The central engines of radio-quiet quasars

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ABSTRACT

Two rival hypotheses have been proposed for the origin of the compact radio flux observed in radio-quiet quasars (RQQs). It has been suggested that the radio emission in these objects, typically some two or three orders of magnitude less powerful than in radio-loud quasars (RLQs), represents either emission from a circumnuclear starburst or is produced by radio jets with bulk kinetic powers \(\sim 10^3\) times lower than those of RLQs with similar luminosity ratios in other wavebands. We describe the results of high resolution (\(\sim\) parsec-scale) radio-imaging observations of a sample of 12 RQQs using the Very Long Baseline Array (VLBA). We find strong evidence for jet-producing central engines in 8 members of our sample.

Key words: radio continuum: galaxies – galaxies: active

1 INTRODUCTION & BACKGROUND

The bimodality of radio luminosity in the quasar population (Miller, Peacock & Mead 1990) poses many questions about the fundamental nature of the emission mechanisms in Radio-Quiet Quasars (RQQs) and Radio-Loud Quasars (RLQs). The total radio luminosity is typically two or three orders of magnitude lower for a RQQ than for a RLQ (Miller, Rawlings & Saunders 1993) with similar luminosity ratios in all other wavebands. The double, often co-linear, morphology exhibited by many RLQs on arcsecond scales (e.g., Bridle et al. 1994) usually comprises a bright central core with hotspots at the outermost edges of the radio structure. In addition, lobes of extended emission are seen which are fed by jets, via backflow out of the hotspots. In contrast, radio images of RQQs often show merely a weak component, coincident with the optical quasar nucleus, which in some cases is resolved (Miller et al. 1993).

It has been proposed that the activity in RQQs is supplied by a ‘starburst’, i.e., strongly radiative supernovae and supernova remnants (SNRs) in a very dense environment (Terlevich et al. 1992). Sopp & Alexander (1991) argued this on the basis of the striking continuity between the far-infra red — radio correlation of RQQs and that of star-forming galaxies, ultra-luminous infra-red galaxies and also Seyfert galaxies. This is offset from the same correlation for RLQs and radio galaxies. Alternatively, if the energy supply arises from accretion onto a massive black hole, the radio emission from RQQs (as in RLQs) is caused by radio jets, but the bulk kinetic powers of these jets are for some reason \(\sim 10^3\) times lower than those of RLQs (Miller et al. 1993).

To address the question of whether the radio emission in radio-quiet quasars is associated with starbursts or with weak-jet producing central engines, we have undertaken a programme of imaging a sample of RQQs using VLBI techniques. This provides a definitive test between the two rival hypotheses for the radio emission in a given RQQ, since one can derive a size scale (from milli-arcsecond resolution measurements) from which the observed luminosity is emitted and compare this with the size scales on which SNRs are found to be distributed. Moreover, a mere detection with VLBI implies the brightness temperature of the emission \(T_B \gtrsim 10^6\) K, while typical supernovae supernova remnants have \(T_B \lesssim 10^5\) K (Muxlow et al. 1994).

We previously reported an experiment to image a well-known nearby radio-quiet quasar (E1821+643) with the VLBA (Blundell et al. 1996). In detecting it at 5 and 8 GHz on milli-arcsecond scales, we found a...
high brightness temperature \(T_B \sim 10^9 \, \text{K}\) which precluded the possibility of star-formation as the origin of its radio emission. It was instead consistent with a mechanism similar to the central engines postulated for radio-loud quasars. In order to establish whether this result was typical of the radio-quiet quasar population we performed detection experiments using the VLBA on a sample of 12 RQQs, the results of which we present here.

We describe in Section 2 of this paper the details of our sample selection and include a discussion of the conventional criteria used to classify whether a particular quasar is radio-loud or radio-quiet. In Section 3 we describe our observing method and we summarise our results. In Section 4 we discuss the physical implications of our results for the models discussed earlier; we also explore when a quasar is appropriately classified as radio-quiet and consider what may be the counterparts of the RQQ population which undergo Doppler boosting.

