Diffuse radio emission in the galaxy cluster SPT-CL J2031−4037: a steep-spectrum intermediate radio halo?

Ramij Raja,1,★ Majidul Rahaman,1 Abhirup Datta,1 Jack O. Burns,2 H. T. Interna,3,4 R. J. van Weeren,3 Eric J. Hallman,2 David Rapetti2,5,6 and Surajit Paul7

1Discipline of Astronomy, Astrophysics and Space Engineering, Indian Institute of Technology Indore, Simrol 453552, India
2Center for Astrophysics & Space Astronomy, Department of Astrophysical & Planetary Sciences, 389 UCB, University of Colorado, Boulder, CO 80309, USA
3Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
4International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
5NASA Ames Research Center, Moffett Field, CA 94035, USA
6Universities Space Research Association, Mountain View, CA 94043, USA
7Department of Physics, Savitribai Phule Pune University, Pune 411007, India

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ABSTRACT

The advent of sensitive low-frequency radio observations has revealed a number of diffuse radio objects with peculiar properties that are challenging our understanding of the physics of the intracluster medium. Here, we report the discovery of a steep-spectrum radio halo surrounding the central brightest cluster galaxy (BCG) in the galaxy cluster SPT-CL J2031−4037. This cluster is morphologically disturbed yet has a weak cool core, an example of a cool-core/non-cool-core transition system, which harbours a radio halo \(\sim 0.7\) Mpc in size. The halo emission detected at 1.7 GHz is less extended compared to that in the 325 MHz observation, and the spectral index of the part of the halo visible at the 325 MHz to 1.7 GHz frequencies was found to be \(-1.35 \pm 0.07\). Also, \(P_{1.4\text{GHz}}\) was found to be \(0.77 \times 10^{24}\) W Hz\(^{-1}\), which falls in the region where radio mini-haloes, halo upper limits and ultra-steep-spectrum (USS) haloes are found in the \(P_{1.4\text{GHz}}–L_X\) plane. Additionally, simulations presented in the paper provide support for the scenario of the steep spectrum. The diffuse radio emission found in this cluster may be a steep-spectrum ‘intermediate’ or ‘hybrid’ radio halo that is transitioning into a mini-halo.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: clusters: individual: SPT-CL J2031−4037 – radiation mechanisms: non-thermal – X-rays: galaxies: clusters.

1 INTRODUCTION

In the hierarchical structure formation scenario, smaller units like galaxies or groups merge to form large-scale structures in the cross-sections of cosmic web filaments. Major merger events are the most energetic phenomena since the big bang, releasing about \(10^{64}\) erg of energy within a Gyr time-scale. This massive amount of energy dissipates into the intracluster medium (ICM) primarily via shocks and large-scale turbulent motion (e.g. Sarazin 2002; Paul et al. 2011).

Traditionally, cluster-wide diffuse radio synchrotron emission has been divided into three categories: giant radio haloes (GRHs), relics, and mini-haloes (MHs) (Feretti & Giovannini 1996). GRHs are centrally located unpolarized Mpc-scale emission sources found only in merging clusters, whereas MHs are smaller versions (\(\sim 100–500\) kpc) but found only in ‘relaxed’ cool-core clusters. However, recent discoveries of diffuse radio objects, especially at low frequencies, with properties in between GHRs and MHs have made these classifications more complicated (see van Weeren et al. 2019).

The origin of GRHs is merger-driven turbulence in the ICM (Brunetti et al. 2001; Petrosian 2001); in this scenario, less-energetic events (e.g. minor mergers or mergers in smaller systems) are predicted to generate steep-spectrum haloes (Cassano 2010). On the other hand, MHs are formed due to the turbulence caused by the later stage of a minor merger event, i.e. a sloshing core (Mazzotta & Giacintucci 2008). An ‘intermediate’ state between these was also proposed by Brunetti & Jones (2014), where a radio halo transitions into a mini-halo or vice versa; recent discoveries of \(\sim\)Mpc-scale
Table 1. Global cluster and halo properties.

