The structure at the centre of the giant radio galaxy GRS J0844+4627: a compact symmetric object?

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Accepted 2022 September 01. Received 2022 August 29; in original form 2022 June 05

ABSTRACT

We observed the core region of the giant radio galaxy GRS J0844+4627 with e-MERLIN at 1.52 and 5.07 GHz. These observations revealed that the apparent single feature at the centre of GRS J0844+4627, as seen by GMRT, consists of two components separated by 2.7 kpc in projection. Follow-up observations at 1.66 GHz using the EVN unveiled the complex morphologies of the two components. In particular, the south-western component identified with the SDSS J084408.85+462744.2 galaxy morphologically resembles a compact symmetric object (CSO) with a projected linear size of 115 pc. If the CSO hypothesis turns out to be correct, then the overall radio structure of GRS J0844+4627 is triple–double. Given that CSOs are considered young objects, GRS J0844+4627 would appear as a recently restarted active galaxy.

Key words: galaxies: active – galaxies: individual: GRS J0844+4627 – radio continuum: galaxies

1 INTRODUCTION

GRS J0844+4627 radio source was observed with GMRT1 at 150 MHz when searching the Leiden–Berkeley Deep Survey (LBDS) Lynx field for high-redshift radio galaxies (Ishwara-Chandra et al. 2010) and followed up with GMRT at 325, 610, and 1250 MHz (Sebastian et al. 2018, hereafter Paper I). Based on all four observations mentioned above, it has been found that the central region of GRS J0844+4627, resolved by neither the GMRT at any frequency nor by the VLA at 1.4 GHz (FIRST2 survey), has a steep spectrum: $\alpha = -0.85 \pm 0.032$ ($S \propto \nu^{\alpha}$) – see fig. 6 in Paper I – thus, it belongs to a class of compact steep-spectrum (CSS) sources. It is identified with SDSS J084408.85+462744.2 galaxy at the redshift of $z = 0.5696228$. For this redshift and the cosmological parameters specified at the end of this section, the radio galaxy’s overall angular size of 5.5 arcmin translates to 2.2 Mpc of linear size hence the object qualifies as a giant radio galaxy.

In some sense, GRS J0844+4627 resembles TXS 0818+214. The latter radio source appears in FIRST as a triple, where the central component also has a steep spectrum. Owing to the high resolution provided by MERLIN3 and the EVN4 observations, Marecki & Szablewski (2009) unveiled the nature of the apparent core of TXS 0818+214 – it is a double. Consequently, TXS 0818+214 turned out to be a double–double radio source (Schoenmakers et al. 2000). As a follow-up of GMRT observations (Paper I), we carried out an observing programme similar to that by Marecki & Szablewski (2009) in order to study the CSS source at the centre of GRS J0844+4627. The outcome thereof is reported here.

For consistency with Paper I, the cosmological parameters used here are: $H_0 = 69.3 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\omega_M = 0.286$, and $\omega_{\text{Matter}} = 0.0463$. One arcsec of angular size translates to 6.625 kpc of linear size for these values.

2 OBSERVATIONS AND THEIR RESULTS

2.1 e-MERLIN observations

We observed the CSS source at the centre of GRS J0844+4627 with e-MERLIN at 1.52 GHz (512-MHz bandwidth) on 2018 August 31 and at 5.07 GHz (512-MHz bandwidth) on 2019 September 14. Only Mark2, Knockin, Deford, and Cambridge antennas observed at 1.52 GHz hence the shortest baselines were missing. The observing time was extended to 72 h to compensate for the sensitivity loss caused by the missing antennas. Mark2, Deford, Pickmere, Darnhall, and Cambridge observed at 5.07 GHz, whereas Knockin was missing thus some of the long baselines were absent at 5.07 GHz. The duration of that observation was 20 h. The very different distribution of the spatial frequencies led to a similar restoring beam size for the 1.52- and 5.07-GHz data. The data reduction was carried out in aips.5

The images resulting from our 1.52- and 5.07-GHz e-MERLIN observations are shown in Fig. 1. The apparent single CSS source

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1 Giant Metrewave Radio Telescope (Swarup et al. 1991)

