

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

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ABSTRACT

We present a deep image of the optically powerful quasar E1821+643 at 18 cm made with the Very Large Array. 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. Its radio luminosity at 5 GHz falls in the classification for “radio-quiet” quasars (it is only $10^{23.9}$ W Hz⁻¹ sr⁻¹). Its radio luminosity at 151 MHz (which is $10^{25.3}$ W Hz⁻¹ sr⁻¹) is at the transition luminosity observed to separate FR I and FR II structures. 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 underestimated by existing targeted follow-up observations of other optically selected quasars, which are typically short exposures of $z > 0.3$ objects, and we discuss the implications for the purported radio bimodality in quasars. The nature of the inner arcsecond-scale jet in E1821+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 (E1821+643)

On-line material: color figure

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, Zirbel, & O’Dea 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 I galaxies have lower radio luminosities than the classical double–FR II galaxies (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 requisite large volume of space necessarily involves going out to high redshifts.

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 Bright Quasar Survey (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, although 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 I galaxies 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, Gopal-Krishna, & Biermann (1995) as evidence of the absence of these objects in the universe. This led them to postulate that torus opening angles in FR I galaxies 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 object. 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 FR II/FR I 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, favorable angle to the line of sight. Examples of FR I sources having bona fide quasar nuclei would undermine the theory of Falcke et al. (1995).

Deep low-frequency radio surveys are a means of sampling the high-redshift universe necessary to finding 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 redshift 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 that is optically extremely powerful (unreddened $M_V = -27.5$; Hutchings & Neff 1991).

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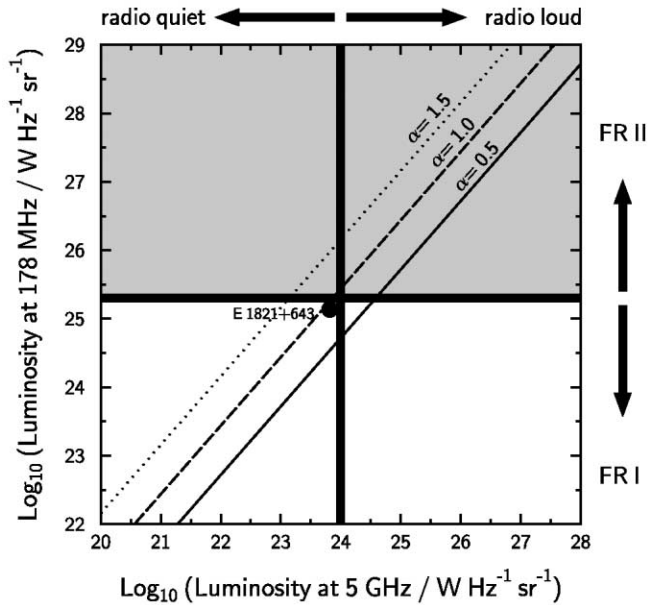


FIG. 1.—Illustration of the relationship between the low-frequency luminosity ranges associated with the two Fanaroff & Riley (1974) classes and the high-frequency luminosity ranges that have been deemed to contain radio-loud or radio-quiet quasars by, e.g., Kellermann et al. 1994; the solid, dashed, and dotted lines indicate the effective spectral indices between 178 MHz and 5 GHz, which must characterize a source appearing in different parts of this plane. Even the *deepest* low-frequency surveys to date (e.g., Riley et al. 1999), with a flux limit of 100 mJy, will only find sources at $z > 1$ whose luminosities at 151 MHz are in the yellow-colored region, i.e., in the traditional FR II regime. [See the electronic edition of the *Journal* for a color version of this figure.]

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 that 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 E1821+643 have revealed. In § 3 we discuss the size and luminosity of its elongated 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 at its true value of $z = 0.297$ (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 Very Large Array (VLA) in its BnA configuration was used to observe E1821+643 at 18 cm for 133 minutes on 1995 September 14; the primary flux calibrator was 3C 48, and the phase calibrator was 1842+681. The data were reduced using

standard procedures using AIPS. Figure 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 been known to lie only approximately cospatially with its host galaxy (Papadopoulos et al. 1995). Despite the somewhat elongated nature of the radio emission Papadopoulos et al. (1995) 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-infrared and radio luminosities of Seyfert galaxies and “radio-quiet” quasars (e.g., Helou, Soifer, & Rowan-Robinson 1985; Sopp & Alexander 1991a, 1991b). 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 $15.3 \text{ mJy beam}^{-1}$, 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, and the ratio of core to total luminosity, host galaxy, and cluster environment (Lacy, Rawlings, & Hill 1992), E1821+643 is like other FR I galaxies.