| RA       | 20°31′51″5′′  |
|----------|----------------|
| Dec.     | −40°37′14″    |
| $R_{500}$ [Mpc] | 1.342     |
| $M_{500}$ [$10^{14} M_\odot$] | 9.83 ± 1.5 |
| $L_{[0.1–2.4 \text{keV}]}$ [10^{44} \text{erg s}^{-1}] | 10.4 |
| $T_{\text{central}}$ [keV] | 12.2 ± 2.4 |
| $S_{325 \text{MHz}}$ [mJy] | 16.93 ± 1.76 |
| $S_{1.7 \text{GHz}}$ [mJy] | 1.4 ± 0.18 |
| $P_{1.4 \text{GHz}}$ [10^{24} \text{W Hz}^{-1}] | 0.77 ± 0.08 |
| $\alpha_{1672}$ [halo] | −1.35 ± 0.07 |

Note: References: Birzan et al. (2017), Bleem et al. (2015), McDonald et al. (2013), Piffaretti et al. (2011).

radio haloes in cool-core and semi-relaxed clusters seem to favour this scenario (e.g. Bonafede et al. 2014; Sommer et al. 2017; Savini et al. 2018; Kale, Shende & Parekh 2019).

In this letter, we report the discovery of diffuse radio emission in the SPT-CL J2031−4037 (hereafter SPT2031) cluster. This cluster was first detected in the REFLEX (ROSAT-ESO Flux Limited X-ray) galaxy cluster survey as reported by Böhringer et al. (2004). Subsequent detections of SPT2031 via the Sunyaev–Zel’dovich effect have been reported by Plagge et al. (2010), Williamson et al. (2011), Bleem et al. (2015) and the Planck Collaboration et al. (2016). SPT2031 is a massive cluster with $M_{500} = (9.83 \pm 1.5) \times 10^{14} M_\odot$ (Bleem et al. 2015) and X-ray luminosity of $L_{[0.1–2.4 \text{keV}]} = 10.4 \times 10^{44} \text{erg s}^{-1}$ (Piffaretti et al. 2011) situated at redshift $z = 0.3416$ (Böhringer et al. 2004). The global cluster properties are presented in Table 1.

In this letter, we assume a $\Lambda$CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. At the cluster redshift $z = 0.3416$, 1 arcsec corresponds to 4.862 kpc.

2 RADIO DATA ANALYSIS

2.1 GMRT observations

GMRT observations of SPT2031 were performed at 325 MHz as part of a larger survey of a sample of SPT clusters. It was observed on 2014 May 31 and August 21 and 23 for a total of about 6.15 h of on-source observing time with 1 GHz of total bandwidth.

The SPAM pipeline was used for data reduction. This is a PYTHON-based AIPS (astronomical image processing system) extension to reduce low-frequency interferometric data, developed by Intema et al. (2009, 2017). The data reduction process starts with initial flagging, bandpass and gain calibration loops. The flux density of the calibrator 3C 48 was set according to the Scaife & Heald (2012) scale. Then, several rounds of self-calibration were performed on the calibrated data along with RFI (radio frequency interference) flagging. Wide-field facet imaging was performed to correct for the non-coplanar array. Finally, direction-dependent calibration was performed for the bright sources present in the field (for details see Intema et al. 2009, 2017). The final calibrated visibility data were used for further imaging with CASA (Common Astronomy Software Applications; McMullin et al. 2007).

2.2 VLA observation

An L-band (1–2 GHz) observation of SPT2031 was made with the EVLA CnB configuration on 2015 January 9 for a total of ∼1.5 h of on-source observing time with 1 GHz of total bandwidth.

CASA was used for the VLA data reduction and imaging, and a brief description of the procedure is given below. First, we applied the RFI mitigation software AOFLAGGER developed by Offringa et al. (2010) and Offringa, van de Gronde & Roerdink (2012) to get rid of the data contaminated by RFI. Next, we ran the VLA calibration pipeline1 on the data, which performed basic calibration and flagging using CASA. A detailed description of the pipeline steps can be found in the link below. 3C 48 was used as the gain and bandpass calibrator, and the flux scale was set according to Perley & Butler (2013). A few spectral windows were affected by RFI very badly and were dropped in the following steps. Visual inspection was done to remove any remaining bad data. Finally, a few rounds of phase-only self-calibration were performed to remove residual phase errors.