2 SAMPLE SELECTION

Our goal was to select a sample of targets which were capable of being imaged with the VLBA and representative of the RQQ population. We used the Bright Quasar Survey (BQS) (Schmidt & Green 1983) which has been studied on arcsecond scales with the Very Large Array (VLA) and also optically (Miller et al. 1993, Kellermann et al. 1994). It is necessary to impose a flux-density limit to allow a reasonable chance of detection: if the core flux density of a RQQ is known to be \(\ll 2\, \text{mJy}\), then the source will not be detected in VLBA observations, even if it is extremely compact, and we would learn nothing. From the sample studied by Miller et al. (1993) we selected those quasars whose core had a peak flux density at 5 GHz (measured using the VLA in A-array) \(\geq 2\, \text{mJy/beam}\). We then selected any other quasars from the sample of Kellermann et al. (1994) which were not in the sample of Miller et al. and had a total flux density measured in VLA D-array to be \(\geq 2\, \text{mJy}\). It was then necessary to eliminate RLOs by applying criteria which identify a quasar as radio-loud. There exist a number of (largely overlapping) criteria which delimit the RLO population from the RQQ population: (1) a ratio \(R\), of radio to optical emission \(\gtrsim 10\) has been taken to indicate that the quasar is radio-loud (Kellermann et al. 1994). (2) If the radio luminosity \(w\) is above \(10^{25}\, \text{W Hz}^{-1}\) (Kellermann et al. 1994) the quasar is deemed to be radio-loud. (3) The distinction between radio-loud and radio-quiet quasars is apparent in the narrow-line luminosity versus radio luminosity plane (Miller et al. 1993) where a clear gap in radio luminosity separates the \(z < 0.5\) RQQs from the \(z < 0.5\) RLQs. Of the radio-quiet quasars, Miller et al. (1993) identified a sub-set they termed ‘radio-intermediate quasars’ (RIQs) with luminosities at 5 GHz between \(10^{23}\) and \(10^{24}\) W Hz\(^{-1}\) sr\(^{-1}\) (see Section 4.3); note the different units used by these authors compared to Kellermann et al. (1994).

A quasar was retained in our sample if it was radio-quiet according to at least one of the three above classifications. Table 1 lists the twelve objects selected, and a key in this table indicates which of the three criteria described above led to the inclusion of a particular quasar. Two other objects met these conditions but were excluded from the observing programme for the following reasons: for 1138+04, the offset between the optical quasar position and radio emission of 24 arcsec (Kellermann et al. 1994) implied that this radio emission was not that of the core; 1634+70 was excluded due to scheduling constraints.

3 OBSERVATIONS & RESULTS

All targets were observed with the 10-antenna VLBA of the National Radio Astronomy Observatory at 8.42 GHz. With the exception of 0007+106 all targets were observed in a phase-referenced mode (Beasley & Conway 1995), i.e. frequent observations of an adjacent bright source were made to provide phase corrections for the interferometer array. For those targets with low flux density (as indicated in Table 1) we used the VLA in phased array mode for extra sensitivity. The data were processed using the VLBA correlator which generated four 8 MHz continuum channels in the four Stokes parameters. Synthesis imaging of the data was performed using the NRAO AIPS system.

The results of our observations are presented in Table 2. We detected 8 out of 12 of the quasars in our sample with brightness temperatures between \(10^7\) and \(10^9\) K derived according to the following formula: 

\[T_B = \lambda^2 S_\lambda (1 + z)/(2k_B \Omega)\] 

where \(T_B\) is the brightness temperature in Kelvin, \(\lambda\) is the wavelength in metres, \(S_\lambda\) is the flux density in Jansky at wavelength \(\lambda\), \(k_B\) is the Boltzmann constant, \(\Omega\) is the solid angle subtended by the emitting region and \(z\) is the redshift. Images of all sources we detected are shown in Figure 1. We see structures indicative of jets in sources 1216+069, 1222+225, 1351+640 and 1407+26 although at these low brightness levels, and with the short snapshot observations used in this detection experiment, it is difficult to ascertain the reality of these features; more detailed observations of one of these sources are underway. The detection of 1700+518 is only at 3\(\sigma\) significance, and we consider this detection marginal. We present the luminosity and a characteristic physical size of the emitting region in Table 2 according to the cosmology assumed throughout this paper.