It seems likely that the jet observed on subarcsecond scales by Blundell et al. (1996) produces the extended emission. Figure 2 shows their MERLIN image in which the jet appears to curve from the line joining the core to E, round toward F. This E-F direction is parallel to A-B on larger scales, which in turn probably represents more recent emission than that along the direction delineated by C-D. The axis of the inner MERLIN jet indicates the most recent directionality of the jet axis. Thus, two clues from these images—taken together—may indicate that the jet is precessing: (1) the curvature of the subarcsecond jet and (2) the similarity in direction of the jet axis A-B on scales of tens of arcseconds compared with E-F on subarcsecond scales. This would be in exact analogy to the way the precessing jets of SS 433 (Hjellming & Johnston 1981) give rise to a projected helical trace on the sky. It is possible that as in SS 433, the precession of the jet axis in this radio-quiet quasar arises from the central engine being a binary. The changes in jet-axis direction may be the manifestation of the active nucleus containing two supermassive black holes in orbit round one another (Begelman, Blandford, & Rees 1980).

The outermost ends of the extended emission do not appear to end in shocks (as might be evinced by an abrupt, rather than a gradual, decrease in surface brightness). This might suggest that the extended emission has grown no faster than the ambient sound speed of the intergalactic medium. The sound speed in an ionized gas at temperature T in units of K is given by $\approx (5 \times 10^{-7}) c T^{1/2}$, where c is the speed of light; for $T = 10^7 \text{ K}$ this gives an assumed transonic advance speed 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 $\sim 3 \times 10^8 \text{ yr}$ ago, so the direction of the jet axis appears to have remained within a 7° cone for at least $\sim 3 \times 10^8 \text{ yr}$. 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 $\sim 10^8 \text{ yr}$. The precession period of SS 433 is 163 days, $\sim 10^8$ times shorter than the likely period

