3C 223.1: A source with unusual spectral properties

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ABSTRACT

Analysis of Giant Metrewave Radio Telescope low frequency data for an X-shaped source, 3C 223.1 has revealed an unusual result. The radio morphologies of it at 240 and 610 MHz show well defined X-shape with a pair of active jets along the north-south axis and a pair of wings along the east-west axis, that pass symmetrically through the undetected radio core. The wings (or low surface brightness jets) have flatter spectral indices with respect to the high surface brightness jets, which confirms the earlier marginal result obtained at high frequency by Dennett-Thorpe et al. (2002). Although unusual, it is a valuable result which puts stringent constraints on the formation models and nature of these sources. This result clearly shows the value of mapping the sample of X-shaped sources at low frequencies.

Key words: galaxies: active – individual: 3C 223.1 – galaxies: formation – radio continuum: galaxies – spectral index

1 INTRODUCTION

The X-shaped or ‘winged’ sources form a peculiar class of extragalactic sources consisting of eleven sources compiled by Leahy & Parma (1992). These sources are characterised by two low surface brightness lobes (the ‘wings’) oriented at an angle to the ‘active’, or high surface brightness radio lobes, giving the total source an ‘X’ shape; both sets of lobes usually pass symmetrically through the centre of the associated host galaxy. Recently Merritt & Ekers (2002) noted that seven out of eleven are of Fanaroff-Riley type II (FR II) and rest are either FR I or mixed.

Source 3C 223.1 (z = 0.1075) is a classical X-shaped source, which does not reside in a rich cluster; instead it probably resides in an environment similar to ‘classical’ FR IIs of similar radio power. Although, the host galaxy seems to be a relatively undisturbed elliptical, its HST image shows a beautiful central bulge with a dusty disk (de Koff 1996). Radio observations show a high degree of polarisation (15-30 per cent) in the wings, and an apparent magnetic field structure parallel to the edge of the source and along the length of the wings (Dennett-Thorpe et al. 2002). Further high frequency and high resolution radio polarisation images showed field lines wrapping around the edges, as well as complex internal structure (Black et al. 1992).

We have started a project to study the sample of X-shaped radio sources at 240 and 610 MHz using the Giant Metrewave Radio Telescope (GMRT). In this paper we present results for 3C 223.1 and describe its morphological and spectral properties. We use the data to study the behaviour of the low frequency spectra at several locations (the north and south lobes and the east and west wings) across the source and compare it with the existing models. We would also discuss the implications of our results on the formation models of X-shaped sources.

2 OBSERVATIONS

The 240 and 610 MHz feeds of GMRT are coaxial feeds and therefore, simultaneous multi-frequency observations at these two frequencies are possible. We made full synthesis observations of 3C 223.1 at 240 and 610 MHz, in the dual frequency mode, using the GMRT on 18 Dec 2003 in the standard spectral line mode with a spectral resolution of 125 kHz. Table I gives the details of the observations. The visibility data were converted to FITS and analyzed using standard AIPS. The flux calibrator 3C 286 was observed in the end as an amplitude calibrator and to estimate and correct for the bandpass shape. We used the flux density scale which is an extension of the Baars et al. (1977) scale to low frequencies, using the coefficients in AIPS task ‘SETJY’. Source 0834+555 was used as the phase calibrator and was observed once every 35 min. The error in the estimated flux density, both due to calibration and systematic, is ≲ 5%. The data suffered from scintillations and intermittent radio frequency interference (RFI). In addition to normal editing of the data, the scintillations affected...
Table 1. Observing log for 3C 223.1. Centre of the field was at RA$_{2000}$ = 09:41:24.0 and Dec$_{2000}$ = 39:44:19.9.

