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Nature of X-shaped radio sources

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Abstract. The nature of X-shaped sources is a matter of considerable debate: it has even been proposed that they provide evidence for black hole mergers/spin reorientation, and therefore constrain the rate of strong gravitational wave events (Merritt & Ekers 2002). Based on morphological and spectral characteristics of these sources, currently a strong contender to explain the nature of these sources is the 'alternative' model of Lal & Rao (2007), in which these sources consist of two pairs of jets, which are associated with two unresolved AGNs. Detailed morphological and spectral results on milliarcsecond-scales (mas) provide a crucial test of this model, and hence these sources are excellent candidates to study on mas; *i.e.*, to detect the presence/absence of double nuclei/AGNs, signs of helical/disrupted jets, thereby, to investigate spatially resolved/unresolved binary AGN systems and providing clues to understanding the physics of merging of AGNs on mas. We conducted a systematic study of a large sample of known X-shaped, comparison FR II radio galaxies, and newly discovered X-shaped candidate sources using Giant Metrewave Radio Telescope and Very Large Array at several radio frequencies. In our new observations of 'comparison' FR II radio galaxies we find that almost all of our targets show standard spectral steepening as a function of distance from the hotspot. However, one source, 3C 321, has a low-surface-brightness extension that shows a flatter spectral index than the high-surface-brightness hotspots/lobes, as found in 'known' X-shaped sources.

Key words. galaxies: active – galaxies: formation – radio continuum: galaxies

1. Introduction

A small but significant fraction of low-luminosity radio galaxies have a pair of large low-surface-brightness lobes oriented at an angle to the high-surface-brightness 'active' radio lobes, giving the total source an 'X' shape. This peculiar and small subclass of extragalactic radio sources is commonly referred to as X-shaped, or 'winged' sources. Typically, both sets of lobes are symmetrically aligned through the centre of the associated elliptical

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host galaxy and are approximately equal in linear extent. Merritt & Ekers (2002) noted that the majority of these sources are FR IIs and the rest are either FR Is or have an intermediate classification.

1.1. Formation scenario

Several authors have attempted to explain the unusual structure in X-shaped sources. In some models these sources have been put forth as derivatives of central engines that have been reoriented, perhaps due to a minor merger (Merritt & Ekers 2002; Dennett-Thorpe et al. 2002; Gopal-Krishna et al. 2003). Alternatively, they may also result from two pairs of jets that are associated with a pair of unresolved AGNs (Lal & Rao 2005, 2007). These, however, are not the only interpretations for the unusual morphologies; some authors suggest a hydrodynamic origin (Worrall et al. 1995; Capetti et al. 2002; Kraft et al. 2005) and some suggest a conical precession of the jet axis (Rees 1978; Parma et al. 1985; Mack et al. 1994). See Lal & Rao (2007) and Cheung (2007) for a detailed account.

In several of the formation scenarios mentioned above for X-shaped sources, the wings are interpreted as relics of past radio jets and the active lobes as the newer ones. Hence, the wings or low-surface-brightness features are expected to show steeper spectra than the high-surface-brightness active lobes in standard models for electron energy evolution ('spectral ageing'). Similarly, in typical FR II radio galaxies, the low-surface-brightness features (regions away from the bright jet and hot-spot emission) are expected to show steeper spectra than the bright jet and/or the hot-spot emission. This can in principle be tested by observation.

Here, we present Giant Metrewave Radio Telescope (GMRT) and Very Large Array (VLA) observations of (i) the known sample of X-shapes sources, (ii) the control sample of low-redshift *normal* FR II radio galaxies, which is matched with the sample of known X-shaped radio sources in size, morphological properties and redshift, and (iii) a new sample selected from the candidate X-shaped sources (Cheung 2007). Using observations carried out in the same manner as those of Lal & Rao (2007), we are able to investigate whether standard spectral ageing models provide an adequate description of sources in these samples, and discuss the implications of our results for models of X-shaped sources.

In the paper, we define the spectral index α as $S_\nu \propto \nu^\alpha$.

2. Samples

Known sample The earlier sample of known X-shaped sources was drawn from the list compiled by Leahy & Parma (1992). There are nearly a dozen such sources, which have been selected solely on the basis of their morphology, and the sample is inhomogeneous and statistically incomplete.

Comparison sample The comparison sample consists of all nearby ($z < 0.1$) normal FR II sources from the 3CRR catalogue. These sources have radio luminosities similar to those of the X-shaped sources, which lie close to the FR I/FR II divide. We impose an angular-size cutoff (based on high-frequency radio maps) on the target sample and ensure that our sample sources are of similar angular sizes to typical X-shaped sources. In addition, all eight sample sources have known weak transverse extensions (proto-wings?) and also have X-ray (*XMM*/*Chandra*) observations.

