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Double Relics in the Outskirts of A3376: Accretion Flows Meet Merger Shocks?

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Abstract. The case of spectacular ring-like double radio relics in the merging, rich galaxy cluster A3376 is of great interest to study non-thermal phenomena at cluster outskirts. We present the first low frequency (330 and 150 MHz) images of the double relics using the GMRT. With our GMRT 330 MHz map and the VLA 1400 MHz map (Bagchi *et al*. 2006), we have constructed and analyzed the distribution of spectral indices over the radio relics. We find flat spectral indices at the outer edges of both the relics and a gradual steepening of spectral indices toward the inner regions. This supports the model of outgoing merger shock waves. The eastern relic has a complex morphology and spectral index distribution toward the inner region. This will be discussed in the context of the effect of large-scale accretion flows on the outgoing merger shocks as reported in the recent simulations.

Key words. Galaxy clusters—relics.

1. Introduction

In the currently accepted picture of structure formation in the Universe, small-scale structures form first and these merge to form large structures such as galaxy clusters. In the process of structure formation, the gravity-driven supersonic flows of intergalactic matter on to dark matter-dominated collapsing structures such as pancakes, filaments and galaxy clusters create Mpc scale cosmic shock waves. The inter-galactic gas heated by these shocks is believed to form the Warm Hot Intergalactic Medium (WHIM), in which about 30% of the baryon mass of the Universe at the present epoch is believed to be in. Direct detection of WHIM is very challenging owing to its low density. However, in the regions surrounding rich clusters where inter-galactic shocks propagate in magnetized inter-galactic medium, WHIM can be probed by synchrotron and inverse-Compton radiation emitted by energetic electrons accelerated at the shock fronts. Around a few clusters of galaxies, diffuse radio emission on Mpc scale has been detected and is suspected to be a result of acceleration of electrons at cosmological shock waves. Such diffuse radio sources around galaxy clusters are termed as radio relics. Abell 3376 is one such cluster where a

pair of radio relics has been discovered (Bagchi *et al*. 2006). We present a low radio frequency study of the spectacular double arc-like relics in A3376.

2. Abell 3376

The galaxy cluster A3376 is a nearby cluster ($z = 0.046$, decl. $\delta \approx -40$) with X-ray luminosity of 2×10^{44} erg s^{-1} (0.1–2.4 keV) and average temperature of 5 keV. The estimated virial mass is 3.64×10^{14} h^{-1} $M_{\odot}$ and virial radius is 0.98 h^{-1} Mpc (Girardi *et al*. 1998; Araudo *et al*. 2008). In A3376, bow shock-like structures have been detected at 1.4 GHz with the VLA in DnC and CnB configuration (Bagchi *et al*. 2006). We refer to the relics as 'east relic' and 'west relic' according to the position relative to the cluster center. Together with strong evidence for mergers based on the X-ray images, A3376 is a unique site where particle acceleration phenomena in the inter-galactic medium can be studied.

3. GMRT observations

We observed the relics in A3376 with the GMRT at 150 and 330 MHz. Bandwidths of 32 and 16 MHz at 330 and 150 MHz were used. The data were analyzed using Astronomical Image Processing System (AIPS). Standard procedures of excision of bad data and calibration were followed. The final calibrated data were imaged and appropriate number of self-calibration iterations were carried out. At 150 MHz, an image with a synthesized beam of $47'' \times 47''$ and rms of 5 mJy beam^{-1} was produced. Both the radio relics were detected. At 330 MHz an image using natural weights for the visibilities with a synthesized beam of $35'' \times 35''$ and rms 0.5 mJy beam^{-1} was produced (Fig. 1). High resolution images at 150 and 330 MHz with synthesized beams of $23'' \times 11''$ (rms 0.4 mJy beam^{-1}) and $13'' \times 5''$ (rms 5 mJy beam^{-1}), respectively were produced and used for estimating the flux densities of unresolved