|                  | 610 MHz | 240 MHz |
|------------------|---------|---------|
| Observing date   | 18 Dec 2003 | 18 Dec 2003 |
| Duration         | 10.45 Hrs | 10.45 Hrs |
| Centre frequency | 606.68 MHz | 237.19 MHz |
| Nominal bandwidth| 16 MHz   | 6 MHz    |
| Effective bandwidth | 14.25 MHz | 5 MHz |
| Primary beam     | 43'      | 108'     |
| Synthesized beam  | 8".6 × 5".0 | 17".4 × 13".3 |
| (P.A.)           | 80°.4    | 80°.3    |
| Sensitivity (σ)  | 0.4 mJy beam$^{-1}$ | 3.0 mJy beam$^{-1}$ |
| Calibrator       | 3C 286   | 3C 286   |
| $S_\nu$ (3C 286) | 21.02 Jy | 28.07 Jy |

data and channels affected due to RFI were identified and edited, after which the central channels were averaged using AIPS task ‘SPLAT’ to reduce the data volume. To avoid bandwidth smearing, 5.00 MHz of clean band at 240 MHz was reduced to 4 channels of 1.25 MHz each. At 610 MHz where there was little RFI, 14.25 MHz of clean band was averaged to give 3 channels of 4.75 MHz each.

While imaging, 55 facets (obtained using AIPS task ‘SETFC’), spread across a ∼2°×2° field were used at 240 MHz and 12 facets covering slightly less than a 0.7°×0.7 field, were used at 610 MHz to map each of the two fields using AIPS task ‘IMAGR’. We used ‘uniform’ weighting and the 3−D option for W term correction throughout our analysis. The presence of a large number of point sources in the field allowed us to do phase self-calibration to improve the image. After 2−3 rounds of phase self-calibration, a final self-calibration of both amplitude and phase was made to get the final image. At each round of self-calibration, the image and the visibilities were compared to check for the improvement in the source model. The final maps were combined using AIPS task ‘FLATN’ and corrected for the primary beam of the GMRT antennas.

The full synthesis radio images shown in Fig. 1 have nearly complete UV coverage, an angular resolution ∼15" and ∼8" and the rms noise in the maps are ∼3.0 and ∼0.4 mJy beam$^{-1}$ at 240 and 610 MHz, respectively. The dynamic ranges in the two maps are ∼900 and ∼1700 respectively at 240 and 610 MHz. 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, giving a maximum baseline length of ∼25 km. The baselines obtained from antennas in the central square are similar in length to those of the VLA D-array, while the baselines between the arm antennas are comparable in length to the VLA B-array. A single observation with the GMRT hence yields information on both small and large angular scales with reasonably good sensitivity.

3 RADIO MORPHOLOGY

The first high angular resolution, high sensitivity images of 3C 223.1 at the lowest frequencies of 240 MHz (upper right panel) and 610 MHz (upper left panel) are shown in Fig. 1. This complex radio source shows an X-shaped morphology at both 240 and 610 MHz. The angular extent is ∼105 arcsec along the apparently active lobes (those with hot-spots) and ∼150 arcsec along the wings. The nuclear source of 3C 223.1 is invisible at both these frequencies and also in the radio maps of Dennett-Thorpe et al. (2002), but is detected and is unresolved at 8.4 GHz (Black et al. 1992). The weak jet detected mid-way between core and north lobe by Black et al. (1992) at 8.4 GHz is not seen in our low resolution maps, because of coarser resolution. Our low resolution maps also suggest of a sharp boundary at the farthest end of the north lobe and a likely ring-like feature in the south lobe, which is consistent with earlier results of Black et al. (1992).

The first calibrated UV data at 610 MHz was mapped using UV taper of 0−22 kλ, which is similar to that of 240 MHz data and then restored using the restoring beam corresponding to the 240 MHz map (Fig. 1 lower left panel). In Table 2 we show the integrated flux densities of 3C 223.1 along with previous measurements at other frequencies. Our estimates at both frequencies, 240 and 610 MHz agrees well with that of the measurements from other instruments. We therefore believe that we have not lost any flux density in our interferometric observations and there are no systematics introduced in our analysis.