* The cosmology which has been assumed in this paper is that \(H_0 = 50\,\text{km s}^{-1}\,\text{Mpc}^{-1}\), \(q_0 = 0\) and \(\Lambda = 0\).
Figure 1. VLBA images at 8.4 GHz. The lowest solid contour levels in each case are: 0007+106, 0.87 mJy/beam; 1216+069, 0.24 mJy/beam; 1222+22, 0.25 mJy/beam; 1309+355, 1.2 mJy/beam; 1351+640, 0.28 mJy/beam; 1407+263, 0.20 mJy/beam; 1700+518, 0.15 mJy/beam; 2209+184, 12.0 mJy/beam. Other solid contours are at $\sqrt{2}$, 2, $2\sqrt{2}$... times these values, while dashed contours are plotted at $-\sqrt{2}$ and $-1$ times these values. Extended structures indicative of jets are seen some of the maps although at these low brightness levels, and with the short snapshot observations used in this detection experiment, it is difficult to comment on the reality of these features.

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Table 1. Observed VLBA RQQ sample, including alternative names (if in common usage) and a key classifying the sources as follows: P indicates that the 5-GHz luminosity $< 10^{25}$ W Hz$^{-1}$; R indicates that $R < 10$; I indicates RIQ while Q = RQQ, as designated by Miller et al. (1993). The fifth column lists the core flux density at 5 GHz measured with the VLA in A-array by Miller et al. except for those sources marked † where this value is the integrated 5-GHz flux density (measured by Kellermann et al. 1994). Redshifts of 0157+001 to 1351+640 (except for 1222+22) as listed above were taken from Miller et al. (1992). The redshift of 1407+26 is quoted from McDowell et al. (1995); the redshifts of 0003+199, 1222+22, 1700+518 and 2209+184 are quoted from Schmidt & Green (1983); the redshift of 0007+106 is quoted from Sargent (1970). This table also lists the on-source time in minutes, indicates those sources for which the VLA was used in phased-array mode, the phase calibrator used for the phase referencing, and the date of the quoted observations.

| PG name          | Alternative name | Key | VLA 5 GHz flux density | Redshift | On-source time (mins) | Phase calibrator | Date       |
|------------------|------------------|-----|------------------------|----------|-----------------------|------------------|------------|
| 0003+199         | Mkn 335          | PRQ | 3.1                    | 0.025    | 48                    | 0007+171         | 96 Jun 09  |
| 0007+106         | III Zw 2         | I   | 155.0                  | 0.089    | 88                    | self             | 96 Jun 09  |
| 0157+001         | Mkn 1014         | PRQ | 6.0                    | 0.164    | 48                    | 0215+015         | 96 Jun 09  |
| 0923+129         | Mkn 705          | PRQ | 2.8                    | 0.029    | 92 + VLA              | J0921+1350       | 96 Sep 22  |
| 1116+215         | –                 | R   | 11.8                   | 2.046    | 48                    | 1222+216         | 96 Jun 09  |
| 1216+069         | –                 | R   | 5.0                    | 0.334    | 84                    | 1219+044         | 96 Jun 15  |
| 1222+22          | –                 | R   | 11.8                   | 2.046    | 48                    | 1222+216         | 96 Jun 09  |
| 1309+355         | –                 | R   | 54.1                   | 0.184    | 48                    | 1315+346         | 96 Jun 09  |
| 1351+640         | –                 | PRQ | 20.0                   | 0.088    | 48                    | 1342+662         | 96 Jun 09  |
| 1407+26          | –                 | R   | 7.9                   | 0.94     | 84                    | 1404+286         | 96 Jun 15  |
| 1700+518         | –                 | PRQ | 2.2                    | 0.292    | 69 + VLA              | J1705+5109       | 96 Sep 22  |
| 2209+184         | II Zw 171        | P   | 117.0                  | 0.07     | 48                    | 2209+236         | 96 Jun 09  |

