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Tracing the ICM with extended radio emission

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Abstract. Diffuse radio emission permeating galaxy clusters reveals the widespread presence of relativistic particles and magnetic fields in the intracluster medium (ICM). We present low frequency radio (VLA and GMRT) and X-ray (*Chandra*) data on the unusual radio emission in the ultra-steep spectrum (USS) relic cluster Abell 2443, as well as in Abell 2626 which contains a unique steep-spectrum diamond-shaped radio structure surrounding the core.

The USS source in Abell 2443 is likely an adiabatically compressed radio relic. Deep *Chandra* observation reveal the presence of two surface brightness edges while our new GMRT observations provide details of the complex morphology and spectral properties of the radio relic. GMRT observations of Abell 2626 reveal the presence of a previously unknown fourth radio arc completing the unique diamond-shape radio region that surrounds the cluster-center.

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1. Introduction

A number of galaxy clusters show extended synchrotron emission not directly associated with the individual galaxies, but rather diffused through the intracluster medium

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(ICM). These radio sources have low surface brightnesses, large sizes (~ 1 Mpc) and steep spectra (see review by Ferrari et al. 2008). They are classified broadly as halos and relics. Halos are located at the cluster centers, show a rather regular structure and little or negligible polarization. Relics are at cluster peripheries, are generally elongated and are highly polarized. About 50 clusters have been confirmed to contain halos and or relics, but the origin and evolution of this diffuse emission is not well understood. Their existence *only* in clusters undergoing major mergers indicates that they are somehow related to the merger process through either shocks or turbulence.

A handful of the halos and relics are classified as ultra-steep spectrum sources (USS); those which have radio spectral indices around 1.4 GHz steeper than $\alpha \sim -2$ ($S_\nu \propto \nu^\alpha$). The detection and characterization (spatial extent/structure and spectral/polarization properties) of new objects of this class is important to help establish correlations between the radio source properties and the parent cluster properties, and to discriminate among the proposed theoretical models of their origins. We present here a brief summary of the observational characteristics of two systems hosting USS radio emission.

2. Abell 2443

VLA radio observations of A2443 (z = 0.108) at 74, 325 and 1425 MHz revealed the presence of an ultra-steep spectrum radio source as well as several head tail galaxies (Cohen & Clarke 2011). The steep, curved spectrum as well as the spatial coincidence with an apparent X-ray shock led Clarke et al. (2013) to characterize the relic as an adiabatically compressed relic.

New GMRT observations at 235 and 610 MHz reveal additional details of the radio structure detected in VLA low frequency data and allow us to determine the spectral index and its variation between 74 MHz and 1400 MHz. We show in the left panel of Figure 1 the GMRT 240 MHz radio contours of the central 700 kpc region. The two head-tail galaxies to the NW (identified as A & B by Cohen & Clarke 2011) are clearly visible as well as the compact radio emission associated with the cD galaxy which is the brightest emission seen in the image. The remainder of the emission filling the cluster core is associated with the radio relic. The GMRT data show the relic consists of a number of clumps, a bright ridge, and filamentary loops to the east and west.

We have recently obtained a 100 ks *Chandra* exposure on the system which is shown in the right panel of Figure 1 (Mroczkowski et al., in preparation). We have smoothed the *Chandra* data and overlaid the GMRT 240 MHz contours. The cD galaxy appears at the head of a cone-shaped cool gas clump. Clear X-ray edges are seen in the cluster. The edge to the NE region of the dense core is consistent with a cold-front contact discontinuity while the edge to the SE of the core is consistent with a shock and is co-spatial with the radio relic emission.

