Evidence for a black hole in a radio-quiet quasar nucleus
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ABSTRACT

We present the first milli-arcsecond 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 headings: quasars: radio-quiet, 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 and Saunders 1993) and in plots of far-infrared luminosity vs. radio luminosity (Sopp and Alexander 1991a). Furthermore, all RQQs seem to have luminosities at 5 GHz below \( 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1} \) (Miller, Peacock and 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 and Rees 1984), the mechanism by which the weaker radio emission in RQQs arises is uncertain. It has been proposed (Sopp and 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 HII regions. Indeed, it has been argued that the entire RQQ phenomenon can be produced by a massive starburst (e.g., Terlevich [1990], Terlevich and 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 \( \lesssim 10^5 \text{K} \) (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 pc-scale features having some correspondence to features on the kpc-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 \( (\gtrsim 10^6 \text{K}) \) \( T_B \) emission (e.g., Ulvestad et al. 1987, Roy et al. 1994, Lonsdale et al. 1992). The much lower bolometric luminosities of these objects compared with RQQs, however, make direct comparisons difficult.

To carry out such a test on a RQQ we used very long baseline interferometry (VLBI) techniques to examine E1821+643. This quasar is radio-quiet (see Lacy et al. 1992) with \( R \approx 1.5 \) and is highly luminous in all wavebands from the infra-red (Hutchings and Neff 1991) to the X-ray (Pravdo and Marshall 1984) and 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 and Lacy 1995) showed that, besides steep spectrum extended emission, the quasar has a compact \( (< 0.1 \text{ arcsec}) \) inverted-spectrum core, which strongly suggested 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 and Alexander 1991b); even radio variability, present in some radio-quiet quasars (c.f., Barvainis et al. 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 and Perley’s (1984) criteria for jet identification.
2. Observations

We observed E1821+643 for 8 hours 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 observed with the VLBA in a phase-referenced mode (Beasley and 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$^{h}$ 21$^{m}$ 57.214$^{s}$ 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 are 0.12 and 0.079. The data were processed using the VLBA correlator, which generated data with four 8.4 MHz continuum channels in the four Stokes parameters. Observations 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 hours on 1996 February 8 using the 8 antennas of array including the 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 intermediate frequencies (differing from our chosen MERLIN frequency by only 7 MHz) from a 40-min 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 milli-arcsecond scales is compact: the FWHM of the synthesized beams are 2.4 × 1.4 and 1.6 × 1.0 milli-arcseconds 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 × 0.3 milli-arcseconds, 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 ± 0.2 and 11.9 ± 0.2 mJy/beam. We have found with the VLA that at 8.4 GHz the flux density of the radio core was constant over nearly three years (on 1995 September 14 the peak in flux density at 8.4 GHz was 12.80 ± 0.03 mJy/beam while on 1992 December 15 the peak (at the same resolution) was 12.79 ± 0.05 mJy/beam). No polarization was detected with the VLBA at 8.4 GHz, down to a 4σ limit of 4.2%.

Using the FWHM of the synthesised 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 × 10$^{8}$ K.

\footnote{One milli-arcsecond corresponds to 5.6 pc at the redshift of this quasar, if we assume that $H_{0} = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_{0} = 0.5$ and $\Lambda = 0$.}
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 $1.4 \times 10^9$ K.

The maps at 1.7 GHz made from MERLIN and VLA data show a number of components at a resolution of $160 \times 120$ milli-arcseconds. 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]) towards knot ‘E’ (involving a change in position angle of $\approx 80$ degrees). Knot ‘E’ itself is resolved into two components with the MERLIN data, which lie on a continuation of this curved path.

4. The 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 $\sim 10^{21}$ WHz$^{-1}$, so roughly one thousand of these would be needed to power E1821+643 at 5 GHz. Since the typical lifetime of such a supernova event is $\sim 1$ yr, this implies a supernova rate $\nu_{SN} \sim 1000$ 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 pc, 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 $\nu_{SN}$ 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 $\nu_{SN} = 100$ 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. The 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 south-westerly 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 the same (0.17") as that of the 15 GHz map described in Blundell & Lacy (1995). Using the convention that $S_\nu \propto \nu^{-\alpha}$ (where $S$ is the flux density at frequency $\nu$) we obtained a spectral index $\alpha_{15} = -0.83 \pm 0.06$, i.e., as in our VLA study (Blundell and Lacy 1995) the core spectrum is found to be inverted, though not quite as steeply. The second component to the north-east, 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 and Perley (1984) that the jet is at least four 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 and 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: i) the emission is compact on similar physical scales to those seen in RLQs (see e.g., Zensus 1994), ii) the brightness temperature is $> 10^{9}$K iii) on our MERLIN+VLA maps we see jet-like features on scales of 100 – 1000 pc, iv) 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 RQQs.

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The contour levels in both VLBA maps (which are both naturally-weighted) are logarithmic with ratio 2; the lowest levels in mJy/beam are: for the 5 GHz map, 0.3 and for the 8.4 GHz map, 0.2. Where a grey-scale is plotted the units are mJy/beam. The VLA image (from Blundell and Lacy [1995]) has its lowest contour at 0.048 mJy/beam; the contours are spaced by factors of $\sqrt{2}$. The circular beam has FWHM 0.3$''$; co-ordinates are given in B1950.0 on the VLA map. The MERLIN map has lowest contour of 0.26 mJy/beam; contours are separated by factors of $\sqrt{2}$. The cross on the MERLIN map shows the position of the VLBA core; the total extent represents 25$\times$ the uncertainty in the relative position.