A radio halo surrounding the Brightest Cluster Galaxy in RXCJ0232.2–4420: a mini-halo in transition?

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ABSTRACT
Diffuse radio sources associated with the intra-cluster medium are direct probes of the cosmic ray electrons and magnetic fields. We report the discovery of a diffuse radio source in the galaxy cluster RXCJ0232.2–4420 (SPT-CL J0232–4421, z = 0.2836) using 606 MHz observations with the Giant Metrewave Radio Telescope. The diffuse radio source surrounds the Brightest Cluster Galaxy in the cluster-like typical radio mini-haloes. However the total extent of it is 550 × 800 kpc², which is larger than mini-haloes and similar to that of radio haloes. The BCG itself is also a radio source with a marginally resolved core at 7 arcsec (30 kpc) resolution. We measure the 606 MHz flux density of the RH to be 52 ± 5 mJy. Assuming a spectral index of 1.3, the 1.4 GHz radio power is 4.5 × 10²⁴ W Hz⁻¹. The dynamical state of the cluster has been inferred to be ‘relaxed’ and also as ‘complex’, depending on the classification methods based on the morphology of the X-ray surface brightness. This system thus seems to be in the transition phase from a mini-halo to a radio halo.

Key words: acceleration of particles – radiation mechanisms: non-thermal – galaxies: clusters: individual – RXCJ0232.2–4420 – galaxies: clusters: intra-cluster medium – radio continuum: galaxies – X-rays: galaxies: clusters.

1 INTRODUCTION
The origin and evolution of cosmic rays and magnetic fields in galaxy clusters are a long-standing puzzle. Diffuse radio emission on cluster-wide scales (megaparsec) associated with the intra-cluster medium (ICM) and not with individual galaxies are direct probes of these components. These are typically classified into three classes: radio haloes, radio relics, and mini-haloes (Brunetti & Jones 2014). Radio relics are believed to be direct tracers of cluster merger shocks and observational evidence (e.g. van Weeren et al. 2010; Kale et al. 2012; Stroe et al. 2014) strongly supports this idea though the details of the acceleration mechanism are still under debate (e.g. Brunetti & Jones 2014; Guo, Sironi & Narayan 2014).

Radio haloes and mini-haloes nearly circular in morphology and located co-spatially with the X-ray emission from the ICM (e.g. Feretti et al. 2012; Brunetti & Jones 2014). Mini-haloes are 100–300 kpc in size and are found in cool-core clusters (e.g. Giacintucci et al. 2017). They are always found to surround the Brightest Cluster Galaxy (BCG). Radio haloes are much more extended and can reach sizes of 1–2 Mpc (Brunetti & Jones 2014). These have been found with higher probability in massive and merging clusters (Cassano et al. 2013).

A component of the relativistic electron population that powers mini-haloes and radio haloes comes from the hadronic collisions in the ICM (e.g. Dennison 1980; Brunetti et al. 2001; Gitti et al. 2004; Keshet & Loeb 2010). For radio haloes it has been found that this component alone is not sufficient and an additional form of turbulent re-acceleration is required (Donnert et al. 2010; Brunetti et al. 2012). Cluster mergers are a natural origin for the turbulence involved and thus the turbulent re-acceleration model can explain the high occurrence of radio haloes in massive and merging clusters (e.g. Schlickeiser, Sievers & Thiemann 1987; Brunetti et al. 2001; Cassano et al. 2013). The mini-haloes on the other hand could either be exclusively of hadronic origin or may need turbulence driven by sloshing of sub-clusters or minor mergers (Gitti et al. 2004; Mazzotta & Giacintucci 2008; ZuHone et al. 2014; Giacintucci et al. 2014a; Giacintucci et al. 2017; Jacob & Pfrommer 2017).

Although the radio haloes and mini-haloes are known to occur in merging and relaxed clusters, respectively, there are systems that are intermediate in their merging status. It has been discussed that a transition from a mini-halo to a radio halo triggered by a merger is a possibility (Brunetti & Jones 2014; van Weeren et al. 2019). The transition can also mark the change from a hadronically dominated source to that dominated by turbulent re-acceleration.

In this Letter we report the detection of a diffuse radio source that has the properties of mini-haloes and also of radio haloes that is hosted by the cluster RXCJ0232.2–4420 (Table 1). This cluster was discovered in the ROSAT all sky survey (Crudace et al. 2002) and...
is known to contain two brightest cluster galaxies (BCGs) separated by 100 kpc (Pierini et al. 2008). It is part of the Archive of Chandra Cluster Entropy Profile Tables (ACCEPT) sample (Cavagnolo et al. 2009) and they report a central entropy ($K_0$) of 44.62 ± 12.42 keV cm$^2$ for this cluster.

We assume a lambda cold dark matter cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_L = 0.73$. This implies a scale of 4.24 kpc arcsec$^{-1}$ at the redshift 0.2836 of RXCJ0232.2–4420. The luminosity distance is $D_L = 1444$ Mpc.