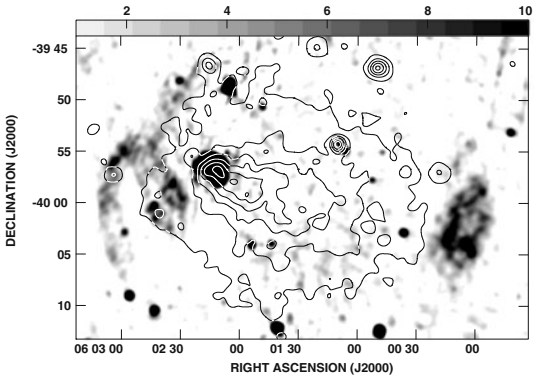

Figure 1. GMRT 330 MHz image (grey-scale flux density range 1–10 mJy beam^{-1}) and ROSAT X-ray image (contours, 0.1–2.4 keV) of A3376. The elongated arc-like features seen in grey-scale on the east and the west of the X-ray emission contours are the two radio relics in A3376.

sources. The largest linear sizes of the relics are 1.6 Mpc (east relic) and 0.8 Mpc (west relic).

4. Spectral index maps

The GMRT 330 MHz and the VLA (C+D) 1.4 GHz images with synthesized beams of $35'' \times 35''$ were used to construct spectral index maps of each of the relic. Shortest baselines of 36 m with the VLA D array at 1.4 GHz and 100 m with the GMRT at 330 MHz correspond to sampling of the UV-plane at similar distances of ~ 0.18 and ~ 0.11 kλ, respectively. Further, since the extents of structures detected at 1.4 GHz and 330 MHz are similar, we do not expect artefacts in the spectral index map due to UV-coverage. Primary beam gain correction was applied to both the images prior to making spectral index maps. The spectral indices over the regions of the relics vary between -0.5 and -2.5. The spectral indices steepen from outer to inner edges of the relics indicating the presence of outgoing shocks.

5. Discussion

The multifrequency images and the spectral index maps of the double relics in A3376 show consistency with the picture of acceleration of electrons at the outgoing merger shocks. However, it is noticed that the east relic is not a smooth arc but it has a

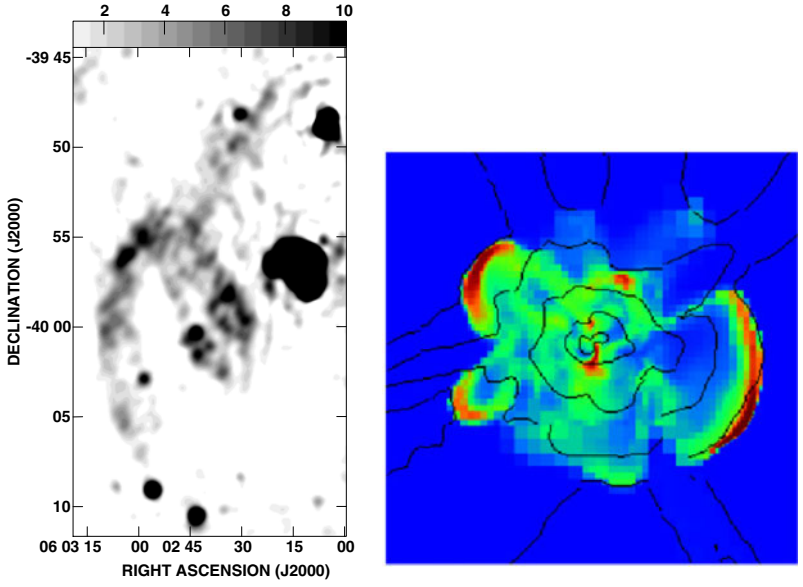

Figure 2. East relic in A3376 (*left*) shown for comparison alongside a slice from cluster merger simulation (*right*) (Paul *et al*. 2011). The colour indicates temperature over a range of 1 eV (blue) to 5 keV (red) and the contours show the density. The break up of a shock front due to a filament can be seen on the left-hand side in the slice. If at such a broken up shock, radio emission due to accelerated electrons is produced, it will look very similar to the east relic of A3376, shown in the left panel.

notch-like feature (Fig. 2, left). Cosmological simulations have shown that outgoing shocks are created when clusters merge. When these shocks reach the virial radius of the cluster, they encounter cold incoming flows along the filaments. Due to these the shock front breaks up. These effects have recently been shown in simulations by Paul *et al*. (2011). The east relic of A3376 could be an example of a broken up shock front (Fig. 2). Deep optical observations to map out the large scale structure around A3376 is required to find out whether a filament corresponding to the notch exists.

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