New sample The new sample is drawn from the compiled list of nearly 100 new candidate X-shaped radio sources through a search of the FIRST survey database (Cheung 2007). Our sample sources have (i) characteristic 'X' shape, (ii) both set of lobes passing symmetrically through the centre of the associated host galaxy, and (iii) an angular size of more than 1.2′ as seen in the VLA–FIRST 1.4 GHz images, which provided us with sixteen sources.

3. GMRT observations

The GMRT has a hybrid configuration (Swarup et al. 1991) with 14 of its 30 antennas located in a central compact array with size ~1.1 km and the remaining antennas distributed in a roughly 'Y' shaped configuration,

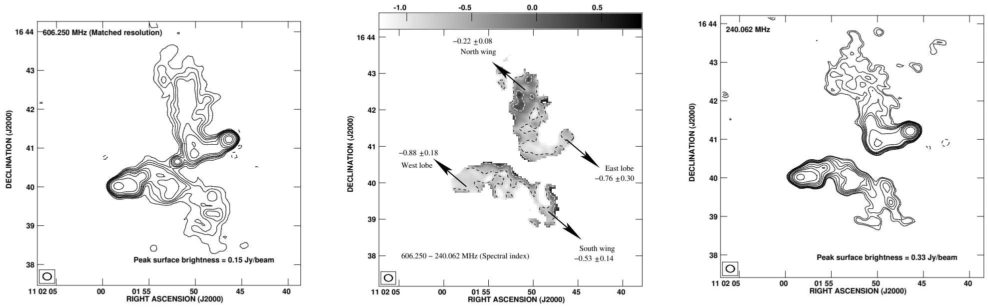

Fig. 1. GMRT map of B1059+169 (a known X-shaped source) at 610 MHz (left panel), 240 MHz (right panel) and the spectral index (240 MHz, 610 MHz) map (middle panel). The 610 MHz map is matched with the resolution of 240 MHz. The CLEAN beam for the matched maps is $13.0'' \times 11.1''$ at a P.A. of 82.5°.

giving a maximum baseline length of ~25 km. The 240 MHz and 610 MHz feeds of GMRT are coaxial feeds enabling simultaneous multi-frequency observations at these two frequencies. We made synthesis observations of all sources in three samples at 240 MHz and 610 MHz, during several observing GTAC cycles, in the standard spectral line mode. We also used archival data at 1.4 GHz from the VLA.

4. Results

Fig. 1 and 2 show examples of the images, which have nearly complete (u, v) coverage, an angular resolution $\sim 12''$ and $\sim 6''$ and the r.m.s. noise in the maps are ~2.0 mJy beam^{-1} and ~0.2 mJy beam^{-1} at 240 MHz and 610 MHz, respectively.

The spectral characteristics of known X-shaped sources seem to fall (nearly) equally into three distinct categories, namely, sources in which (i) the wings have flatter spectral indices than the active lobes, (ii) the wings and the active lobes have comparable spectral indices, and (ii) the wings have steeper spectral indices than the active lobes. It is probable that the three categories of sources are unrelated to one another, which makes it challenging to construct a single framework explaining these spectral properties of X-shaped sources. A strong contender to explain the nature of these sources is the 'alternative' model of Lal & Rao (2007), in which these sources consist of two pairs of jets associated with two unresolved AGNs. Almost all our 'comparison sample' sources show monotonic steepening of the radio spectrum from brighter hotspots to low surface brightness features, a classical spectral signature seen in almost all normal FR II radio galaxies. Preliminary analysis of the 'new sample' also shows similar result. In contrast to this, a significant fraction of the 'known sample' of X-shaped sources has wings with flatter, or at least comparable, spectral indices to those in the brighter active lobes. This implies that the wings of X-shaped sources do not simply behave like the low-surface-brightness regions of more typical FR II sources. The low surface brightness feature in 3C 321, a classical FR II radio source, also shows an unusual spectral behaviour, *i.e.*, the low-surface-brightness extension to one lobe shows a flatter spectral index than the high-surface-brightness hotspots/lobes, similar to the spectral behaviour seen in wings in some of the X-shaped sources. This raises the possibility that 3C 321 consists of two pairs of jets, which are associated with two unresolved AGNs, a possible formation model for known X-shaped sources (Lal & Rao 2007). Another possibility is simply that our current understanding of spectral ageing in radio lobes, particularly at low frequencies, is incorrect.