2 Faint Images of the Radio Sky at Twenty-Centimeters (Becker, White, & Helfand 1995)

3 Multi-Element Remotely-Linked Interferometer Network (www.e-merlin.ac.uk)

4 European VLBI Network (www.evlbi.org)

5 Astronomical Image Processing System (www.aips.nrao.edu)
at the centre of GRS J0844+4627, as seen by GMRT, reveals two components separated by 0.4 arcsec (2.7 kpc in projection). The line connecting them has a position angle (PA) of 43°, coinciding with the PA of the large-scale lobes (Paper I, fig. 2). The optical object SDSS J084408.85+462744.2 is identified with the south-western component. We measured the flux densities of those two components at both frequencies and calculated the spectral indices – see Table 1. The uncertainties on the flux densities have been estimated using aips task JMFIT. The sum of the 1.52-GHz flux densities given in Table 1 is consistent with the flux density listed in FIRST (950 µJy). The missing flux may be due to the poor sensitivity of e-MERLIN to possible extended structures caused by the absence of the two telescopes forming the three shortest baselines. Both components remain unresolved at 1.52 GHz and only partly resolved at 5.07 GHz when observed with e-MERLIN. To reveal the details of their morphology, we performed an EVN follow-up observation.

### 2.2 The EVN observation

The 12-hour EVN observation of GRS J0844+4627 (project EM146) was conducted on 2021 May 28 at 1.66 GHz using 17 radio telescopes, including Lovell and four e-MERLIN antennas. JVAS J0847+4609 was used as a phase calibrator. The length of the target-calibrator cycle was 10 min, of which 7 min 40 s was spent on the target source. The data were recorded at 1-Gbps rate in four 32-MHz-wide sub-bands per each of the two circular polarizations. For e-MERLIN stations, the recording rate was 512 Mbps and there were two sub-bands per polarization. For these parameters, the image thermal noise estimated using the EVN Calculator\(^6\) amounts to

\[^6\) http://old.evlbi.org/cgi-bin/EVNcalc.pl

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**Figure 1.** e-MERLIN images of the central region of GRS J0844+4627 at 1.52 GHz (left-hand panel) and 5.07 GHz (right-hand panel). Contours increase by a factor of \(\sqrt{2}\); the first contour level is 70 µJy per beam for the 1.52-GHz image and 52 µJy per beam for the 5.07-GHz image. They both correspond to a 4σ level. The beam sizes are 127 × 120 mas at the position angle of −13° for the 1.52-GHz image and 144 × 110 mas at the position angle of 70° for the 5.07-GHz image.

**Figure 2.** EVN image of the central region of GRS J0844+4627 at 1.66 GHz. Contours increase by a factor of \(\sqrt{2}\); the first contour level is 15.8 µJy per beam, which corresponds to a 5σ level. The beam size is 6.08 × 4.59 mas at the position angle of −20°.

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**Table 1.** Flux densities and spectral indices of the two features at the centre of GRS J0844+4627 as measured with e-MERLIN.

| Component | Flux density [µJy]  | α     |
|-----------|---------------------|-------|
|           | 1.52 GHz            | 5.07 GHz |
| NE        | 693±34              | 222±25 | −0.94 |
| SW        | 188±27              | 216±23 | 0.12  |
3.16 \mu Jy per beam (1\sigma). The data were correlated at JIVE\(^7\). We carried out the reduction of the resulting visibilities in \(\mu\)as in a standard way.

The EVN image of the central region of GRSJ0844+4627 is shown in Fig. 2. As in Fig. 1, two components are present; here, they are separated by 0.409 arcsec (2.71 kpc in projection) at the PA = 42°9. To make it possible to explore each of them in detail, they have been featured separately in Fig. 3. The south-western component (Fig. 3, right-hand panel) is a triple of 17.4 mas angular size, i.e. 115 pc of the projected linear size. Its axis is oriented at the PA = 62°7. The flux densities, sizes, and deconvolved sizes of the three subcomponents of the SW component fitted with JMFIT are shown in Table 2. Since the north-eastern component is diffuse, fitting Gaussian subcomponents with JMFIT was problematic. The flux density of that region estimated with the \(\mu\)as TVSTAT utility amounts to \sim 0.4 mJy.

