LETTER TO THE EDITOR

A perfect power-law spectrum even at the highest frequencies: The Toothbrush relic*

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ABSTRACT

Radio relics trace shock fronts generated in the intracluster medium (ICM) during cluster mergers. The particle acceleration mechanism at the shock fronts is not yet completely understood. We observed the Toothbrush relic with the Effelsberg and Sardinia Radio Telescope at 14.25 GHz and 18.6 GHz, respectively. Unlike previously claimed, the integrated spectrum of the relic closely follows a power law over almost three orders of magnitude in frequency, with a spectral index of $α_{18.6\,\text{GHz}} = -1.16 \pm 0.03$. Our finding is consistent with a power-law injection spectrum, as predicted by diffusive shock acceleration theory. The result suggests that there is only little magnetic field strength evolution downstream of the shock. From the lack of spectral steepening, we find that either the Sunyaev-Zeldovich decrement produced by the pressure jump is less extended than $\sim 600 \, \text{kpc}$ along the line of sight or, conversely, that the relic is located far behind in the cluster. For the first time, we detect linearly polarized emission from the “brush” at 18.6 GHz. Compared to 8.3 GHz, the degree of polarization across the brush increases at 18.6 GHz, suggesting a strong Faraday depolarization toward lower frequencies. The observed depolarization is consistent with an intervening magnetized screen that arises from the dense ICM containing turbulent magnetic fields. The depolarization, corresponding to a standard deviation of the rotation measures as high as $σ_{\text{RM}} = 212 \pm 23 \, \text{rad}\,\text{m}^{-2}$, suggests that the brush is located in or behind the ICM. Our findings indicate that the Toothbrush relic can be consistently explained by the standard scenario for relic formation.

Key words. Galaxies: clusters: individual (1RXS J0603.3+4213) – Galaxies: clusters: intracluster medium – large-scale structures of universe – Acceleration of particles – Radiation mechanism: non-thermal: magnetic fields

1. Introduction

Radio relics are large, diffuse sources that are associated with powerful shock fronts originating in the intracluster medium (ICM) during cluster mergers (for a review, see e.g., Feretti et al. 2012; van Weeren et al. 2019). One striking observational feature of radio relics is their high degree of polarization. The magnetic field vectors are often found to be well aligned with the shock surface (van Weeren et al. 2010; Bonafede et al. 2012; Owen et al. 2014; de Gasperin et al. 2014; Kierdorf et al. 2017).

Despite progress in understanding radio relics, the actual acceleration mechanism at the shock fronts is not fully understood. It is generally believed that diffusive shock acceleration (DSA; Drury 1983) generates the observed cosmic ray electrons (CRe). However, it is currently debated if the acceleration starts from the thermal pool (standard scenario; Ensslin et al. 1998; Hoeft & Brüggen 2007) or from a population of mildly relativistic electrons (re-acceleration scenario; Kang & Ryu 2011, 2016).

The standard scenario has successfully reproduced many of the observed properties of relics; however, the following three major difficulties remain: (i) the spectra of some relics are reported to show a spectral break above 10 GHz (Stroe et al. 2016), which is incompatible with the power-law spectrum predicted by DSA theory; (ii) a power-law energy distribution from the thermal pool CRe energies relevant for the synchrotron emission may require an unphysical acceleration efficiency (van Weeren et al. 2016; Botteon et al. 2020), and (iii) the Mach numbers derived from X-ray observations are often significantly lower than those derived from the overall radio spectrum (Akamatsu et al. 2012; Botteon et al. 2020).

According to the re-acceleration scenario, the shock fronts reaccelerate electrons from a pre-existing fossil population. There are a few examples, which seem to show a connection between the relic and active galactic nuclei. (Bonafede et al. 2014; van Weeren et al. 2017; Di Gennaro et al. 2018; Stuardi et al. 2019). If relics originate according to the re-acceleration scenario, weak shocks may become radio bright, solving issues (ii) and (iii). A break in the radio spectrum is expected at a high frequency, when the shock passes through a finite size cloud of a fossil electron population (Kang & Ryu 2016). If the fossil population is homogeneously distributed, the re-acceleration scenario also predicts a power-law spectrum.

Article number, page 1 of 6
The merging galaxy cluster 1RXS J0603.3+4213, located at a redshift of \( z = 0.225 \), is one of the most intriguing clusters hosting a spectacular toothbrush-shaped relic (van Weeren et al. 2012, 2016; Rajpurohit et al. 2018, 2020; de Gasperin et al. 2020). It consists of three distinct components, namely the brush (B1) and two parts forming the handle (B2+B3). The relic shows an unusual linear morphology and is quite asymmetric with respect to the merger axis. The handle extends into the very low density ICM.

Stroe et al. (2016) report evidence for a spectral steepening above 2.5 GHz in the integrated radio spectrum of the relic. This claim is mainly based on the 16 GHz and 30 GHz radio interferometric observations. It has been suggested that the steepening in the integrated radio spectrum can be reproduced with the re-acceleration scenario (Kang 2016). