.4×10^{13} $L_\odot$ for J0756+4104, and 7×10^{12} $L_\odot$ for J1044–0125. Using equation (4) in Carilli et al. (2004) implies massive (> 5 $M_\odot$) star formation rates of 200, 1000, and 500 $M_\odot$ year^{-1}, respectively. At these extreme star-formation rates most of the stars in a large spheroidal galaxy could form in a dynamical time of 10^8 years.

Having four radio sources in the $2'$ field centered on the highest redshift QSO (J1030+0524) is unusual in that the sub-mJy source counts of Fomalont et al. (2004) predict only 0.5 sources by chance for a $2'$ field. We feel it unlikely that the sources are at the redshift of

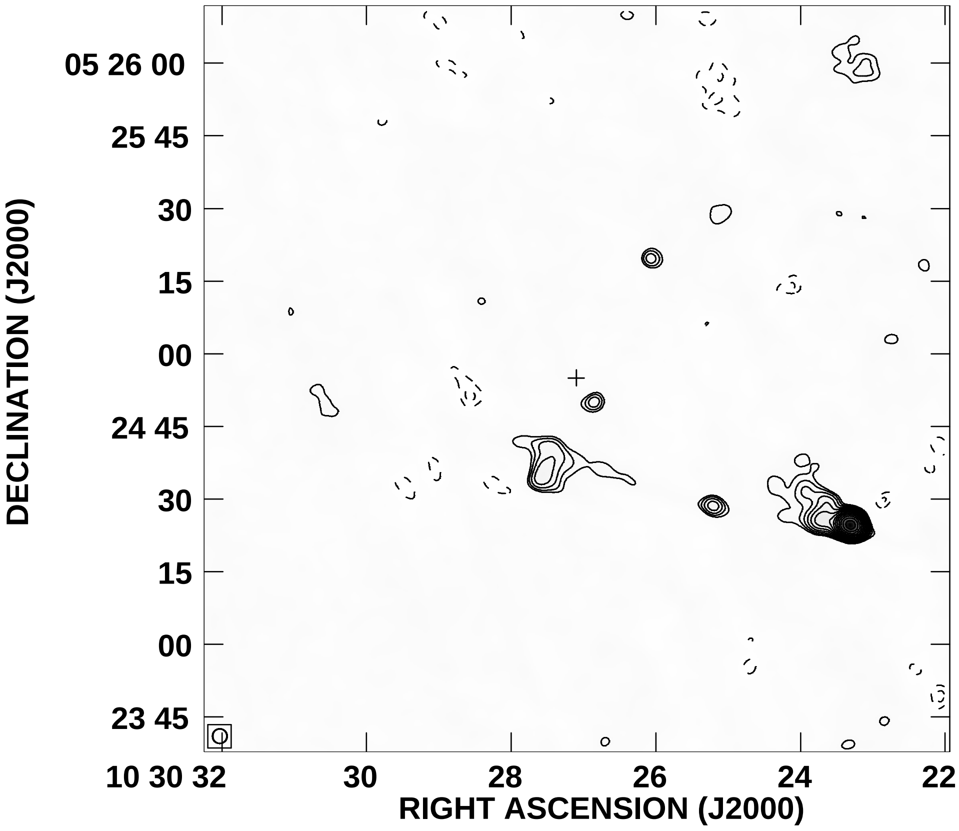

Fig. 1.2. An image of J1030+0524 at 1.4 GHz made using the VLA. The FWHM of the Gaussian restoring beam is 3" $\times$ 3". Contour levels are a geometric progression in the square root of two starting at $2\sqrt{2}\ \sigma$, with σ = 48 μJy. Three negative contours (dashed) are included. The cross shows the position of the optical QSO.

the QSO, since an arcmin-scale double radio galaxy has never been detected beyond $z \sim 3$ (Carilli et al. 1997), and an inspection of the DPOSS suggests that this double source may be associated with a relatively low redshift elliptical galaxy. A more likely explanation is that these four radio sources are in a group or cluster that happens to lie along the line-of-sight to this very high redshift QSO.

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