Radio structure of the most distant radio-detected quasar at the ten milli-arcsecond scale

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ABSTRACT

We present a high resolution radio image of SDSS 0836+0054 identified recently as the most distant radio-detected quasar at a redshift of \( z = 5.82 \). The observation was carried out with ten antennas of the European VLBI Network, spread from Europe to China and South Africa, at 1.6 GHz frequency on 2002 June 8. The source is detected with a total flux density of 1.1 mJy, equal to its flux density measured in the VLA FIRST survey. We found no indication of multiple images produced by gravitational lensing. The radio structure of the quasar at \( \sim 10\text{-mas angular resolution appears somewhat resolved. It resembles the radio structure typical for lower redshift radio-loud active galactic nuclei. We obtained so far the best astrometric position of the source with an accuracy better than 8 mas, limited mainly by the structural effects in the phase-reference calibrator source.

Key words: techniques: interferometric – radio continuum: galaxies – galaxies: active – quasars: individual: SDSS 0836+0054 – quasars: individual: PKS 0837+012 – cosmology: observations

1 INTRODUCTION

The object SDSSp J083643.85+005453.3 (hereafter: SDSS 0836+0054) is the highest redshift radio-detected quasar known to date (\( z = 5.82 \)) discovered using multicolor imaging data from the Sloan Digital Sky Survey (SDSS) \cite{Fan2003}. The object is one of the seven \( z > 5.7 \) quasars known. Six of them form a complete colour-selected flux-limited sample from an area of 2870 \( \text{deg}^2 \) \cite{Fan2003}. The quasar SDSS 0836+0054 was identified with an unresolved radio source within 1" in the VLA FIRST survey \cite{White1997}, where the source total flux density was 1.11 \( \pm 0.15 \) mJy at 1.4 GHz (21 cm wavelength). The total flux density in the NRAO VLA Sky Survey (NVSS) \cite{Condon1998} was 2.5 \( \pm 0.5 \) mJy at the same frequency.

According to the recent studies (e.g. \cite{Barkana2002} and references therein), \( z \sim 6 \) is close to the reionization epoch of the Universe. In the optical spectrum of SDSS 0836+0054, however, the Gunn–Peterson effect is not seen. There is detectable emission blueward of the Ly\( \alpha \) line, i.e. the intergalactic medium is already highly ionized at \( z \sim 5.8 \) along this line of sight \cite{Fan2001}.

The estimated mass of the central black hole in SDSS 0836+0054 is \( 4.8 \times 10^9 \)M\(_\odot\), assuming that the quasar is emitting at the Eddington luminosity and its apparent flux is not significantly magnified by beaming or gravitational lensing \cite{Fan2001}. There are, however, indications that the latter assumptions may not be correct. Simulations show that up to one third of \( z \sim 6 \) quasars may be magnified due to gravitational lensing by a factor of ten or more. Therefore their black hole masses are overestimated by the same factor \cite{Wyithe2002}. The probability estimations strongly depend on the quasar luminosity function used. Considering a wider range of possible luminosity functions, \cite{Comerford2003} conclude that present data allow lensing probability of essentially 100%. In turn, the luminosity function can be constrained using the detections or absence of lensing events with multiple images of \( z \sim 6 \) quasars.

Black hole mass values of \( z \gtrsim 6 \) quasars have great importance for hierarchical structure formation models in the early Universe, placing important constraints on parameters such as the seed mass, velocity dispersion, radiative efficiency and accretion luminosity. The time needed for a supermassive \( \sim 10^9 \)M\(_\odot\) black hole to grow from a stellar-mass seed may be comparable to the age of the Universe at this redshift \cite{Haiman2001}.

The first four \( z > 5.7 \) SDSS quasars \cite{Fan2001}, including SDSS 0836+0054 are detected in X-rays \cite{Brandt2002}. Short exploratory Chandra observations revealed that SDSS 0836+0054 is consistent with a point-like X-ray source \cite{Brandt2002, Mathur2002, Schwartz2002}. \cite{Bechtold2003}. Its position agrees with the optical position within the astrometric precision of Chandra (\( \sim 1'' \)). Based on the limited data available, the broad-band X-ray and optical properties of the extremely distant quasars are apparently similar to those of...
lower redshift ones, implying no strong evolution out to \( z \sim 6 \) (Mathur et al. 2002). On the contrary, Bechtold et al. (2003) found that high-redshift quasars are significantly more X-ray quiet than their low-redshift counterparts.

