VLBA OBSERVATIONS OF $z > 4$ RADIO-LOUD QUASARS

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ABSTRACT

We present high-resolution ($\leq 20$ mas) observations of the radio continuum emission at 1.4 GHz from three high-redshift quasars: J1053–0016 ($z = 4.29$), J1235–0003 ($z = 4.69$), and J0913+5919 ($z = 5.11$), thereby doubling the number of $z > 4$ radio-loud quasars that have been imaged at milliarcsecond resolution. The observations were carried out with the Very Long Baseline Array (VLBA) of the NRAO. All three sources are unresolved in these observations, with source size limits of a few milliarcseconds. In all cases the flux densities measured by the VLBA are within 10% of those measured with the Very Large Array (VLA), implying that the sources are not highly variable on yearly time scales. We find no indication for multiple images that might be produced by strong gravitational lensing on scales from 20 mas (VLBA) to a few arcseconds (VLA), to dynamic range limits of $\sim 100$.

Key words: galaxies: active — galaxies: high-redshift — radio continuum: galaxies — techniques: interferometric

1. INTRODUCTION

Surveys such as the Sloan Digital Sky Survey (SDSS) (York et al. 2000) and the Digitized Palomar Sky Survey (Djorgovski et al. 1999) have revealed large samples of quasi-stellar objects (QSOs) out to $z \sim 6$. Studies by Fan et al. (2002) have shown that at such a high redshift we are approaching the epoch of reionization, the edge of the “dark ages,” when the first stars and massive black holes were formed. Eddington-limit arguments suggest that the supermassive black holes at the center of these QSOs are on the order of $10^9 M_\odot$. If the correlation between bulge and black hole masses (Gebhardt et al. 2000; Ferrarese & Merritt 2000) also holds at these high redshifts, then these sources have associated spheroids with masses on the order of $\sim 10^{12} M_\odot$. It is challenging to explain the formation of such massive structures on relatively short time scales ($\sim 1$ Gyr). However, Wyithe & Loeb (2002) estimate that almost one-third of known quasars at $z \sim 6$ ought to be lensed by galaxies along the line of sight. If these quasars are indeed gravitationally lensed, the estimated masses of their associated spheroids could be smaller by up to an order of magnitude; this would allow a less efficient assembly process.

High-resolution radio observations of high-redshift radio-loud quasars can be used to test for strong gravitational lensing by looking for multiple imaging on scales from tens of milliarcseconds to arcseconds. Also, Very Long Baseline Interferometry (VLBI) observations of core-jet radio sources in quasars over a large range in redshift have been used to constrain the cosmic geometry, under the assumption that such sources are (roughly) “standard rulers” (Gurvits, Kellermann, & Frey 1999). In general, the high resolution of the VLBI observations permits a more detailed look at the physical structures in the most distant cosmic sources.

To date, only three radio loud quasars at $z > 4$ have been imaged at milliarcsecond resolution (Frey et al. 1997, 2003). In this paper we present Very Long Baseline Array (VLBA) observations of three more quasars at $z > 4$: SDSS J105320.42–001649.7 at $z = 4.29$, SDSS J123503.04–000331.7 at $z = 4.69$, and SDSS J091316.56+591921.5 at $z = 5.11$ (hereafter J1053–0016, J1235–0003, and J0913+5919). J1053–0016 was first identified by Irwin, McMahon, & Hazard (1991) and Smith, Thompson, & Djorgovski (1994) as BRI 1050–0000, while the other two sources were discovered in the five-color imaging data from the SDSS (Fan et al. 2000; Anderson et al. 2001). All three quasars are known to be radio-loud (Carilli et al. 2001; Petric et al. 2003).

Throughout this paper we assume a flat cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$. In this model 1 mas corresponds to about 7 pc at $z = 4.5$.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out at 1425 MHz using the 10 stations of the Very Long Baseline Array (VLBA) of the NRAO. The sources J0913+5919, J1235–0003, and J1053–0016 were observed on the 2003 March 1, 21, 29, respectively. The total observing time on each source was 7 hr. The observations employed nodding-style phase referencing with a cycle time of 3.5 minutes. The phase calibrators

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of J1053−0016, J1235−0003, and J0913+5919 were J1048+0055, J1232−0224, and J0921+6215, respectively. Phase-referencing observations allow the determination of the absolute position of the target source and its components, if any, from the position of the calibrator (Walker 1999). In applying the phase-referencing technique, the accuracy of the calibrator position is important. The positions of our phase-reference sources are obtained from the VLBA Calibrator Survey (Beasley et al. 2002) and are accurate to about 1 mas.

Two adjacent 8 MHz baseband channel pairs were used in the observations of each source, both with right- and left-hand circular polarizations, sampled at two bits. The data were correlated at the VLBA correlator in Socorro, New Mexico, with 2 s correlator integration time. Data reduction and analysis were performed using NRAO’s Astronomical Image Processing System (AIPS).

After applying a priori flagging, amplitude calibration was performed using measurements of the antenna gain and the system temperature of each station. Ionospheric corrections were applied using the AIPS task TECOR. The phase calibrators were self-calibrated in both phase and amplitude, and imaged in an iterative cycle. The self-calibration solutions of the phase calibrators were applied to the respective target sources. To further improve the signal-to-noise ratio of the images, we self calibrated the target sources themselves.

3. RESULTS

Figures 1, 2, and 3, are our VLBA images of J1053−0016, J1235−0003, and J0913+5919, respectively. The rms noise in each image is 68.5 μJy beam−1, with dynamic ranges of 180, 252, and 293, respectively. All these sources are unresolved at the angular resolution of the VLBA at the observed 1.4 GHz frequency, suggesting that the radio emission from each object is confined to a compact region less than 10 mas in size.