3 RESULTS

3.1 325 MHz data

The Chandra X-ray image in Fig. 1 shows the disturbed nature of the cluster stretching in the east–west direction. The GMRT 325 MHz radio contours reveal the diffuse radio emission surrounding the central radio galaxy, typical of radio mini-haloes, but the emission has a similar east–west stretch to the X-ray, roughly tracing the possible merger axis like giant radio haloes. The position of this radio galaxy coincides with the X-ray luminous core, and the Hubble Space Telescope (HST) optical image clearly shows the BCG as the optical counterpart. The BCG emission was also detected in the 150 MHz TIFR GMRT Sky Survey (TGSS; Intema et al. 2017) with a flux density of $S_{150} = 232.6 \pm 24.3 \text{ mJy}$ and in the 843 MHz Sydney University Molonglo Sky Survey (Bock, Large & Sadler 1999; Mauch et al. 2003) with a flux density of $S_{43} = 42.1 \pm 1.8 \text{ mJy}$.

The 325 MHz image of the SPT2031 cluster is presented in Fig. 1 with red contours. This is a full-resolution image with Briggs’ robust parameter (Briggs 1995) set to 0.5. The total extent of the diffuse emission is $2.7 \times 2.1 \text{ arcmin}$ or $0.79 \times 0.62 \text{ Mpc}$. To estimate the integrated flux density of the diffuse radio emission at 325 MHz, we used the following approach. First, we made an image excluding baselines shorter than 5 kλ (corresponding to a physical scale of about 200 kpc) and using robust $\approx −1$ to get rid of the extended emission. After subtracting the modelled BCG flux density from the UV data, we re-imaged the diffuse radio emission. We estimated the total radio emission enclosed within the 3σrms contour to be $S_{325 \text{MHz}} = 16.93 \pm 1.76 \text{ mJy}$. The uncertainty in the flux density measurement was estimated based on the map noise and assuming an absolute flux calibration uncertainty of 10 per cent (e.g. Cassano et al. 2007).

3.2 1–2 GHz data

In Fig. 2, we present the 1.7 GHz observation of the SPT2031 cluster. MS-MFS (Rau & Cornwell 2011) imaging was performed using the CASA task CLEAN with two Taylor terms for spectral modelling.
325 MHz, we have calculated the spectral index taking precisely since the diffuse emission at 1.7 GHz is not as extended as in the 325 MHz radio contours excluding baselines shorter than 5 k\(\lambda\). Negative contours are indicated with dotted lines. The black X-ray contours are spaced by a factor of 2. The bright X-ray source west of the BCG, 1RXS J203150.4–403656, which also has optical identification in the 1.7 GHz image to match the resolution of both images. The spectral index between frequencies 325 MHz and 1.7 GHz came out to be \(\alpha_{325}^{1.7} = -1.35 \pm 0.07\) (where \(S_\nu = \nu^{\alpha}\)) and the corresponding k-corrected 1.4 GHz radio power is \(P_{1.4GHz} = (0.77 \pm 0.08) \times 10^{24}\) W Hz\(^{-1}\). Some amount of large-scale diffuse emission observed at 325 MHz is not detected at 1.7 GHz, and only an upper limit to the spectral index can be derived. To derive an upper limit to the spectral index, we followed a method similar to that described in Kale et al. (2015). We injected a 2 × 1.5 arcmin disc into the UV data with the CASA tasks FT and UVSUB. The injected flux densities were calculated from the less bright part of the 325 MHz diffuse emission that is not detected at 1.7 GHz, scaled with varying spectral index values. Starting from spectral index \(-1.35\), we lowered it to \(-1.52\) where the injected diffuse source can no longer be considered to be detected. So, the upper limit to the spectral index of steep-spectrum diffuse emission is \(\alpha_{325}^{1.7} \leq -1.52\).

