THE OPTICALLY-POWERFUL QUASAR E1821+643 IS ASSOCIATED WITH A 300-KPC SCALE FR I RADIO STRUCTURE

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To appear in ApJ Letters

ABSTRACT

We present a deep image of the optically-powerful quasar E 1821+643 at 18 cm made with the Very Large Array (VLA). This image reveals radio emission, over 280 $h^{-1}$ kpc in extent, elongated way beyond the quasar’s host galaxy. Its radio structure has decreasing surface brightness with increasing distance from the bright core, characteristic of FR I sources (Fanaroff & Riley 1974). Its radio luminosity at 5 GHz falls in the classification for ‘radio-quiet’ quasars (it is only $10^{23.9}$ WHz$^{-1}$sr$^{-1}$ see e.g. Kellermann et al. 1994). Its radio luminosity at 151 MHz (which is $10^{25.3}$ WHz$^{-1}$sr$^{-1}$) is at the transition luminosity observed to separate FR IIs and FR IIs. Hitherto, no optically-powerful quasar had been found to have a conventional FR I radio structure. For searches at low-frequency this is unsurprising given current sensitivity and plausible radio spectral indices for radio-quiet quasars. We demonstrate the inevitability of the extent of any FR I radio structures being seriously under-estimated by existing targeted follow-up observations of other optically-selected quasars, which are typically short exposures of $z > 0.3$ objects, and discuss the implications for the purported radio bimodality in quasars.

The nature of the inner arcsec-scale jet in E 1821+643, together with its large-scale radio structure, suggest that the jet-axis in this quasar is precessing (cf. Galactic jet sources such as SS 433). A possible explanation for this is that its central engine is a binary whose black holes have yet to coalesce. The ubiquity of precession in ‘radio-quiet’ quasars, perhaps as a means of reducing the observable radio luminosity expected in highly-accreting systems, remains to be established.

Subject headings: galaxies: jets — quasars: general — quasars: individual E 1821+643

1. INTRODUCTION

Radio sources from the 3CRR sample (Laing, Riley & Longair 1983) whose nuclei are quasars tend to be associated with classical double [FR II, Fanaroff & Riley (1974)] structures. This sample contains no examples of radio sources clearly having the other characteristic structure, the FR I type (where the brightness decreases with increasing distance from the core), powered by quasar nuclei. This, together with a consistent picture from similar samples, led some to postulate that there is a deep association between the nature of the central engine and whether the radio-structure is type FR I or FR II (Baum et al. 1995).

In principle, a survey like 3CRR is hindered from finding FR I radio structures associated with quasars because of two effects. First, as pointed out by Fanaroff & Riley (1974), FR IIs have lower radio luminosities than the classical double FR IIs (see Fig.1); this means they are not found at high redshifts in a bright flux-limited sample. Second, the rarity of quasars means that searching the sky in highly-accreting systems, remains to be established.

An alternative means of finding quasars associated with FR I radio structures is to begin with an optical survey of quasars and then make follow-up radio observations to establish the nature of their structures. In the case of the BQS sample of quasars (Schmidt & Green 1983) the radio structures, when prominent, are only of the classical double FR II type. Observations to date show the other quasars appear to have weak, though compact (Blundell & Beasley 1998), radio emission associated with their nuclei. This indicates a seeming gap in radio luminosity for quasars of a given optical luminosity, as pointed out by e.g. Miller, Rawlings & Saunders (1993): at radio luminosities corresponding to the FR IIs from the 3CRR sample, there are no BQS quasars.

The absence of evidence of quasars with these radio luminosities (the radio luminosities of FR I radio galaxies in 3CRR) was taken by Falcke et al. (1995) as evidence of the absence of these objects in the Universe. This led them to postulate that torus opening angles in FR Is are too small to observe a quasar nucleus: for most angles to the line-of-sight the nucleus would be obscured by the torus, while for very small angles to the line-of-sight the nuclear emission would be that of a strongly core-boosted BL Lac. The wider opening angles of FR II sources permit a significant fraction of these objects to be observed as quasars. Thus, the seeming absence of FR I quasars was taken by Falcke et al. (1995) as evidence that the nature of the torus is closely linked to the FRII/FRI transition.

A possible counter to their claim was the discovery by Lara et al. (1999) of an FR I radio structure whose nuclear identification, while not a bona fide quasar, exhibits broad lines. With a projected linear size of ~ 0.5 Mpc it seemed most unlikely that this object was being viewed at a very small, favourable angle to the line-of-sight. Examples of FR I sources having bona fide quasar nuclei would undermine Falcke et al. (1995)’s theory.