### 3 INTERPRETATION OF THE OBSERVATIONS

Based on the morphology of the SW component, it could be hypothesized that it is a compact symmetric object (CSO, Wilkinson et al. 1994). CSOs are objects with sub-kpc linear sizes and a two-sided structure expanding at rates exceeding 0.1 c. Both these factors imply low kinematic age; in the case of GRS J0844+4627 it is of the order of 10\(^3\) yr. On the other hand, the spectral age of the large-scale structure of GRS J0844+4627 may reach 20 Myr (Paper I), so if the CSO hypothesis is correct, then GRS J0844+4627 manifests restarted activity and the CSO is the emanation of the most recent active period. Large-scale radio emission has been found around several compact radio sources – see section 3.3 of O’Dea & Saikia (2021) – which remains in line with the notion that the compact triple at the position of SDSS J084408.85+462744.2 is a rejuvenated radio source – see table 1 in O’Dea & Saikia (2021). By taking the size as an indicator of kinematic age, this looks like one of the youngest and smallest known CSOs.

It has been claimed in Paper I that GRS J0844+4627 is a double–double source. Due to the presence of the putative CSO at the centre of the source, the overall radio structure appears to be triple–double. Despite the number of active episodes, the orientation of each pair of lobes has not changed significantly, unlike in Seyfert galaxies, where the elements pertinent to the different active episodes are often misaligned with each other (see e.g. Sebastian et al. 2019). The consistency in the direction could be because, unlike the smaller black holes in Seyferts, the larger-mass black holes hosted by elliptical galaxies are more resistant to spin flips.

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\(^7\) Joint Institute for VLBI ERIC (www.jive.eu)
The nature of the north-eastern component (Fig. 3, left-hand panel) is unclear. Its highly steep spectrum and the lack of the optical identification suggest that it could be a relic lobe, but the putative south-western counterpart is neither visible in the e-MERLIN images nor the EVN ones. There is a possibility that the NE component is a knot due to local inhomogeneity and no such knot has been formed in the SW direction. The spectral index of the NE component might have also been affected by resolution, i.e. there could be missing-flux issues at higher frequencies driving the spectral index to a steeper side, though knots are not expected to have steep spectral indices.

Confirming the CSO hypothesis would require measuring the sub-components’ motion or establishing their spectral indices. In either case, new observations are necessary. If the CSO hypothesis turns out to be false, then the SW component is a core-jet source. This interpretation could explain the NE component as a part of the jet further away. Under the assumption that the SW component has a core-jet structure, the jet/counter-jet ratio is ≥18 based on the flux densities from our image. While the inclination angle and the bulk velocities both determine the jet/counter-jet ratio, we make some assumptions about the inclination angle since GRS J0844+4627 is a giant radio galaxy. The size of the largest known giant radio galaxy is ∼5 Mpc (Oei et al. 2022). If the deprojected size of GRS J0844+4627 is also 5 Mpc then the inclination angle would be 26°. For a typical spectral index of α ∼ −0.6 (Laing & Bridle 2013), the bulk velocity turns out to be 0.56 c. Given that such velocities are not unusual in core-dominated quasars (O’Dea, Barvainis, & Challis 1988), the core-jet scenario cannot be ruled out at the present stage.

ACKNOWLEDGEMENTS
MERLIN is a National Facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of STFC.

This work has benefited from research funding from the European Community’s sixth Framework Programme under RadioNet R113CT 2003 5058187.

We thank Thomas Muxlow and Javier Moldon from Jodrell Bank Centre for Astrophysics for their help with e-MERLIN data reduction.

The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. Scientific results from data presented in this publication are derived from the EVN project EM146.

This research has made use of the NASA/IPAC Extragalactic Database (NED), which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology.

CHIC acknowledges the support of the Department of Atomic Energy, Government of India, under the project 12-R&D-TFR-5.02-0700.

DATA AVAILABILITY
The data underlying this paper will be shared on reasonable request to the corresponding author.

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