4 LOW FREQUENCY RADIO SPECTRA

The observations and morphology described above allow us to investigate in detail the spectral index distribution of 3C 223.1. The restored and matched maps at 240 and 610 MHz, were used further for the spectral analysis. We determine the spectral index distribution using the standard direct method of determining the spectral index between maps $S_{\nu_1}(x, y)$ and $S_{\nu_2}(x, y)$ at two frequencies $\nu_1$ and $\nu_2$, given by

$$\alpha_{\nu_1, \nu_2}(x, y) = \frac{\log (S_{\nu_1}(x, y)/S_{\nu_2}(x, y))}{\log(\nu_1/\nu_2)}.$$  

The low frequency flux densities plotted in Fig. 2 are calculated using the images shown in Fig. 1 (upper right and lower left panels), which are matched to the same resolution, and these values are tabulated in Table 2. The flux densities at higher frequencies in this table are quoted using earlier observations in Dennett-Thorpe et al. (2002). The flux densities for the active lobes and the wings are integrated over the region, which is at least 4 times the beam size and above their 3σ contour to reduce statistical errors. Analysis of the spectrum in different regions of the source shows remarkable variation across the source (Fig. 1 lower right panel).

We have obtained the best power-law fit ($S \propto \nu^\alpha$). The low frequency (240−610 MHz) fitted spectra have $-0.37 < \alpha < -1.08$ for all regions across the source. The source also shows evidence for steeper spectra in the active lobes than in the wings. The east and west wings have low frequency (240−610 MHz) spectral indices, $-0.37 \pm 0.03$ and $-0.62 \pm 0.02$ respectively, whereas the north and south active lobes have $-1.08 \pm 0.01$ and $-1.08 \pm 0.01$ respectively (also see Fig. 1).
GMRT observations of 3C 223.1

Figure 1. Upper: Full synthesis GMRT maps of 3C 223.1 at 610 (left panel) and 240 MHz (right panel). The CLEAN beams for 610 and 240 MHz maps are $6'' .1 \times 4''.8$ at a P.A. of $66''.8$ and $13''.1 \times 10''.8$ at a P.A. of $35''.2$ respectively; and the contour levels in the two maps, respectively are $-0.06, 0.06, 0.08, 0.16, 0.24, 0.48, 1, 2, 4, 8, 16$ Jy beam$^{-1}$ and $-0.08, 0.08, 0.16, 0.24, 0.48, 1, 2, 4, 8, 16$ Jy beam$^{-1}$ per cent of the peak surface brightness. Darker regions correspond to higher surface brightness. Lower left: The map of 3C 223.1 at 610 MHz matched with the resolution of 240 MHz. The contour levels are $-0.08, 0.08, 0.16, 0.24, 0.48, 1, 2, 4, 8, 16$ Jy beam$^{-1}$ per cent of the peak surface brightness. Here again, the darker regions correspond to higher surface brightness. Lower right: The distribution of the spectral index, between 240 and 610 MHz, for the source. The spectral index contours are spaced at $-2.4, -1.2, 0.6$ per cent of the peak spectral index. The lighter regions represent the relatively steep spectrum regions as compared to the darker regions which represent flat spectrum (although the full range of spectral index is $-3.4$ to $+1.1$, we have shown only $-1.0$ to $+0.8$ for clarity). The spectral indices quoted for four regions are determined using integrated flux densities found over a circular region of $\sim 5$ pixels radius centered at the position of tail of the arrows shown. The error-bars on the spectral index are determined using error-bars on the flux density found at a source free location using similar sized circular region, which are $\sim 3.0$ and $\sim 0.4$ mJy beam$^{-1}$ at 240 and 610 MHz, respectively. These error-bars, both spectral indices and flux densities, do not change significantly with increasing or decreasing the size of circle and they also do not change significantly by changing slightly the position of circular region. The maximum possible systematic error in spectral index is either 0.05 across the source or 0.14 for the wings and 0.01 for the active lobes (see Sect. 4).
Table 2. The total intensity and spectral comparisons for source and source regions. The total flux densities quoted are in Jy along with corresponding error-bars (1σ). †: Large Cambridge interferometer (Ryle 1960); ‖: our GMRT measurements; ††: Ficarra et al. (1985); ‡: VLA FIRST survey (Becker et al. 1995); ‡‡: Kellermann (1969); ‡∥: Green Bank, Northern Sky Survey (White & Becker 1992). Last two rows show best fitted spectra to source and source regions. †: Low frequency (between 240 and 610 MHz) spectral indices; ‖: high frequency (between 1400 and 3200 MHz) spectral indices (Dennett-Thorpe et al. 2002).