Deep, low-frequency, radio surveys are a means of sampling the high-z Universe necessary to find rare quasars. However, in the low-radio luminosity regime where FR I sources are found, current surveys remain challenged by sensitivity. But despite the limited sky coverage of red-

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shift surveys of deep low-frequency radio sources to date, a low-radio luminosity source from the 38-MHz selected 8C sample (Lacy et al. 1999), which we find to have an FR I structure over 280 kpc in extent, is associated with a well-studied quasar which is optically extremely powerful (Hutchings & Neff 1991, unreddened $M_V = -27.5$).

What are the chances that optically-selected quasars will be found to have associated FR I structures? Given that optically-powerful quasars are too rare to populate the nearby Universe and the consequences of redshift on surface brightness discussed in §4, the short interferometric snapshots which comprise most observations of these objects to date are inadequate to reveal any such structures. Psychology presumably plays its part in discouraging observers, or at least proposal referees, from making deep radio observations of seemingly ‘radio-quiet’ quasars. In §2 we briefly describe what our deep observations of E 1821+643 have revealed. In §3 we discuss the size and luminosity of its extended emission and consider the stability in jet-axis direction that is implied by the large-scale radio emission. In §4 we consider the detectability, given current technology, of the extended emission if the quasar were located at $z = 1$ instead of its true value $z = 0.297$ (Schneider et al. 1992).

In §5 we discuss the challenges this quasar presents to the implications of the radio bimodality in quasars, the radio-optical correlation (e.g. Rawlings & Saunders 1991; Willott et al. 1999) and the assumed mapping between jet power and observable radio luminosity.

We assume that $h$ is the Hubble constant in units of $50 \text{ km s}^{-1}\text{Mpc}^{-1}$, and that $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS

The VLA in its BnA configuration was used to observe E 1821+643 at 18 cm for 133 minutes on 14 September 1995; the primary flux calibrator was 3C 48 and the phase calibrator was 1842+681. The data were reduced using standard procedures using AIPS. Fig. 2 shows that at 18 cm low-surface brightness emission (which contributes to a total of 47.7 mJy associated with the quasar) is extended over 45″ (280 kpc), way beyond the confines of its host galaxy (Hutchings & Neff 1991). Previously, extended radio emission had only been known to lie approximately co-spatially with its host galaxy (Papadopoulos et al. 1995). Despite the somewhat elongated nature of the radio emission Papadopoulos et al. found, they thought it likely that this emission was associated with star formation within the galaxy; this was concluded because of the proximity of this quasar to the seemingly tight line of correlation between the far-infra-red and radio luminosities of Seyfert galaxies and radio-quiet quasars (e.g. Helou et al. 1985; Sopp and Alexander 1991a,b). The increased radio emission we have discovered lifts this object further away from that tight correlation.

3. RESULTS

The total luminosity of this source at 18 cm is $10^{24.6} \text{ W Hz}^{-1}\text{sr}^{-1}$. At the resolution of the 18 cm image, the core component accounts for 15.3 mJy/beam, i.e. half of the luminosity in the extended emission. Its linear extent is 280 kpc in the assumed cosmology, and its width is 60 kpc. Thus in terms of radio size, luminosity, the ratio of core to total luminosity, host galaxy and cluster environment (Lacy et al. 1992), E 1821+643 is like other FR Is.

![Diagram](image-url)
of 0.0015c. If this were the constant speed at which the plumes had emerged from the radio-quiet quasar, then this would have commenced ∼ 3 × 10^8 yrs ago so the direction of the jet-axis appears to have remained within a 7 degree cone for at least ∼ 3 × 10^8 yrs. With the A–B distance being somewhat under half the C–D distance, this still gives that the characteristic time for the stability of the jet axes is ∼ 10^8 yrs. The precession period of SS 433 is 163 days, ∼ 10^8 times shorter than the likely period of E 1821+643; thus the ratio of precession periods in these very different objects would be similar to the ratio of their masses.

We now consider an estimate of the stability timescale of the optical emission: Fried (1998) found extended line emission 2.5'' (7.5 kpc) from the nucleus in E 1821+643, with line ratios typical of nuclear photoionization, suggesting stability over ∼ 10^8 yrs. The width of this emission perpendicular to the mean jet-axis is similar to the width of the radio emission, suggesting that the radio source may be interacting with this gas.

4. THE CONSEQUENCES OF REDSHIFT

We now consider whether extended radio emission is likely to be a general characteristic of radio-quiet quasars or whether E 1821+643 is simply an exceptional case. Radio maps of other radio-quiet quasars from e.g. Kukula et al. (1998) and White et al. (2000) had an on-source time of only a few minutes, compared with 2 hrs for the image we present here: longer integration time brings with it not just a simple increase in signal-to-noise ratio but also substantially better UV-plane coverage.