Any indication of a milli-arcsecond scale “core–jet” radio structure revealed by Very Long Baseline Interferometry (VLBI) could be considered as a strong support for the existence of a supermassive black hole powering SDSS 0836+0054. These structures are common in radio-loud active galactic nuclei (AGN) in the broadest range of redshifts from \( z \sim 0.01 \) to \( z \sim 4 \) (e.g., Paragi et al. 1999; Fomalont et al. 2000). According to the AGN paradigm, the radio emission originates from incoherent synchrotron emission in compact (parsec-scale) jets in the close vicinity of the central black hole.

Here we describe a 1.6-GHz European VLBI Network (EVN) observation of SDSS 0836+0054 and present the high resolution radio image of the quasar. Based on our phase-reference VLBI observation, we derive the accurate astrometric position of the object. We conclude that the image of the quasar is unlikely to be split by gravitational lensing. Throughout this letter, we adopt a flat cosmological model with \( \Omega_m = 0.3 \), \( \Omega_L = 0.7 \) and \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \). In this model, 1 milli-arcsecond (mas) angular separation corresponds to a linear separation of 6.25 pc at the distance of SDSS 0836+0054.

2 OBSERVATION AND DATA REDUCTION

We used ten antennas of the EVN to observe SDSS 0836+0054 at 1.6 GHz (18 cm wavelength) in phase-reference mode. The radio telescopes and their parameters are listed in Table 1. Due to the redshift, the observing frequency corresponds to 11 GHz in the rest frame of the source.

Phase-referencing is a technique of extending the signal coherence time in order to increase the sensitivity of the VLBI array. This is done by regularly interleaving observations between the weak target source and a nearby strong reference source. Delay, delay rate and phase solutions obtained for the phase-referencer calibrator are interpolated and applied for the target source, thus removing most of the phase errors introduced by geometric, ionospheric, atmospheric and instrumental effects (e.g., Beasley & Conway 1995). The ability of the EVN to detect weak (sub-mJy), compact radio sources has been demonstrated recently (e.g., Garrett et al. 2001; Garrington et al. 2001).

The observation of SDSS 0836+0054 took place on 2002 June 8. We selected PKS 0837+012 (J0839+0104; \( z = 1.123 \), Owen et al. 1995) as the phase-reference calibrator. The angular separation between the target and the reference source is \( \sim 0.8 \text{\arcsec} \). The ICRF coordinates of PKS 0837+012 are available from the VLBA Calibrator Survey (Beasley et al. 2002), with an accuracy of 0.35 and 0.58 mas in right ascension and declination, respectively. In principle it allows us to make a precise determination of the poorly known position of SDSS 0836+0054 through differential astrometry inherently provided by the phase-referencing technique. The source J0825+0309 was used as a fringe-finder.

At the frequency of 1.6 GHz, variations in the ionospheric electron column density dominate the propagation effects affecting the quality of phase transfer between the target and calibrator sources. These variations have static and dynamic components, both spatial and temporal, which limit the maximum achievable dynamic range (\( D \)) of VLBI phase-referencing. According to Beasley & Conway (1995), the upper limit of \( D \) is given by

\[
D \simeq 30 \times 10^{-17} (\Delta I)^{-1},
\]

where \( \Delta I \) is peak daily residual total electron content (TEC, in units of \( 10^{17} \text{~m}^{-2} \)), \( \nu \) is the observing frequency in GHz, \( \theta \) is the angular distance between the target and reference sources (in degrees). Our observation took place relatively close after the peak of the solar cycle. Considering the worst case of the maximum TEC as \( \Delta I = 5 \times 10^{-17} \text{~m}^{-2} \) (which corresponds to the solar maximum daytime value, Beasley & Conway 1995), the conservative estimate of the maximum achievable dynamic range is \( D \simeq 12 \). The dynamic component is caused essentially by medium-scale travelling ionosphere disturbances (MSTIDs). These are time-variable and highly unpredictable. MSTIDs are known to vary on the time scale of tens of minutes to hours and linear scale of hundreds of kilometres (e.g., van Velthoven & Spoelstra 1992).

At the maximum, which normally lasts for up to 5% in time, the amplitude of MSTIDs could worsen the upper limit of the achievable dynamic range by a factor of \( \sim 2 \) at our target–reference separation comparing to the worst case of static component (e.g., Conway & Vermeulen 1993). By splitting up the data set into four equal time intervals, we did not notice any significant difference between our results on this time scale.

