EVIDENCE FOR A BLACK HOLE IN A RADIO-QUIET QUASAR NUCLEUS

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ABSTRACT

We present the first milliarcsecond-resolution radio images of a radio-quiet quasar, detecting a high brightness temperature core with data from the VLBA. On maps made with lower frequency data from MERLIN and the VLA, jets appear to emanate from the core in opposite directions which correspond to radio emission on arcsecond scales seen with the VLA at higher frequencies. These provide strong evidence for a black hole–based jet-producing central engine, rather than a starburst, being responsible for the compact radio emission in this radio-quiet quasar.

Subject heading: quasars: individual (E1821+643)

1. INTRODUCTION

The quasar population is divided into two classes: radio-loud quasars (RLQs) and radio-quiet quasars (RQQs). These two populations are seen to be distinct in several respects. For example, RLQs have ratios of total radio luminosity at 5 GHz to optical luminosity \( R \approx 10–100 \), whereas RQQs have \( R \approx 0.1–1 \) (Kellermann et al. 1989). Such distinctions are also apparent in the narrow-line luminosity–radio luminosity plane (Miller, Rawlings, & Saunders 1993) and in plots of far-infrared luminosity versus radio luminosity (Sopp & Alexander 1991a). Furthermore, all RQQs seem to have luminosities at 5 GHz below \( 10^{25} \) W Hz\(^{-1}\) sr\(^{-1}\) (Miller, Peacock, & Mead 1990).

The physical reason for this bimodality is not clear: while there is compelling evidence for a relativistic jet-producing central engine (almost certainly involving a black hole) as the source of the radio emission in RLQs (Begelman, Blandford, & Rees 1984), the mechanism by which the weaker radio emission in RQQs arises is uncertain. It has been proposed (Sopp & Alexander 1991a) that the radio emission from RQQs is due to a circumnuclear starburst. In this scenario, radio emission originates from synchrotron-emitting electrons accelerated in supernova remnants and/or flat spectrum thermal bremsstrahlung from \( \text{H} \text{II} \) regions. Indeed, it has been argued that the entire RQQ phenomenon can be produced by a massive starburst (e.g., Terlevich 1990; Terlevich & Boyle 1993; Terlevich et al. 1995).

An alternative explanation (Miller et al. 1993) is that the radio emission arises from weak radio jets originating from the active galactic nucleus (AGN) in a scaled-down version of the mechanism present in RLQs. An important test between these alternative hypotheses is the measurement at high angular resolution of the brightness temperature \( T_b \) and structure of the radio emission. If the emission arises in a star-forming region, we might expect to see the emitting region resolved into a number of small sources, each with brightness temperature \( \lesssim 10^7 \) K (Muxlow et al. 1994). If, however, the emission arises from an AGN, we would expect to see an unresolved point source, and/or a jet, with a high brightness temperature and possibly with parsec-scale features having some correspondence to features on the kiloparsec scale. To date, only nearby Seyfert galaxies have been the target of very high resolution radio imaging, and the results have been ambiguous, with \( \approx 50\% \) showing high \( (\gtrsim 10^6 \) K) \( T_b \) emission (e.g., Ulvestad, Neff, & Wilson 1987; Roy et al. 1994; Lonsdale, Lonsdale, & Smith 1992). The much lower bolometric luminosities of these objects compared with RQQs, however, make direct comparisons difficult.

To carry out such a test on an RQQ we used very long baseline interferometry (VLBI) techniques to examine E1821+643. This quasar is radio-quiet (see Lacy, Rawlings, & Hill 1992) with \( R \approx 1.5 \) and is highly luminous in all wavebands from the infrared (Hutchings & Neff 1991) to the X-ray (Pravdo & Marshall 1984). In addition, since it is at the moderate redshift of 0.298 (Schneider et al. 1992), its radio flux density is high enough to allow detailed mapping with the Very Large Array (VLA) telescope. Our VLA images of this object (Blundell & Lacy 1995) showed that, besides steep-spectrum extended emission, the quasar has a compact (less than \( 0.1' \)) inverted-spectrum core, which strongly suggests the presence of a “central engine” and encouraged us to make higher resolution observations with the Multi-Element Radio Linked Interferometer (MERLIN) and the Very Long Baseline Array (VLBA). However, the compact radio emission could also have been produced by free-free absorption of a compact starburst (Sopp & Alexander 1991b); even radio variability, present in some radio-quiet quasars (see Barvainis, Lonsdale, & Antonucci 1996), could be explained by an ensemble of radio supernovae.