Have previous observations of radio-quiet quasars simply had insufficient surface-brightness sensitivity for diffuse extended radio structures to be detected at even moderate redshifts? We performed an experiment similar to one performed by Neeser et al. (1995) in a different context: we took our image of E 1821+643 and calculated what it would look like if instead of being located at the redshift of 0.297 (Schneider et al. 1992), it were located at the maximum redshift at which an otherwise identical but unreddened E 1821+643 could be detected by the BQS survey, namely z ∼ 1. For constant WHz^-1 kpc^-2 over physical sizes exceeding the pixel size (in kpc at any considered z), the surface brightness will vary with redshift as (1+z)^{(1+α)} (where α is the spectral index), thus the surface brightness of the object at z = 1 would be lower than if it were at z = 0.297 by a factor of 5.4. The estimated source structure is shown in the left panel of Fig. 2: at the risk of stating the obvious there would be no reason to deduce the presence of 100 kpc-scale emission on the basis of such an image. For sources at moderate to high redshift, it is difficult to observe any low-luminosity extended emission.

5. JET POWER AND LUMINOSITY IN FR I S AND RQQS

The FR I radio galaxies in 3C may differ from E 1821+643 in that the presence or absence of examples clearly indicating precession requires MERLIN-scale imaging. The FR I radio galaxies in 3C definitely differ from E 1821+643 in that their optical luminosities are 10^8 × lower, though their radio luminosities are similar.

Do any other ‘radio-quiet’ quasars have 100-kpc-scale jets (manifested as FR Is)? Figure 1 clearly demonstrates that with plausible radio spectral indices, and given current sensitivity at low-frequency, the relevant part of parameter space is not sampled, so for the time being this question remains unanswered, though it is possible that some do have such jets (e.g. those with elliptical hosts) and some do not (e.g. those with spiral hosts). Only if the answer to this question turns out to be negative (after deeper exposures at low-z with existing facilities, and ultimately with e-MERLIN, e-VLA, LoFAR and SKA, have sampled this parameter space) would it be possible to posit a bimodality, rather than a continuity, in the luminosities of the jet output of quasars.

Implicit in the work of Rawlings & Saunders (1991), Miller, Rawlings & Saunders (1993) and Willott et al. (1999) was the view that there is a physical dichotomy between ‘radio-loud’ objects (which channel power into jets of the same order as is released by accretion) and ‘radio-quiet’ objects (whose jet powers are a negligible fraction of the bolometric accretion luminosity). This view does not rest easily with the optically-powerful E 1821+643 since it has nearly all of the attributes (§3) of a low-jet-power FR I radio source and is therefore intermediate between high-power FR IIs and classically ‘radio-quiet’ objects. One way of retaining a physical dichotomy would be to postulate a different mapping between jet power and observed low-frequency radio luminosity in (at least) this FR I. Could FR I-like structures from optically-powerful nuclei emerge from different physical processes? We speculate that the radio luminosity of some radio-quiet quasars may be reduced by significant precession in their jet-axes. This precession could arise if insufficient time has elapsed for orbiting black holes in the central engine to have coalesced.

The correlation with radio luminosity of the structural classifications of Fanaroff & Riley (1974) is one of the most persistent and robust correlations in astronomy: there are no examples of highly radio-luminous FR Is. This suggests that high jet power is necessary for a highly collimated non-dissipative jet which is ultimately capable of forming compact hotspots and a characteristic FR II structure. As lower jet powers are considered, a jet may be more likely to disrupt and dissipate within a few kpc of the cores, characteristic of FR Is [see e.g. De Young (1993)], but giving a low luminosity source. The density and inhomogeneity of the environment into which the jet is expanding determines the exact threshold value of jet power above which a jet can give rise to an FR II and below which a jet will give rise to an FR I. For a given jet power, if the jet axis is precessing, this may favour the disruption and hence dissipation of the jet, lowering the likelihood of an FR II.

6. CONCLUDING REMARKS

Our discovery of an FR I radio structure associated with an unusually-nearby optically-powerful quasar, together with consideration of the inadequacy of existing observations of optically-similar objects to reveal similar radio structures, overturn previous assertions that quasar nuclei cannot be associated with FR I radio structures.

The large-scale radio emission of E 1821+643, elongated way beyond the quasar’s host galaxy, is powered by oppositely directed jets which appear to precess on timescales which are scaled up in approximate proportion with the mass of the central engine compared to the Galactic radio jetted source, SS 433. We speculate that the central engine
in this quasar may be composed of two black holes which have yet to coalesce (cf. Begelman et al. 1980).