2 OBSERVATIONS AND DATA REDUCTION

We have observed cluster RXCJ0232.2–4420 using the GMRT at 610 MHz with 33 MHz bandwidth under observation cycle 31 on 2017 February 18 (31_065 PI R. Kale). The cluster was observed for 6 h with the integration time of 16.10 s. The data were recorded in 256 frequency channels. We used NRAO’s Common Astronomy Software Applications (CASA) package for data analysis. A semi-automated pipeline was written for the analysis in PYTHON that utilized CASA tasks. The standard steps of flagging (removal of bad data), calibration of complex gains, and bandpass were carried out. The flux scale of Perley–Butler 2017 (Perley & Butler 2017) was used for absolute flux calibration. Several rounds of phase only self-calibration followed by amplitude and phase self-calibration were carried out to improve the sensitivity. We imaged the final visibilities with the weighting scheme ‘briggs’ (Briggs1995) with robust $= 0$. We imaged the discrete sources using the UV-distance cut of > 5 k$\lambda$ and subtracted them from the visibilities. A low-resolution image of the diffuse source using the UV-distance cut of < 10 k$\lambda$ was produced. It was convolved to a circular beam of 20 arcsec × 20 arcsec for further analysis. The primary beam correction was applied to all the images that were used in the analysis.

3 RESULTS

The GMRT 606 MHz image with robust $= 0$ weighting of the visibilities is shown in Fig. 1. It has an rms noise of 0.04 mJy beam$^{-1}$. The discrete radio sources in the field within 2 arcmin around the centre are labelled as S1, S2, S3, and S4. The source S1 is associated with the BCG-A in the cluster and shows an extension towards north-west; it is unclear at this resolution if it is a jet (Fig. 2). The source S4 is marginally resolved and does not show association with any galaxy. The sources S2 and S3 are unresolved. The 606 MHz flux densities and the sources within the beam found from the NASA Extragalactic Database (NED) that are the most likely counterparts of these discrete radio sources are given in Table 2.

We have discovered extended diffuse radio emission surrounding the BCG-A in this cluster. Based on the location surrounding the BCG at the peak of X-ray emission from the ICM, it looks like a typical mini-halo. However, the largest extent of this emission is 800 kpc, which is nearly that of giant radio haloes (≳700 kpc; Cassano et al. 2013). We refer to this radio emission as a radio halo.

Table 1. Properties of RXCJ0232.2–4420.

| Property                         | Value                  |
|----------------------------------|------------------------|
| RA(J2000) (h:m:s)               | 02:32:18.7             |
| Dec. (J2000) (°:′:″)            | −44:20:41              |
| Redshift (z)                    | 0.2836                 |
| $L_{X[0.1–2.4keV]}$ (erg s$^{-1}$) | $13.3 \times 10^{44}$ |
| $M_{500}$ ($10^{14} M_{\odot}$) | 12.01 ± 1.80$^a$       |
| $kT$ (keV)                      | $8 \pm 1.4^b$          |
| Radio halo                      |                        |
| Size (kpc$^2$)                  | $550 \times 800$       |
| $S_{606MHz}$ (mJy)              | $52 \pm 5$             |
| $P_{1.4GHz}$ (W Hz$^{-1}$)      | $4.5 \times 10^{24}$   |

Notes: $^a$Bleem et al. (2015, and references therein), $^b$Laganà et al. (2013).
The RH has a flux density of 52 ± 0.3 mJy at 606 MHz (S_{606MHz}) as measured within the area covered by the contour at 3σ = 0.3 mJy beam$^{-1}$ in the low-resolution (20 arcsec) image. The error on the flux density was calculated according to \( \sqrt{\sigma^2 + (\sigma_{\text{abs}, S_{606MHz}})^2} \), where \( \sigma \) is the number of beams in the extent of the emission, \( \sigma_{\text{abs}} \) is the percentage error on the absolute flux density scale. We used \( \sigma_{\text{abs}} = 0.1 \) (e.g. Kale & Parekh 2016) and found \( \sigma_{\text{abs}} = 75.6 \) to get the error of 5 mJy on S_{606MHz}. The GLEAM catalogue flux density of the central source S1–S4. The SUMSS catalogue flux density of the central source J023218–442052 are 22 ± 14 mJy at 223–231 MHz and 149 ± 67 mJy at 72–80 MHz. These imply a spectral index of 1.7. The GLEAM beam is 134.7 arcsec × 131.6 arcsec, position angle −30° at 200 MHz and thus cannot resolve the sources S1–S4. The SUMSS catalogue flux density of the central source at 843 MHz is 50.0 ± 3.1 mJy (Mauch et al. 2008). Between SUMSS and GLEAM-ADR the spectral index is 1.0. The steeper spectrum within the GLEAM bands may be contribution from the RH. However images with better resolution are needed to separate the discrete and the diffuse emission to determine the spectral index of the diffuse emission.