| Freq (MHz) | Total Flux density (Jy) |
|-----------|-------------------------|
| 178†      | 8.7                     |
| 240‖      | 8.33 ±0.41              |
| 408†      | 4.72 ±0.10              |
| 610‖      | 3.56 ±0.17              |
| 1400‖     | 1.90 ±0.28              |
| 2695‡     | 1.23 ±0.61              |
| 4850†     | 0.78 ±0.11              |
|           | N lobe  | W wing | S lobe | E wing |
| 178†      | ±0.003 | ±0.003 | ±0.003 | ±0.003 |
| 240‖      | ±0.003 | ±0.003 | ±0.003 |
| 408†      | ±0.001 | ±0.001 | ±0.001 |
| 610‖      | ±0.001 | ±0.001 | ±0.001 |
| 1400‖     | ±0.001 | ±0.001 | ±0.001 |
| 2695‡     | ±0.001 | ±0.001 | ±0.001 |
| 4850†     | ±0.001 | ±0.001 | ±0.001 |

α†  = −0.91 ±0.07
α‖  = −0.75 ±0.02

5 DISCUSSION

Many authors have attempted to explain the unusual structure in X-shaped sources. The first attempt was made by Reed (1973), who suggested that the jet direction precesses due to a realignment caused by the accretion of gas with respect to the central black hole axis. Dennett-Thorpe et al. (2002) discussed four possible scenarios for the formation of such radio morphology: (1) backflow from the active lobes into the wings (Leahy & Williams 1984; Capetti et al. 2002); (2) slow conical precession of the jet axis (Parma et al. 1983; Mack et al. 1994); (3) reorientation of the jet axis during which flow continues; and (4) reorientation of the jet axis, but with the jet turned off or at greatly reduced power during the change of direction. Merritt & Ekers (2002) suggested another possible scenario, i.e. the reorientation of black hole’s spin axis due to a minor merger, leading to a sudden flip in the direction of any associated jet. A variant of Merritt & Ekers (2002) model was suggested by Gopal-Krishna et al. (2003), where the sources with Z morphology within their X-shapes evolve along a Z-X morphological sequence. Presently, most of the observational results seem to prefer possibilities 3, 4 of Dennett-Thorpe et al. (2002) or Merritt & Ekers (2002) or Gopal-Krishna et al. (2003). The key difference between Dennett-Thorpe et al. (2002) and Merritt & Ekers (2002) reorientation models is in terms of mechanism of reorientation; former favoured the disc instability mechanism because
of little evidence for recent merger in their sample, while the latter preferred the coalescence scenario. Nevertheless, in these favoured scenarios (and also in other models), the wings are interpreted as relics of past radio jets and the active lobes as the newer ones.

Using these radio observations, the spectra at different locations in the source might be used to distinguish between some of the models suggested for these sources. In the simplest picture, the low surface brightness wings would have an older population of the electrons and therefore should have steeper spectral index as compared to the active high surface brightness radio lobes if the magnetic fields are uniform in the measured regions. But, the spectra of low surface brightness jet (or the wings) being flatter than the active high surface brightness jet, is opposite to this simple picture.