Any precession in the jet-axis of a radio source may smear out its extended radio emission and promote dissipation in the jet, affecting its potential to form an FR II structure, hindering its detectability at radio wavelengths.

The ubiquity of precession as a means by which lower radio luminosity is manifested from highly-accreting yet ‘radio-quiet’ quasars remains to be established. This is essential to developing our understanding of the quasar phenomenon, and beckons the emerging generation of radio telescopes such as e-MERLIN, e-VLA, LoFar and SKA.

K.M.B. thanks the Royal Society for a University Research Fellowship. The VLA is a facility of the NRAO operated by Associated Universities, Inc., under co-operative agreement with the NSF. MERLIN is a UK national facility operated by the University of Manchester on behalf of PPARC. We thank the referee for helpful comments.

REFERENCES

Baum S.A., Zirbel E.L. & O’Dea C.P., 1995, ApJ, 451, 88
Begelman M.C., Blandford R.D. & Rees M.J., 1980, Nature, 287, 307
Blundell K.M., Beasley A.J., Lacy M. & Garrington S.T., 1996, ApJ, 468, 191
Blundell K.M. & Beasley A.J., 1998, MNRAS, 299, 165
De Young D.S., 1993, ApJ, 405, L13
Falcke H., Gopal-Krishna & Biermann P.L., 1995, A&A, 298, 395
Fanaroff B.L. & Riley J.M., 1974, MNRAS, 167, 31
Fried J.W., 1998, A&A, 331, L73
Helou G., Soifer B.T., and Rowan-Robinson M., 1985, ApJ, 298, L7
Hjellming R.M. & Johnston K.J., 1981, ApJ, 246, L14
Kellermann K.I., Sramek R.A., Schmidt M., Green R.F. and Shaffer D.B., 1994, AJ, 108, 1163
Hutchings J.B. and Neff S.G. 1991, AJ, 101, 2001
Kukula M., Dunlop J.S., Hughes D.H. & Rawlings S., 1998, MNRAS, 297, 366
Lacy M., Rawlings S. and Hill G.J. 1992, MNRAS, 258, 828
Lacy M., Kaiser M.-E., Hill G.J., Rawlings S. & Leyshon G. 1999, MNRAS, 420

Laing R.A., Riley J.M., & Longair M.S., 1983, MNRAS, 204, 151
Lara L., Marquez I., Cotton W.D., Feretti L., Giovannini G., Marcaide J.M. & Venturi T., 1999, New A Rev., 43, 643–646
Miller P., Rawlings S. and Saunders R. 1993, MNRAS, 263, 425
Neeser M.J., Eales S.A., Law-Green J.D., Leahy J.P. & Rawlings S., 1995, ApJ, 451, 76
Papadopoulos, P.P., Seaguest, E.R., Wrobel J.M. and Binette L. 1995, ApJ, 446, 150
Rawlings S. & Saunders R., 1991, Nature, 239, 138
Riley J.M., Rawlings S., McMahon R.G., Blundell K.M., Miller P., Lacy M. and Waldram E.M. 1999, MNRAS, 307, 293
Schmidt M. & Green R.F., 1983, ApJ, 269, 352
Schneider, D.P., Bahcall, J.N., Gunn, J.E. and Dressler A. 1992 AJ, 103, 1047
Sopp, H.M. and Alexander, P. 1991a, MNRAS, 251, L14
Sopp, H.M. and Alexander, P. 1991b, MNRAS, 251, 112
White R.L., et al, 2000, ApJS, 126, 133.
Willett C.J., Rawlings S., Blundell K.M. & Lacy M., 1999, MNRAS, 309, 1017

Fig. 2.—The central panel is a VLA image of E1821+643 at 1.4 GHz with arcsec resolution which shows the quasar to also have an FR I structure extending over 280 kpc. The northern source is a known FR I radio galaxy in the same cluster (Lacy et al. 1992). The bright component in this image is shown at higher resolution in the right image from MERLIN (reproduced from Blundell et al. 1996) to contain oppositely directed twin jets with evidence for some curvature. The left image shows the effect of redshifting this (most radio luminous of radio-quiet quasars) out to redshift 1 assuming a spectral index of 0.9 for the extended emission and making the assumptions about surface brightness discussed in the text, and observing it at 1.4 GHz for the same length of time and with the same UV-coverage as in the central panel. This is approximately the same as a 5-min snapshot of the source at its true redshift of 0.297, though the reality would not be as good because of deconvolution difficulties arising from significantly poorer UV-plane coverage.