The total observing time was 5 hours with dual circular polarization at all antennas but Sheshan where only left circular polarization was observed. The data were recorded with the Mark IV VLBI data acquisition system at the rate of 256 Mbit/s per station with 2-bit sampling, resulting in 64 MHz total bandwidth. The correlation took place at the EVN Data Processor at the Joint Institute for VLBI in Europe (JIVE), Dwingeloo, The Netherlands.

We used 5-min switching cycles between SDSS 0836+0054 and the phase-referencer calibrator quasar J0839+0104. The target source was observed for \( \sim 210 \) s intervals in each cycle. The total on-source time for SDSS 0836+0054 was 2.9 hours. The achievable 1-\( \sigma \) image noise was estimated to be 27 \( \mu \text{Jy/beam} \).

The NRAO AIPS package (e.g., Diamond 1995) was used for initial data calibration and imaging. A priori calibration of visibility amplitudes was done using measured system temperatures for all antennas. The data for the calibrator and fringe-finder sources (J0839+0104 and J0825+0309, respectively) were fringe-fitted in AIPS using 3-min solution intervals. The solutions were interpolated and applied to the data of SDSS 0836+0054 as well. We then imaged the phase-referencer calibrator source with the conventional self-calibration and CLEAN technique (e.g., Walker 1995) using the

\begin{table}[h]
\begin{tabular}{lll}
\hline
Radio telescope (Country) & Diameter (m) & SEFD\(^a\) (Jy) \\
\hline
Effelsberg (Germany) & 100 & 19 \\
Hartebeesthoek (South Africa) & 26 & 450 \\
Jodrell Bank Mk2 (United Kingdom) & 25 & 320 \\
Medicina (Italy) & 32 & 582 \\
Nanshan (P.R. China) & 25 & 1068 \\
Noto (Italy) & 32 & 784 \\
Onsala (Sweden) & 25 & 390 \\
Sheshan (P.R. China) & 25 & 1130 \\
Toru\'i (Poland) & 32 & 230 \\
Westerbork (The Netherlands) & 93\(^b\) & 30 \\
\hline
\end{tabular}
\caption{EVN telescopes and their characteristics at 1.6 GHz}
\end{table}

\(^a\) System Equivalent Flux Density \\
\(^b\) equivalent diameter of the phased array

\footnote{http://magnolia.nrao.edu/vlba_calib}
Radio structure of the most distant radio-detected quasar at the ten milli-arcsecond scale

3 RESULTS AND DISCUSSION

The quasar SDSS 0836+0054 is clearly detected with VLBI and appears somewhat resolved at a linear resolution of ~ 70 pc (Fig. 2). However, the apparent structural extension may be due to remaining residual phase errors after phase-reference calibration.

As seen in Fig. 2, the position of SDSS 0836+0054 differs from the optical position reported by Fan et al. (2001), but is within the given error of 200 mas in both right ascension and declination. The optical position was used in the correlation of our VLBI data as the phase center. Also within the errors, the coordinates are consistent with the values taken from the VLA FIRST survey. Our values $\alpha_{J2000} = 08^h36^m43.8606$ and $\delta_{J2000} = 0^\circ54'53".232$ are determined with respect to the accurately known position of the phase-reference calibrator J0839+0104.

However, the differential astrometry is complicated by the fact that the structure of our reference source, J0839+0104, is rather complex. As seen in Fig. 1, there is a low surface brightness extended feature to the SW of the brightest component. A similar structure in terms of position angle is seen in snapshot VLBA images taken at higher frequencies (2.3 and 8.4 GHz) in the VLBA Calibrator Survey (Beasley et al. 2003). With a higher E-W resolution (uniform weighting, Fig. 1a), the “core” splits into two distinct components 6.6 mas apart. Supposing that the jet is one-sided, we suspect that the true flat-spectrum VLBI core of the quasar is the eastern one which is weaker at 1.6 GHz. Most likely this is the reference point of which the accurate coordinates are determined using 8.4-GHz VLBI observations. On the other hand, the brightest feature in our image may well be a steep-spectrum jet component which appears stronger than the core at this lower frequency. It could not be excluded, however, that the brightest component in Fig. 1 coincides with the core. This remains to be checked.
with high-resolution VLBI imaging of J0839+0104 at frequencies higher than 1.6 GHz.

Since the brightest component of the reference source, which is presumably not identical with the radio core, is in the phase center of our image, the relative position determination of the target source may be corrupted by a systematic error. Therefore we give a conservative error estimate of 8 mas for the position of SDSS 0836+0054. This reflects the uncertainty in the identification of the reference position in the radio image of the phase-reference calibration source J0839+0104.