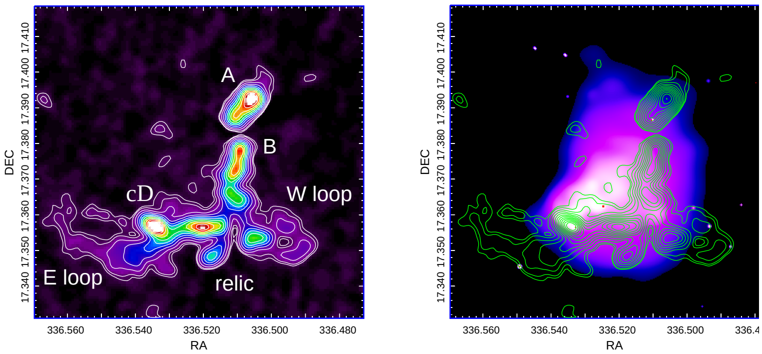

Figure 1. Left: GMRT 240 MHz image of the USS relic in Abell 2443. The rms in the image is 0.75 mJy/bm and the resolution is 23x20 arcsec. Contours start at 5σ. Right: Smoothed *Chandra* X-ray surface brightness image of Abell 2443 with GMRT 240 MHz radio contours overlaid.

Preliminary analysis suggests that the dense X-ray emission cone is a merging subcluster with a large component of its motion toward us. The surrounding region shows evidence of hot shocked X-ray gas due to the on-going merger. The radio relic is confined to regions ahead of the merging component and to the west along the edge of the dense gas component. Spectral analysis of the radio emission shows that the western loop of emission may be flatter spectral index $\alpha_{235MHz}^{147MHz} \sim -1.4$ while the spectral index of the eastern loop is much steeper at $\alpha_{235MHz}^{147MHz} \sim -2.9$.

3. Abell 2626

A number of cool-core clusters are host to small diffuse radio sources (minihalos) within the cool-core regions (see Giacintucci et al. 2014 for a recent study). These clusters are also generally host to active central radio galaxies whose presence within the faint minihalo makes it difficult to disentangle the emission.

Abell 2626 ($z = 0.0553$) is a well-known cool-core cluster hosting a very steep spectrum radio source (Slee & Siegman 1983). Initial low resolution observations showed the steep spectrum source had an unusual boxy shape (Marković 2004). A recent study by Gitti (2013) discussed the minihalo and showed the details of the morphology with clear arcs to the north and south as well as their discovery of a western radio arc.

We show a GMRT 610 MHz image of the central 180 kpc region of Abell 2626 in Figure 2. This image shows the first detection of a fourth radio arc to the east of the cluster core. This arc completes the unique diamond-shaped region that surrounds the dual nucleus cD galaxy. In addition to the four arcs, Figure 2 shows the compact core and extended emission to the SW of the core. The radio core is associated with the SW AGN nucleus identified in the *Chandra* analysis of Wong et al. (2008). While the

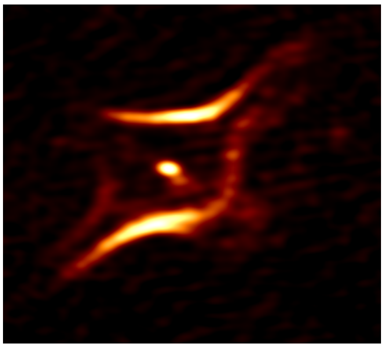

Figure 2. GMRT 610 MHz image of the central 180 kpc region of Abell 2626 showing that the diamond-shaped region surrounding the cluster center consists of four arcs. The arcs to the north, south, and west were recently presented in Gitti et al. (2013). Our new image shows the first details of the eastern arc which appears to complete the diamond. The resolution is 7.4x4.5 arcsec and the noise is σ=0.2 μJy/bm.

origin of the arcs is still uncertain, it is possible that they are a result of dual precessing (roughly orthogonal) jets from the two nuclei in the cD galaxy.

Combining the GMRT data together with VLA observations we are able to measure a preliminary spectral index of the four arcs and we find that they are indeed very steep spectrum sources with average spectral indices of $\alpha_{1425MHz}^{618MHz} \sim -2.7$ for all four arcs. The northern arc appears to show a spectral gradient with flatter spectrum emission on the eastern edge. A recent deep *Chandra* X-ray observation of the system will allow us to study the two cD nuclei, search for evidence of X-ray jets, and investigate interactions of the radio arcs and ICM.

Acknowledgements

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