4 DISCUSSION

4.1 Dynamical state of RXCJ0232.2–4420

In the context of the origin of the diffuse radio emission, the dynamical state of the cluster is important. Lovisari et al. (2017) have carried out a detailed X-ray morphology analysis of a large sample (189) of clusters, including RXCJ0232.2–4420 using XMM–Newton images. Among eight different parameters that they calculate to infer the dynamical state of the cluster, they conclude that centroid shift (\( w \)) and concentration (\( c \)) are the best estimators of dynamical state. The \( w - c \) plane is shown in Fig. 4 for their sample where RXCJ0232.2–4420 is classified as a 'relaxed' cluster. In the Archive of Chandra Cluster Entropy Profile Tables (ACCEPT1) (Cavagnolo et al. 2009), the central temperature of RXCJ0232.2–4420 is reported to be 5.71 ± 0.19 keV and the central cooling time to be 1.38 ± 0.19 Gyr. This central cooling time is consistent with a 'weak' cool-core cluster (e.g. Hudson et al. 2010). According to the classification criteria based on central gas density used in Planck Collaboration XI (2011), this cluster has been classified as a 'cool-core' cluster. Thus the properties of the core show evidence of cooling. Weißmann, Böhringer & Chon (2013) have discussed morphological classification of galaxy clusters based on the power ratios (\( P_s/P_b \)) and centroid shifts (\( w \)) using observations with the XMM–Newton for a sample of 80 clusters that includes RXCJ0232.2–4420. This cluster is classified as 'complex' that in their definition is a cluster that does not have two maxima in the X-ray surface brightness but has a complex global structure. Thus the works discussed above do not categorize this cluster to be a

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1https://web.pa.msu.edu/astro/MC2/accept/
major merger but do indicate the presence of departure from strong cool-core clusters. The presence of two BCGs in the cluster further indicates a merger in the past.

4.2 Mini-halo to radio halo transition system

The populations of clusters hosting giant radio haloes and mini-haloes are distinct in their dynamical properties (e.g. Cassano et al. 2010; Kale et al. 2015). It has been proposed that a cool-core cluster with a mini-halo may transition into a radio halo cluster if it undergoes a merger (Brunetti & Jones 2014). While mini-haloes could have significant emission due to relativistic electrons that are by-products of hadronic collisions (Zandanel, Pfrommer & Prada 2014), a merger can trigger transport of the electrons and turbulent re-acceleration in the outskirts leading to the formation of a radio halo (Brunetti & Jones 2014; van Weeren et al. 2019). The morphology of the RH is nearly symmetric about the BCG-A and shows a southern extension that could be following a sloshing cold-front as found in the case of the mini-halo RX J1720.1+2638 (Giacintucci et al. 2014b).

Giacintucci et al. (2017) have studied the distribution of central entropies (K_0) in galaxy clusters with mini-haloes and radio haloes. They found that the clusters hosting mini-haloes have K_0 < 20 keV cm^2 and those hosting radio haloes typically have K_0 > 50 keV cm^2. With the K_0 = 44.62 ± 12.42 keV cm^2, this cluster is in the intermediate zone of radio haloes and mini-haloes. This is further evidence of it being a transition system. We compared the radio power of RH with that of the mini-haloes and radio haloes in the P_1.4GHz−M_500 plane (Fig. 5). The RH radio power is well within the typical powers of radio haloes as is also the case for a few other mini-haloes. It is among the highest mass clusters hosting mini-haloes.

The diffuse radio sources in the clusters Abell 2142, Abell 2390, Abell 2261, and CL1821+643 have been classified as peculiar Mpc sized radio sources in cool-core clusters. A two-component radio halo is reported in Abell 2142 and is thus unlike typical mini-haloes (Venturi et al. 2017). The systems Abell 2390, Abell 2261 (Sommer & Basu 2014), and CL1821+643 (Bonafede et al. 2014; Kale & Parekh 2016) are similar to the radio halo reported here. Recently low brightness and steep spectrum emission have been found surrounding the known mini-haloes in the clusters PSZ1G139.61+24.20 (Savini et al. 2018) and RXJ1720.1+2638 (Savini et al. 2019). It has been suggested by the authors that slosching may result in triggering acceleration on large scales. We await our Upgraded GMRT observations to find the spectral index distribution across the radio halo in RXCJ0232.2−4420 and further analysis of the X-ray data to shed more light on the origin of the radio halo.

5 CONCLUSIONS

We report the discovery of diffuse radio emission of size 550 × 800 kpc^2 surrounding the primary BCG in the cluster RXCJ0232.2−4420 using 606 MHz observations from the GMRT. The 606 MHz flux density of the diffuse radio source is 52 ± 5 mJy. The diffuse source on one hand is similar to mini-haloes in cool-core clusters that surround a BCG and on the other has an extent typical of radio haloes. The dynamical state of the cluster based on the X-ray morphology has been termed as ‘relaxed’ and complex making it a transition system between a merger and a cool-core. The 1.4 GHz radio power of the RH is 4.6 × 10^{24} W Hz^{-1}. Assuming a spectral index of 1.3, in the P_1.4GHz−M_500 plane, it falls within the general trend of the radio haloes. Mini-haloes are more scattered in this plane and, if classified as a mini-halo, it will be the second most massive cluster to host it. The RH properties support the scenario that it is rare system where a mini-halo is transitioning into a radio halo.

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\(^2\)http://www.astropy.org

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