3.1 Comparison of VLA and VLBA flux densities

Although we are not in possession of multi-epoch radio images on these milli-arcsec scales, comparison of our integrated VLBA flux densities at 8.4 GHz with VLA flux densities at 5 GHz measured over a decade ago (Miller et al. 1993, Kellermann et al. 1994) indicate differences of only a factor of a few, which can be interpreted as arising from the resolving out of some extended emission, in combination with spectral differences and intrinsic radio variability. In no case does the 8.4 GHz flux density measured with the VLBA in 1996 exceed the measurements made at 5 GHz in the 1980s by Miller et al. and Kellermann et al. We are able to make a comparison between the simultaneous VLA and VLBA measurements of flux densities for those 3 sources which were observed with the VLA in phased array, and indicated in Table 3. For the two objects which we did not detect with the VLBA but which we did observe with the VLA the flux densities are very low (4 mJy for 0923+129 and 1.5 mJy for 1116+215). For now we proceed with the question of the properties of the central engine which must be present in RQQs to sustain, over many years, the luminosities quoted in Table 3.

4 DISCUSSION

4.1 Implications

Our high detection rate from these snapshot observations supports the findings of our initial experiment on the RQQ, E1821+643 (Blundell et al. 1996). The 4 RQQs which we did not detect in these observations are those with the lower VLA flux densities (see Table 3). Table 3 shows that the RQQs require central engines which can supply luminosities of $10^{24.6} - 10^{25.6}$ W Hz$^{-1}$ sr$^{-1}$ arising from regions of a few cubic parsec. The peak luminosity at 5 GHz of the most powerful supernova known (1986J) (Rupen et al. 1987) is $\sim 10^{29}$ W Hz$^{-1}$ sr$^{-1}$ so between 10 and 1000 ($10^5$ for the two high redshift, very luminous objects) of these close to peak luminosity would thus be required to power a single RQQ. This would require a very sustained supernova rate with an unprecedented supernova space density: the (conservatively derived) values for the size of the emitting region yield volumes between $10^5 - 10^7$ times smaller than in the starburst model of Terlevich and Boyle (1993) or observed in the M82 starburst galaxy (Muxlow et al. 1994). The brightness temperature quantifies this by consideration of the flux emanating from a given solid angle — thus radio emission powered by a starburst would not be expected to have a high brightness temperature because of the spatial separation expected for the supernovae.

These results strongly suggest that for these radio-quiet quasars which we detected, their radio emission is not dominated by starbursts and imply that they have central engines similar to those in RLQs, but producing only weak radio jets.

In a recent study (Falcke, Patnaik & Sherwood 1996) high brightness temperatures were found for three RIQs (which are common to our sample) based on fits to the emission region size deconvolved from the synthesised beam of the telescope. Our observa-
Table 2. Results from the VLBA observations are tabulated: columns 2 and 3 list the (J2000) Right Ascension and Declination respectively and column 4 lists the peak flux densities which were obtained using the Gaussian-fitting task \texttt{imfit} within \texttt{AIPS} in units of mJy/beam. Non-detections are quoted as $< 3\sigma$. Column 6 shows the total flux density measured by the VLBA in mJy. Column 7 lists the VLA flux densities measured simultaneously with the VLBA observations for those sources where the VLA was used in phased array mode.