In this Letter, we first describe details of our observations with the VLBA, MERLIN, and the VLA. Following this, we demonstrate that the compact core detected by the VLBA precludes star formation as the origin of this radio emission. We then discuss the emission on scales of hundreds of parsecs shown on the MERLIN map, and interpret these features in the light of Bridle & Perley’s (1984) criteria for jet identification.

2. OBSERVATIONS

We observed E1821+643 for 8 hr on 1996 February 14 using the 10 antenna VLBA (see Napier 1995) of the US National Radio Astronomy Observatory. Images in total intensity at 4.9 and 8.4 GHz are shown in Figure 1. The quasar was

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observed with the VLBA in a phase-referenced mode (Beasley & Conway 1995), i.e., frequent observations of an adjacent bright source (J1828+64) were made to provide phase corrections for the interferometer array. The pointing center was 18° 21′ 57.214, 64° 20′ 36.231 (J2000.0). On-source times were 57.6 and 86.4 minutes for the 4.9 and 8.4 GHz observations, respectively. The rms noise on the two maps, respectively, in mJy beam^{-1} is 0.12 and 0.079. The data were processed using the VLBA correlator, which generated data with four 8 MHz continuum channels in the four Stokes parameters. Observa-
tions of 1928+738 were interspersed throughout the observation to allow calibration of the polarization response of the receivers. Our MERLIN observations were made at 1.7 GHz for 10 hr on 1996 February 8 using all eight antennas of array including the 76 m Lovell telescope. Phase referencing was again employed, using 1827+645 as the phase calibrator and 0552+398 as a point source calibrator. We concatenated these data with one of the two intermediate frequencies (differing from our chosen MERLIN frequency by only 7 MHz) from a 40 minute observation with the VLA in BnA array on 1995 September 14. Synthesis imaging of all data was performed using the NRAO AIPS system.

3. RESULTS

The VLBA maps (Fig. 1) show that at 4.9 and 8.4 GHz, the emission on milliarcsecond scales is compact: the FWHM of the synthesized beams are $2.4 \times 1.4$ and $1.6 \times 1.0$ mas at 4.9 and 8.4 GHz. An upper limit to the deconvolved size of the radio core at 8.4 GHz is $0.3 \times 0.3$ mas, which corresponds to a physical area of 2.8 pc$^2$. There are signs that the emission is very slightly resolved, particularly at 4.9 GHz. Measurements of peak intensity were made by fitting a Gaussian to each point source. The peak fluxes measured in this way, at 4.9 and 8.4 GHz, respectively, are $8.6 \pm 0.2$ and $11.9 \pm 0.2$ mJy beam$^{-1}$. We have found with the VLA that at 8.4 GHz the flux density of the radio core was constant over nearly 3 yr (1995 September 14 the peak in flux density at 8.4 GHz was $12.80 \pm 0.03$ mJy beam$^{-1}$, while on 1992 December 15 the peak (at the same resolution) was $12.79 \pm 0.05$ mJy beam$^{-1}$). No polarization was detected with the VLA at 8.4 GHz, down to a 4 $\sigma$ limit of 4.2%.

Using the FWHM of the synthesized beam from a uniformly weighted map made at 8.4 GHz, we calculated a lower limit to the brightness temperature (corrected for redshift) of $2.2 \times 10^9$ K. However, this lower limit can be raised by considering that the angular size of the emitting region must be considerably smaller than the point-spread function of the image if the emission is to appear unresolved. Use of the (upper limit to the) deconvolved size (above) gives a lower limit to the brightness temperature of $1.4 \times 10^8$ K.

The maps at 1.7 GHz made from MERLIN and VLA data show a number of components at a resolution of $160 \times 120$ mas. There is diffuse emission in the vicinity of the core, and a second compact component in the region of the core is found, together with slightly extended components which seem to follow a curved path (roughly following features C and D on our VLA map [Fig. 1]) toward knot E (including a change in position angle of $\approx 80^\circ$). Knot E itself is resolved into two components with the MERLIN data, which lie on a continuation of this curved path.