Table 1 shows the results of fitting Gaussian models to the observed source spatial profiles using the AIPS task JMFIT. The source names, redshifts, and positions are listed in columns (1), (2), (3), and (4), respectively. Their total flux densities are listed in column (5), and the derived upper limits to deconvolved source sizes are given in column (6).

The VLA flux densities of these objects at 1.4, 5, and 15 GHz are listed in Table 2 (Stern et al. 2000; Carilli et al.)
In all cases, the 1.4 GHz flux densities measured by the VLA and VLBA are equal to better than 10%. These results imply that the sources are not highly variable on time scales of years. Two of these objects, namely, J1053−0016 and J1235−0003, have flat spectra between 1.4 and 5 GHz but have steeper spectra between 5 and 15 GHz. The source J0913+5919 is a steep spectrum compact source between 1.4 and 5 GHz. Note that an observing frequency of 1.4 GHz corresponds to a rest frequency of about 8 GHz at \( z = 4.5 \).

We have synthesized larger images (\( 2'' \times 2'' \)) using the VLBA and found no other radio components at \( \geq 3 \sigma \) level \((\sim 200 \mu\text{Jy beam}^{-1})\) in the field. The implied dynamic range limit between the target sources themselves and any companion structures is then larger than 60 to 100. A similar limit to extended and/or multiple structures has been found on larger scales (\( 2'' \times 2'' \)) for all these three sources using the VLA (Carilli et al. 2001; Petric et al. 2003; M. P. Rupen 2003, private communication). In all cases, the 1.4 GHz flux densities measured by the VLA and VLBA are equal to better than 10%. These results imply that the sources are not highly variable on time scales of years. Two of these objects, namely, J1053−0016 and J1235−0003, have flat spectra between 1.4 and 5 GHz but have steeper spectra between 5 and 15 GHz. The source J0913+5919 is a steep spectrum compact source between 1.4 and 5 GHz. Note that an observing frequency of 1.4 GHz corresponds to a rest frequency of about 8 GHz at \( z = 4.5 \).

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4. DISCUSSION

The VLBA imaging of three \( z > 4 \) radio loud quasars (J1053−0016, J1235−0003, and J0913+5919) shows that these sources are smaller than a few milliarcseconds in size, corresponding to physical scales of \( \leq 20 \) pc. Moreover, all three sources show falling spectra at high frequency, and none of the sources are variable on yearly time scales. These results suggests that the sources are likely core-jet radio sources and hence may be used to extend to very high redshifts the studies of cosmic geometry using core-jet radio sources (Gurvits et al. 1999). Higher frequency VLBA observations at higher spatial resolution are planned to test this possibility.

We find no indication of multiple radio components in the fields of these sources on scales of 20 mas to a few arcseconds, to dynamic range limits of \( \sim 100 \). A similar conclusion was reached for three other \( z > 4 \) radio-loud quasars (Frey et al. 1997, 2003). These results imply that at least these six high-z quasars are not strongly gravitationally lensed.

The compact nature of these quasars make them excellent candidates for future \( \text{H} \iota 21 \text{ cm} \) absorption experiments to detect the neutral IGM in their host galaxies (Furlanetto & Loeb 2002), in particular the steep spectrum source J0913+5919. Such a search is currently underway using the Giant Meter Wave Radio Telescope. Knowledge of source structure, as presented herein, is critical for both identifying potential candidates for \( \text{H} \iota 21 \text{ cm} \) absorption searches and for subsequent interpretation of the results.
Fig. 3.—Naturally weighted continuum image of J0913+5919 (z = 5.11) at 1.4 GHz. The restoring beam size is $10.96 \times 6.19$ mas in position angle $-2^\circ$. The peak flux density is $19.34$ mJy beam$^{-1}$, and the contour levels are at $-3, 3, 6, 12, \ldots, 192$ times the rms noise level, which is $66$ μJy beam$^{-1}$. The gray-scale range is indicated by the step wedge at the right side of the image. The reference point $(0, 0)$ is $\alpha(J2000.0) = 09^h13^m16^s5472$, $\delta(J2000.0) = +59^\circ19^\prime21^\alpha66$. 

| Source          | $z$   | R.A. (J2000.0)   | Decl. (J2000.0) | Total Flux Density | Size   |
|-----------------|-------|-----------------|-----------------|-------------------|--------|
| J1053−0016       | 4.29  | 10 53 20.4264   | −00 16 49.6438  | 12.413 ± 0.118    | < 3.2  |
| J1235−0003       | 4.69  | 12 35 03.0469   | −00 03 31.7606  | 17.155 ± 0.116    | < 3.3  |
| J0913+5919       | 5.11  | 09 13 16.5472   | +59 19 21.6656  | 19.407 ± 0.115    | < 1.3  |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
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Table 2

| Source       | $S_{1.4}$ (mJy) | $S_{5}$ (mJy) | $S_{15}$ (mJy) | Ref. |
|--------------|----------------|---------------|---------------|-----|
| J1053--0016  | 11.5           | 10.2          | 6.5           | 1, 2, 3 |
| J1235--0003  | 18.8           | 17            | 6.9           | 1, 3  |
| J0913+5919   | 18.95          | 8.1           | ...           | 4    |

References.—(1) Carilli et al. 2001; (2) Stern et al. 2000; (3) Petric et al. 2003; (4) M. P. Rupen 2003, private communication.