### 3.3 Spectral index estimation

Since the diffuse emission at 1.7 GHz is not as extended as in the 325 MHz, we have calculated the spectral index taking precisely the same region where radio emission is present in both frequencies. The 325 MHz image was smoothed with the restoring beam of the 1.7 GHz image to match the resolution of both images. The spectral index between frequencies 325 MHz and 1.7 GHz came out to be \(\alpha_{325}^{1.7} = -1.35 \pm 0.07\) (where \(S_\nu = \nu^{\alpha}\)) and the corresponding k-corrected 1.4 GHz radio power is \(P_{1.4GHz} = (0.77 \pm 0.08) \times 10^{24}\) W Hz\(^{-1}\). Some amount of large-scale diffuse emission observed at 325 MHz is not detected at 1.7 GHz, and only an upper limit to the spectral index can be derived. To derive an upper limit to the spectral index, we followed a method similar to that described in Kale et al. (2015). We injected a 2 × 1.5 arcmin disc into the UV data with the CASA tasks FT and UVSUB. The injected flux densities were calculated from the less bright part of the 325 MHz diffuse emission that is not detected at 1.7 GHz, scaled with varying spectral index values. Starting from spectral index \(-1.35\), we lowered it to \(-1.52\) where the injected diffuse source can no longer be considered to be detected. So, the upper limit to the spectral index of steep-spectrum diffuse emission is \(\alpha_{325}^{1.7} \leq -1.52\).

### 4 Cluster Dynamical State

To understand the origin of cluster-wide synchrotron emission, it is necessary to know the dynamical state of the cluster. For the morphological classification of SPT2031, we checked different classification parameters widely used in the literature. Broadly speaking, cluster dynamical state is classified by whether the cluster hosts a cool core or not and how disturbed the cluster is. One of the most popular classification parameters to test for the presence of a cool core is the surface brightness ‘concentration’ parameter \(c_{SB}\) introduced by Santos et al. (2008). McDonald et al. (2013) reported \(c_{SB} = 0.05\) for SPT2031. The threshold for a non-cool core (NCC) is \(c_{SB} < 0.075\) (Sanchez et al. 2008), which categorizes this cluster as NCC. Hudson et al. (2010) found a trimodal distribution of clusters for both central specific ‘entropy’ \(K_{0}\) and ‘cooling time’ \(t_{cool}\). In this distribution, the CC/NCC partition in cooling time is at \(\sim 7.7\) h\(^{-1}\) Gyr and the strong cool-core (SCC)/weak cool-
core (WCC) partition is at $\sim 1 \, h^{-1} \, \text{Gyr}$. In the case of entropy, SCC clusters have low central entropy ($\lesssim 30 \, h^{-1} \, \text{keV cm}^2$), WCC clusters around $50 \, h^{-1} \, \text{keV cm}^2$, and NCC clusters $>110 \, h^{-1} \, \text{keV cm}^2$. $K_0$ and $\tau_{\text{cool}}$ for SPT2031 are 189.8 $h^{-1} \, \text{keV cm}^2$ and 3.43 Gyr (McDonald et al. 2013), which classifies this cluster as NCC and WCC respectively. Apart from that, Morandi et al. (2015) classified SPT2031 as a CC system. Burns et al. (2008) showed that it is hard to destroy the cool core (WCC) for its stability with respect to the observational data. We also note that, apart from the possible future mini-halo, the SPT2031 cluster is massive enough to host a radio mini-halo ($>6 \times 10^{14} \, M_\odot$; Giacintucci et al. 2017) and the radio BCG coincides with the X-ray brightness peak, suggesting that this cluster may have harboured a radio mini-halo in the past, but it is not possible to verify this possibility with the current observational data.

According to fig. 2 of Nurgaliev et al. (2017), $A_{\text{phot}} = 0.25$ corresponds to a post-merger time of about $\sim 2 \, \text{Gyr}$. The spectral index of the halo emission visible in both frequencies, i.e. along the merger axis, is about $\alpha_{1.4} = -1.35 \pm 0.07$, whereas the upper limit to the off-axis region is $\alpha_{1.4} \lesssim -1.52$. The derived radio power is below the expected level from the GRH $L_X - P_{\text{1.4 GHz}}$ correlation and falls in a region between the ultra-steep-spectrum (USS) haloes, mini-haloes and radio halo upper limits (Fig. 3). So, the scenario could be that the observed halo emission is caused by a past less-energetic merger event and after $\sim 2 \, \text{Gyr}$ has passed, the radio emission at a higher frequency is visible only along the merger axis where energy injection was highest. Since the cool core is not destroyed and the radio BCG is coincident with a cool core, the late stage of this merger event can trigger a sloshing motion in the ICM, resulting in mini-halo emission. Consequently, the diffuse emission in SPT2031 of $\sim 0.7 \, \text{Mpc}$ size surrounding the BCG in a WCC system can be classified as a steep-spectrum ‘intermediate’ radio halo (van Weeren et al. 2019) that is in transition into a possible future mini-halo. Also, the SPT2031 cluster is massive enough to host a radio mini-halo ($>6 \times 10^{14} \, M_\odot$; Giacintucci et al. 2017) and the radio BCG coincides with the X-ray brightness peak, suggesting that this cluster may have harboured a radio mini-halo in the past, but it is not possible to verify this possibility with the current observational data. We also note that, apart from the possible lower merger energy injection in the off-axis region, the poor UV coverage below $3 \, k\lambda$ in the $1.7 \, \text{GHz}$ observation might also be responsible for the missing large-scale halo emission. However, the procedure used for injections (Section 3.3) already accounts for the interferometric response on scales that cover most of the halo emission at $325 \, \text{MHz}$ and allows us to infer a limit to the spectral slope of $\lesssim -1.52$.