4. ORIGIN OF THE COMPACT RADIO EMISSION

We now examine whether radio supernovae or supernova remnants in star-forming regions can plausibly be retained as the explanation for the compact radio emission in this radio-quiet quasar. Although individual supernovae have brightness temperatures higher than the brightness temperature of E1821+643, the most luminous known radio supernova, 1986J (Rupen et al. 1987), had a peak luminosity at 5 GHz of only $\approx 10^{31}$ W Hz$^{-1}$, so roughly 1000 of these would be needed to power E1821+643 at 5 GHz. Since the typical lifetime of such a supernova event is $\approx 1$ yr, this implies a supernova rate $v_{\text{SN}} \sim 1000$ yr$^{-1}$. Such rates are in line with those required to power the most luminous RQQs in the starburst scenario (Terlevich 1990). However, to explain the compact radio emission from E1821+643 they must be localized within a few cubic parsecs, corresponding to a density $10^7$ times higher than observed in M82 (Muxlow et al. 1994), and higher than in the starburst model of Terlevich & Boyle (1993) by a similar factor. Although it is possible that in the dense central region of the nucleus the radio luminosity of individual supernovae could be substantially enhanced, any reduction in $v_{\text{SN}}$ below $\sim 100$ yr$^{-1}$ would be likely to result in detectable variability on a timescale $\sim 1$ yr. If the supernovae occur at random, one would expect $\sim 10\%$ variability for $v_{\text{SN}} = 100$ yr$^{-1}$, higher than the observed limit at 8.4 GHz. If, alternatively, we try to explain the radio emission in terms of supernova remnants, it becomes very difficult to explain the high brightness-temperature observed since the typical value for such sources is nearer $10^4$ K (Muxlow et al. 1994).

5. NATURE OF THE CORE-JET STRUCTURE

Of the two compact components on the MERLIN map which are located near the optical position of the quasar, the more southwesterly of the two is in good agreement (10 $\pm$ 15 mas) with the position of the compact emission seen on the VLBA image, and we therefore identify it with the flat-spectrum core. The error in the MERLIN-VLBA registration is, at present, dominated by the uncertainty in the MERLIN phase calibrator position. The absence of polarization of this feature found by the VLBA is also consistent with it being a core.

The spectral index of the core was calculated by making a MERLIN map with a resolution of 0".17, the same as that of the 15 GHz map described in Blundell & Lacy (1995). Using the convention that $S_\nu \propto \nu^{-\alpha}$ the (where $S_\nu$ is the flux density at frequency $\nu$) we obtained a spectral index $\alpha_\nu = -0.83 \pm 0.06$; i.e., as in our VLA study (Blundell & Lacy 1995), the core spectrum is found to be inverted, though not quite as steeply. The second component to the northeast, possibly a jet knot, is not detected with our 15 GHz data, giving a lower limit to the spectral index of 0.4.

We contend that the feature to the south of the core on the MERLIN map is a jet. It appears to satisfy the criterion of Bridle & Perley (1984), namely, that the jet is at least 4 times as long as it is wide (which is true for the knots which follow a curved path from the core south to knot E). Moreover, these features satisfy the other criteria of Bridle & Perley, namely, that they are separable at high resolution from other extended structure, and they are aligned with the core where closest: the line joining the two components closest to the core on either side of it passes through the core.

The curvature of the jet to the south may be consistent with a scenario in which the jet axis precesses causing the jets to follow approximately helical paths. Such a scenario would also explain the misalignment of the jets and the overall linear structure of low surface brightness emission (Papadopoulos et al. 1995; this misalignment is exaggerated if the quasar is at a small angle to the line of sight and the jets slightly relativistic). We will describe our investigations of these and other possibilities, together with results from low-frequency observations with the compact VLA arrays, in a subsequent paper.
6. CONCLUSIONS

We now summarize the evidence that a jet-producing “central engine” powers this radio source as follows: (1) the emission is compact on similar physical scales to those seen in RLQs (see, e.g., Zensus 1994), (2) the brightness temperature is \( \gtrsim 10^9 \) K, (3) on our MERLIN+VLA maps we see jetlike features on scales of 100–1000 pc, and (4) the core luminosity at 5 GHz is \( \sim 10^{23} \) W Hz\(^{-1}\) sr\(^{-1}\) and arises from a region smaller than a few cubic pc. Most if not all of the radio emission from this RQQ, just as in the radio-loud population, is thus powered by a central engine, probably involving a black hole, rather than star formation. To confirm that the behavior seen in E1821+643 is typical of the radio-quiet quasar population, we are pursuing a program of VLBI imaging of a wider sample of ROQs.

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