| PG name  | R.A. | Dec. | VLBA 4.8 GHz peak (mJy/beam) | Synthesised beam FWHM (mas) | Total flux density from VLBA (mJy) | Total flux density from VLA (mJy) |
|----------|------|------|-------------------------------|-----------------------------|----------------------------------|-------------------------------|
| 0003+199 | –    | –    | $< 0.8$                       | –                           | –                                | –                             |
| 0007+106 | 00 10 31.00587 | 10 58 29.5037 | 57.7                          | $1.98 \times 0.83$          | 68.3 $\pm$ 1.4                 | –                             |
| 0157+001 | –    | –    | $< 1.5$                       | –                           | –                                | –                             |
| 0923+129 | –    | –    | $< 0.4$                       | –                           | –                                | –                             |
| 1116+215 | –    | –    | $< 0.3$                       | –                           | –                                | –                             |
| 1216+069 | 12 19 20.93171 | 06 38 38.4679 | 1.7                           | $1.87 \times 0.84$          | 2.0 $\pm$ 0.3                  | –                             |
| 1222+22  | 12 25 27.40090 | 22 35 13.0522   | 2.1                           | $1.88 \times 0.80$          | 3.2 $\pm$ 0.4                  | –                             |
| 1309+355 | 13 12 17.75278 | 35 15 21.0857   | 14.9                          | $1.73 \times 0.80$          | 23.8 $\pm$ 2.1                 | –                             |
| 1351+640 | 13 53 15.83069 | 63 45 45.6856   | 1.5                           | $1.66 \times 0.76$          | 2.9 $\pm$ 0.5                  | –                             |
| 1407+26  | 14 09 23.90866 | 26 18 21.0557   | 2.3                           | $2.33 \times 0.98$          | 4.7 $\pm$ 0.4                  | –                             |
| 1700+518 | 17 01 24.82093 | 51 49 20.4955   | 0.8                           | $1.98 \times 0.98$          | 0.8 $\pm$ 0.2                  | 4.9                           |
| 2209+184 | 22 11 53.88876 | 18 41 49.8634   | 69.8                          | $1.88 \times 0.80$          | 179.7 $\pm$ 17.1               | –                             |

Table 3. Derived physical parameters from the VLBA observations. Column 2 shows the brightness temperatures derived according to the formula quoted in the main text, using the sizes of the synthesised beam and total VLBA flux densities listed in Table 2. Where our snapshot data permitted robust and well-constrained deconvolved sizes to the emitting regions to be fitted, we tabulate those in column 3, together with re-derived brightness temperatures using these deconvolved sizes and the peak VLBA flux densities. Also listed are the luminosities (in W Hz$^{-1}$sr$^{-1}$) at 8.4 GHz of the compact emission of the RQQs we detected together with the characteristic size of the emitting region (this is the geometric mean of the major and minor axes of the synthesised beam converted into a physical distance in parsecs within the assumed cosmology).

| PG name  | $T_B$ (K) | Deconvolved size (mas) | Limit $T_B$ (K) | Log$_{10}$($L_{8.4}$) (W Hz$^{-1}$sr$^{-1}$) | Emitting region (pc) |
|----------|-----------|------------------------|----------------|---------------------------------|---------------------|
| 0003+199 | –         | –                      | –              | –                               | –                   |
| 0007+106 | $7.5 \times 10^8$ | 0.4 $\times$ 0.4     | $7.7 \times 10^9$ | 23.22                          | 2.9                 |
| 0157+001 | –         | –                      | –              | –                               | –                   |
| 0923+129 | –         | –                      | –              | –                               | –                   |
| 1116+215 | –         | –                      | –              | –                               | –                   |
| 1216+069 | $2.8 \times 10^7$ | 0.7 $\times$ 0.4     | $1.6 \times 10^8$ | 22.92                          | 8.0                 |
| 1222+22  | $8.3 \times 10^7$ | 0.9 $\times$ 0.4     | $3.5 \times 10^8$ | 24.99                          | 19.4                |
| 1309+355 | $2.5 \times 10^8$ | –                      | –              | –                               | –                   |
| 1351+640 | $2.4 \times 10^7$ | –                      | –              | –                               | –                   |
| 1407+26  | $1.1 \times 10^9$ | 0.7 $\times$ 0.4     | $8.6 \times 10^9$ | 25.56                          | 24.3                |
| 1700+518 | $1.0 \times 10^7$ | –                      | –              | –                               | –                   |
| 2209+184 | $9.7 \times 10^8$ | –                      | –              | –                               | 23.09               |