Further clues about the nature of X-shaped sources may be obtained from milliarcsecond-scales (mas) study to search for signs of binary AGN systems in X-shaped radio sources (Lobanov 2006) either directly by spatially re-

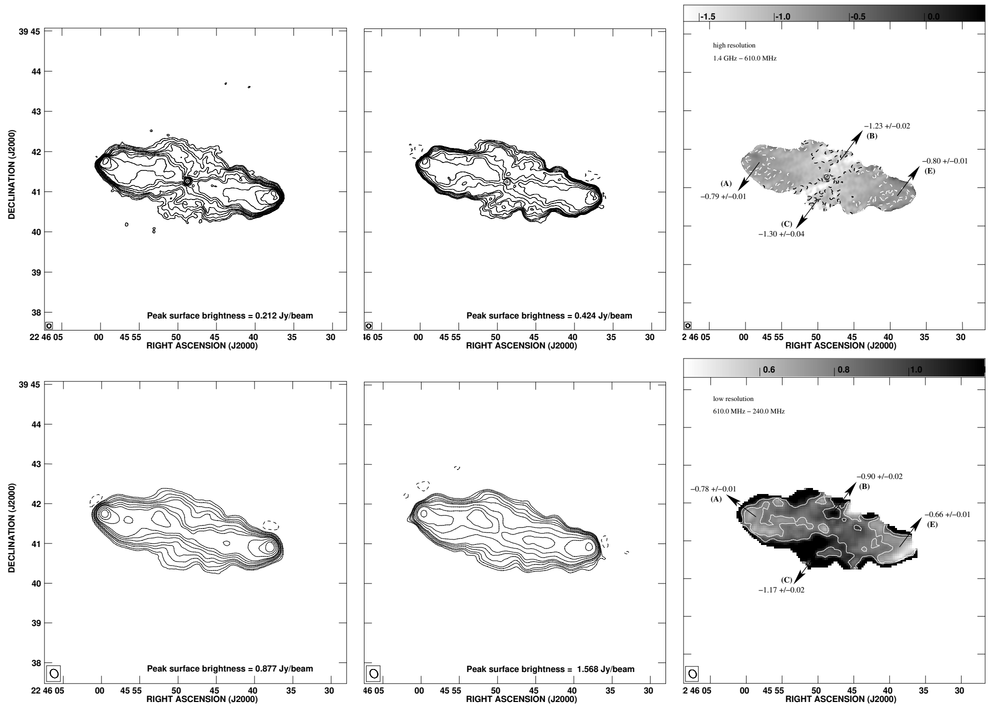

Fig. 2. Images of 3C 452 (a FR II sample source). Upper left: The VLA map of 3C 452 at 1.4 GHz. Upper middle: The GMRT map of 3C 452 at 610 MHz. Lower left: The GMRT map of 3C 452 at 610 MHz matched with the resolution of 240 MHz. Lower middle: The GMRT map of 3C 452 at 240 MHz. Upper right and lower right panels: The distribution of the spectral index, between 1.4 GHz and 610 MHz (upper right), and 240 MHz and 610 MHz (lower right), for the source. The r.m.s. noise values in the radio images found at a source free location are ~0.2, ~0.6 and ~3.1 mJy beam^{-1} at 1.4 GHz, 610 MHz and 240 MHz, respectively. The uniformly weighted CLEAN beams for upper and lower panel maps are 6.0″ × 6.0″ at a P.A. of 0.0° and 13.6″ × 11.2″ at a P.A. of +29.7°, respectively.

solving the twin radio cores or indirectly by studying the morphology of radio jets on mas, and hence inferring their presence.

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References

Cheung, C.C., 2007, AJ, 133, 2097
Dennett-Thorpe, J., et al. 2002, MNRAS, 330, 609
Gopal-Krishna, et al. 2003, ApJ, 594, L103
Kraft, R.P., et al. 2005, ApJ, 622, 149
Lal, D.V. & Rao, A.P. 2007, MNRAS, 374, 1085
Lal, D.V., Hardcastle, M.J. & Kraft R.P. 2008, MNRAS (submitted)
Lobanov, A.P. 2006, ArXiv Astrophysics e-prints `astro-ph/0606198`
Merritt, D. & Ekers, R.D. 2002, Sci, 297, 1310
Parma, P., Ekers, R.D., Fanti, R., 1985, A&AS, 59, 511
Rees, M.J., 1978, Nat, 275, 516
Swarup, G., et al. 1991, Cu. Sc., 60, 95
Worrall D.M., Birkinshaw, M., Cameron, R.A., 1995, ApJ, 449, 93