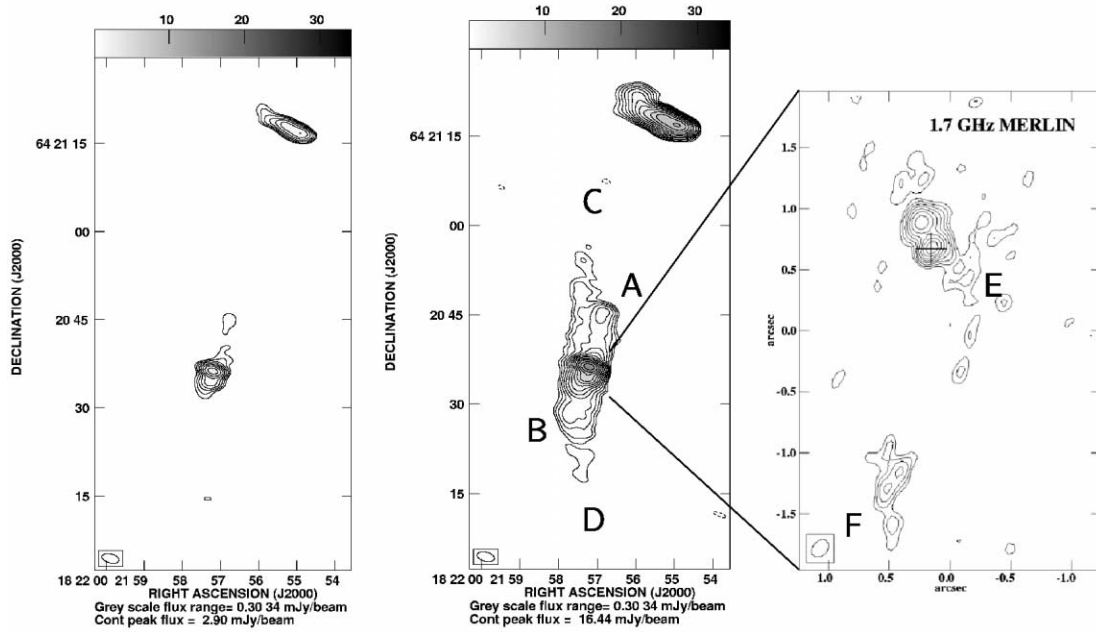


FIG. 2.—*Middle panel:* VLA image of E1821+643 at 1.4 GHz with arcsecond resolution, which shows the quasar to also have an FR I structure extending over 280 kpc. The northern source is a known FR I radio galaxy in the same cluster (Lacy et al. 1992). The bright component in this image is shown at higher resolution in the right image from MERLIN (reproduced from Blundell et al. 1996) to contain oppositely directed twin jets with evidence for some curvature. *Left panel:* The effect of redshifting this (most radio luminous of radio-quiet quasars) out to a redshift of 1, assuming a spectral index of 0.9 for the extended emission, 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 minute snapshot of the source at its true redshift of 0.297, although the reality would not be as good because of deconvolution difficulties arising from significantly poorer u - v plane coverage.

of E1821+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 E1821+643, with line ratios typical of nuclear photoionization, suggesting stability over $\sim 10^4$ yr. 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. CONSEQUENCES OF REDSHIFT

We now consider whether extended radio emission is likely to be a general characteristic of radio-quiet quasars or whether E1821+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 hr 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 u - v 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 E1821+643 and calculated what it would look like if instead of being located at a redshift of 0.297 (Schneider et al. 1992), it were located at the maximum redshift at which an otherwise identical but unreddened E1821+643 could be detected by the BQS survey, namely, $z \sim 1$. For constant $W \text{ Hz}^{-1} \text{ kpc}^{-2}$ over physical sizes exceeding the pixel size (in kiloparsec at any

considered z), the surface brightness varies with redshift as $(1+z)^{3+\alpha}$ (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 Figure 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 SOURCES AND RADIO-QUIET QUASARS

The FR I radio galaxies in 3C may differ from E1821+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 E1821+643 in that their optical luminosities are 10^3 times lower, although their radio luminosities are similar.

Do any other radio-quiet quasars have 100 kpc scale jets (manifested as FR I structures)? 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, although 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 redshift with existing facilities and ultimately with e -MERLIN, E-VLA, the Low Frequency Array [LOFAR], and the Square Kilometer Array [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 et al. (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 that 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 E1821+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 II sources 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 I sources. This suggests that high jet power is necessary for a highly collimated non-dissipative jet that is ultimately capable of forming compact hot spots 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 kiloparsec of the cores, characteristic of FR I sources (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 favor 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 E1821+643, elongated way beyond the quasar’s host galaxy, is powered by oppositely directed jets that appear to precess on timescales that 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 that have yet to coalesce (see 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 and 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*.

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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. 1998, *MNRAS*, 299, 165
 Blundell, K. M., Beasley, A. J., Lacy, M., & Garrington, S. T. 1996, *ApJ*, 468, L91
 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, 31P
 Fried, J. W. 1998, *A&A*, 331, L73
 Helou, G., Soifer, B. T., & Rowan-Robinson, M. 1985, *ApJ*, 298, L7
 Hjellming, R. M., & Johnston, K. J. 1981, *ApJ*, 246, L141
 Hutchings, J. B., & Neff, S. G. 1991, *AJ*, 101, 2001
 Kellermann, K. I., Sramek, R. A., Schmidt, M., Green, R. F., & Shaffer, D. B. 1994, *AJ*, 108, 1163
 Kukula, M., Dunlop, J. S., Hughes, D. H., & Rawlings, S. 1998, *MNRAS*, 297, 366
 Lacy, M., Kaiser, M.-E., Hill, G. J., Rawlings, S., & Leyshon, G. 1999, *MNRAS*, 307, 420
 Lacy, M., Rawlings, S., & Hill, G. J. 1992, *MNRAS*, 258, 828
 Laing, R. A., Riley, J. M., & Longair, M. S. 1983, *MNRAS*, 204, 151
 Lara, L., Márquez I., Cotton, W. D., Feretti, L., Giovaninni, G., Marcaide, J. M., & Venturi, T. 1999, *NewA Rev.*, 43, 643
 Miller, P., Rawlings, S., & 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., Seaquist, E. R., Wrobel, J. M., & 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., & 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., & Dressler, A. 1992, *AJ*, 103, 1047
 Sopp, H. M., & Alexander, P. 1991a, *MNRAS*, 251, 14P
 ———. 1991b, *MNRAS*, 251, 112
 White, R. L., et al 2000, *ApJS*, 126, 133
 Willott, C. J., Rawlings, S., Blundell, K. M., & Lacy, M. 1999, *MNRAS*, 309, 1017