In comparison with other clusters hosting intermediate haloes (e.g. Bonafede et al. 2014; Sommer et al. 2017; Savini et al. 2018; Kale et al. 2019, hereafter BSSK), SPT2031 is slightly different. The BSSK clusters are all strong cool-core clusters ($0.3 < c_{SB} < 0.4$) whereas the SPT2031 has $c_{SB} = 0.05$, indicating the absence of a cool core. However, the central cooling time of SPT2031, $\tau_{\text{cool,0}}$ =

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### Table 2. Dynamical state.

| Parameter | Value         | Morphology | Ref. |
|-----------|---------------|------------|------|
| $c_{SB}$  | $0.05^{+0.00}_{-0.02}$ | NCC        | 1    |
| $\tau_{\text{cool,0}}$ [Gyr] | $3.43^{+0.75}_{-0.72}$ | WCC        | 1    |
| $K_0$ [keV cm$^2$] | $189.8^{+39.9}_{-38.9}$ | NCC        | 1    |
| $E_{\gamma}^{-2}n_{e,0}$ at 0.03R$_{500}$ | $0.017^{+0.001}_{-0.002}$ | Disturbed  | 3    |
| $A_{\text{phot}}$ | $0.25 \pm 0.04$ | Moderate   | 3    |

Note: References: (1) McDonald et al. (2013), (2) Morandi et al. (2015), (3) Nurgaliev et al. (2017). NCC, WCC and CC represent non-cool core, weak cool core and cool core respectively.

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**Figure 3.** The distribution of haloes, mini-haloes, USS haloes and halo upper limits (black arrows) in the $L_X - P_{\text{1.4 GHz}}$ plane (Cassano et al. 2013; Kale et al. 2015) is presented here. The SPT2031 cluster is indicated with a red triangle.
3.43 Gyr, suggests that it has a weak cool core. On the other hand, the centroid shift $w$ of all four clusters is >0.01, which classifies them as disturbed and as potential hosts of radio haloes. However, $w$ values for SPT2031 lie around the disturbed/relaxed boundary and the photon asymmetry measurement ($A_{\text{ph}} = 0.25$) classifies it as a moderately disturbed cluster, which is in agreement with the steep nature of the diffuse radio emission.

6 CONCLUSIONS

We report the discovery of diffuse radio emission in the galaxy cluster SPT2031 with GMRT and VLA observations. The size of this emission at 325 MHz was found to be about $\sim 600-800$ kpc. Diffuse radio emission is present surrounding the central BCG, typical of radio mini-haloes whereas the large size is comparable to that of radio haloes. The dynamical state analysis reveals that it has a weak cool core along with disturbed morphology caused by a past merger event, i.e. it is in a transitional state between a merger and a cool-core cluster. However, the current Chandra X-ray data (10 ks) do not allow us to make a detailed study of the cluster dynamics for conclusive evidence. The spectral index of the halo emission visible in both frequencies, mostly along the merger axis, was found to be $\alpha = -1.35 \pm 0.07$ whereas steeper off-axis halo emission is largely undetected at 1.7 GHz. We speculate that the origin of this emission is a past less-energetic merger event in a cool-core cluster where the observed intermediate radio halo is in transition into a future mini-halo. Future sensitive radio observations at intermediate frequencies may shed light on the true spectral nature of the radio halo emission. Additionally, deep X-ray observations along with resolved radio spectral index maps are needed to study the ICM dynamics in detail for conclusive comment in favour of or against the above-mentioned scenario.

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