5.1 Interpretations based on spectral ageing

Below we present some of the assumptions used in the spectral ageing method for estimating the age and discuss what could be modified to explain the above result.

1. The injection spectral index is assumed to be constant during the active phase of the AGN and the evolution of the synchrotron spectrum is assumed to be due to the synchrotron losses. One of the favoured scenario for the formation of X-shaped sources is the reorientation of the jet axis (Dennett-Thorpe et al. 2002). It is possible that along with the reorientation of the jet axis the injection spectral index also changed. It is then possible to have a flatter spectral index in the wings compared to the active lobes. A similar interpretation was also suggested by Palma et al. (2003), to explain the anomalous spectral index features seen in NVSS 2146+82.

2. In classical radio galaxies, it is the usually the high surface brightness hot-spots which consist of a young population of energetic electrons and they are the source of plasma for the low surface brightness lobes, which eventually consist of older population of electrons. In the case of X-shaped sources, whose formation is yet to be understood, it is possible that this is not the case. Instead, it is possible that the wings are in the process of becoming new active jets, in which case it is not surprising that they have flatter spectral index compared to the active lobes.

3. Reacceleration mechanisms are mainly seen in hot-spots and sites undergoing interactions, which needs to be appropriately accounted for while interpreting evolution of synchrotron spectrum. The diffuse, low surface brightness regions are usually believed to be relaxed systems. It is hard to achieve reacceleration mechanisms in the low surface brightness lobes or wings, via standard Alfvén waves and Fermi mechanisms. Therefore, presently it is difficult to reconcile the observed spectral indices in the wings and the active lobes, unless there exists an additional exotic reacceleration mechanism.

4. Magnetic field strength does not evolve and its distribution is believed to be isotropic, and hence the synchrotron emission is isotropic. Blundell & Rawlings (2000) have questioned this assumption, and have provided an alternative physical picture which could mimic the observed spectral behaviour. They invoke a gradient in magnetic field across the source, together with a curved electron energy spectrum, which would result in spectral indices being different at distinct locations within the source and could possibly explain our observed results.

5.2 X-shaped sources–Merger of two AGNs

We now discuss an alternative scenario, which is not addressed earlier, for the X-shaped sources.

Although there are several examples of resolved binary AGN systems, examples of unresolved binary AGN systems are unknown. X-shaped sources, could be of the latter kind, with two pairs of jets being associated with two unresolved AGNs. An indirect hint for the presence of binary AGNs is using HST to identify inwardly decreasing surface brightness profiles in the galaxy. This is also found to be so using N-body simulations, in which a coalescing binary black hole creates a ‘loss cone’ (displaced matter within a distance which is roughly the separation between the two black holes when they first form a bound pair) around it (Merritt 2004).

We have reanalyzed the archived HST data, and close inspection of the deconvolved brightness profile does not suggest a centrally depressed, nearly flat core. But this could be due to obscuration of the core by the dusty disk, as suggested by de Koll (1996), and therefore we could not see signature of the ejection of stars from the core during the hardening of the AGNs undergoing merger.

Future high resolution, phase-referencing very long baseline interferometry, radio imaging of 3C 223.1 could look for Keplerian orbital motion of some emission component close to black holes, and might be used to detect the presence of binary AGNs containing super massive black holes (e.g. 3C 66B, Sudou et al. 2003).

6 CONCLUSIONS

We have presented the lowest frequency image of 3C 223.1 at 240 MHz. The important consequences of these observations combined with our 610 MHz observations are as follows:

1. The low surface brightness lobes (or the ‘wings’) have flatter spectra as compared to the high surface brightness active radio lobes.

2. This result is not easily explained in most models of the formation of X-shaped sources.

3. Low frequency, high resolution radio images for the entire sample of X-shaped sources would be useful in understanding the formation models for these sources. A project using GMRT is in progress and the analysis is in advanced stage. Our subsequent papers would present the morphological and spectral radio results, and discuss the results statistically for the whole sample of X-shaped sources.

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