We searched for possible multiple images of SDSS 0836+0054 that might have been caused by gravitational lensing. To this end, we investigated a large (4” × 4”) field of view centered around the a priori position of SDSS 0836+0054. To avoid distortion of the field of view due to frequency-average smearing, we averaged our data over only 8-MHz channels for imaging. We used the correlator output averaging time of 4 s which did not limit our field of view. No source of compact radio emission has been detected at the brightness level of ~ 100 µJy/beam (3 times the image noise), apart from what is seen in Fig. 2 Moreover, the total flux density in the CLEAN component model corresponding to the natural weighting of SDSS 0836+0054 (Fig. 2) is 1.1 mJy. This is equal to the flux density in the VLA FIRST survey. Although the source total flux density recently measured with the VLA at 1.4 GHz is 1.76 mJy (A. Petric et al., in preparation), the difference may be attributed to source variability and, to a lesser extent, amplitude calibration uncertainties in our VLBI data as well.

Our result suggests that most if not all of the radio emission of SDSS 0836+0054 is confined to a single compact object within an angular extent of ~ 10 mas. Thus we can conclude that the quasar is not multiply imaged by gravitational lensing at the level of brightness ratio \( \lesssim 7 \). Outside of our field of view, there are no indications of multiple images neither in the VLA FIRST and NVSS surveys, nor in the Chandra X-ray image (e.g. Schwartz 2002). Most recently, Fan et al. (2003) found that the high resolution (0′′.1) HST optical image of SDSS 0836+0054 is consistent with an unresolved point source. However, it does not exclude the possibility that its flux is magnified by a factor of up to ~ 2 (Wyithe & Loeb 2002). Note that, based on the size of the ionized region around another SDSS quasar at \( z = 6.28 \), Haiman & Cet (2002) place an upper limit of 5 for the magnification factor in that case.

Using the two-point radio spectral index of \( \alpha \approx -0.9 \) (based on VLA total flux density measurements at 1.4 and 5 GHz, A. Petric et al., in preparation; \( S \propto \nu^{\alpha} \), where \( S \) is the flux density and \( \nu \) is the frequency), the luminosity of SDSS 0836+0054 at 5 GHz (rest frame) is \( L_5 = 1.1 \times 10^{25} \) W Hz\(^{-1}\) sr\(^{-1}\). Together with the estimated black hole mass of \( M_{\text{bh}} = 4.8 \times 10^9 M_{\odot} \) (Fan et al. 2001), this value is consistent with the \( L_5 \propto M_{\text{bh}}^{3/4} \) relation found for radio quasars at \( z \gtrsim 1 \) (Jarvis & McLure 2002) and references therein).

4 CONCLUSIONS

SDSS 0836+0054, the most distant (\( z = 5.82 \)) radio-emitting quasar known to date, is clearly detected with VLBI observations at 1.6 GHz using the EVN. A VLBI image with a dynamic range of 10:1 is made (Fig. 2). The radio structure of the quasar at ~ 10-mas angular resolution is characterized by a compact component. Using phase-reference observations to a nearby calibrator, we derived the most accurate astrometric position of SDSS 0836+0054 available at present. The accuracy of the coordinates is limited by the complex radio structure of the calibrator quasar PKS 0837+012, which we imaged for the first time at 1.6 GHz. The extremely distant quasar SDSS 0836+0054 is unlikely to be multiply imaged by gravitational lensing. Magnification of its flux due to gravitational lensing or relativistic beaming cannot be ruled out.

ACKNOWLEDGMENTS

We thank Chris Carilli for informing us about the results of their VLA observations, and the anonymous referee for useful suggestions. The European VLBI Network is a joint facility of European, Chinese and South African radio astronomy institutes funded by their national research councils. SF, LM and ZP acknowledge partial financial support received from the Netherlands Organization for Scientific Research (NWO) and the Hungarian Scientific Research Fund (OTKA) (grant no. N31721 & T031723). This research was supported by the European Commission’s IHP Programme “Access to Large-scale Facilities”, under contract No. HPRI-CT-1999-00045. We acknowledge the support of the European Union - Access to Research Infrastructure action of the Improving Human Potential Programme. SF and LM acknowledge the hospitality and support of JIVE personnel during the scheduling of the observations, and the data correlation and analysis. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Radio structure of the most distant radio-detected quasar at the ten milli-arcsecond scale

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