4.2 When should a quasar be deemed radio-quiet?

We return to the question of when a quasar should be appropriately classified as radio-loud. Of the three classifications outlined in the Section 2, none considers the contribution to the total radio emission from cores which might be Doppler boosted, if the cores are indeed powered by relativistic jets. The bimodality in radio-loudness would undoubtedly be more pronounced if instead of comparisons based on total radio luminosity, the ‘total minus core’ radio luminosity, (i.e., only the contribution from unbeamed emission), were to be used (see e.g., Kukula et al. 1998). It is imperative to ascertain whether the radio flux densities quoted from the literature for those quasars believed to be non-radio-loud, which we have detected with the VLBA, are representing the extent of the radio-emission from these objects, and thus that our detections are of genuinely radio-quiet quasars. We thus checked the NVSS survey (Condon 1994) (VLA D-array 1.4-GHz maps), the 6C (Hales et al. 1988, Hales et al. 1990) and the 7C (Waldram et al. 1996) surveys at 151 MHz for evidence of diffuse extended features being considerably shorter do not in all cases allow us to similarly obtain robust, well constrained, fits to the sizes of the emission-regions.
lobe emission related to these RQQs. For the 6C and 7C surveys the rms background measurements are roughly $\sim 25 - 50 \text{ mJy/beam}$ in the absence of any confusion. For the NVSS survey the rms background is $\sim 0.2 \text{ mJy/beam}$. We found no evidence of any related extended lobe emission for our detected RQQs. We therefore believe that all of the objects we detected originally classified as radio-quiet are correctly classified as such, although their radio-quietness would be more dramatically evident were the criteria to be based on extended emission only.

4.3 What are the boosted counterparts of RQQs?

One important question is whether the jets in RQQs are indeed relativistic near the central engine (as in RLQs), albeit with a much lower bulk kinetic power. If so a subset of the RQQ population, namely those whose jet axes are oriented close to our line-of-site, would be expected to exhibit Doppler boosted emission. Such a scenario was first proposed by Miller et al. (1993) based on a study of the [OIII] luminosity versus radio luminosity plane for a sample of optically selected quasars (those quasars from BQS with $z < 0.5$). They found that radio-loud objects exist only at high [OIII] luminosity and that for RQQs there is a tight correlation between the radio and the [OIII] luminosity. A number of objects in the radio-quiet region of the plot did not lie so tightly on this correlation; Miller et al. suggested that their location on the plane could be explained if their radio emission was Doppler boosted, i.e., they were the beamed counterparts of RQQs (with Lorentz $\gamma \sim 5$); they termed such objects radio-intermediate quasars. If the criteria for radio-loudness is based on extended emission alone (as discussed in Section 4.2) then the RIQs are clearly members of the RQQ population. The cores of RIQs might be expected to have higher $T_B$ than objects whose radio emission is not Doppler boosted. While there is no such clear correlation from the numbers in this small sample, we note that the comparison of brightness temperatures is an important tool in testing Miller et al.’s hypothesis.

A number of the sources we detected are among those deemed by Miller et al. as RIQs. It is therefore conceivable that the RIQs represent those RQQs with a jet-producing central engine while the true radio-quiet objects lack such a central engine — but the dichotomy posed at the beginning of the paper is little changed, as it is still necessary to explain why the RIQ population cannot form the powerful radio jets seen in the RLQ population, even though there is now direct evidence that some contain jet-producing central engines.

4.4 Conclusions

Our results have shown that some radio-quiet quasars show evidence for a central engine resembling those in radio-loud quasars; the evidence we present is consistent with the sample objects being boosted examples of a homogeneous population of radio-quiet quasars with relativistic jets. Our study underlines the need to address the important question of why powerful radio jets are not seen in RQQs even though a significant fraction of their central engines possess the essential characteristics of those in RLQs; we note that there have been various suggested explanations of this, including for example, lack of black-hole spin (Blandford 1993) or the necessary presence of a hot atmosphere around the nucleus (Fabian & Rees 1995).

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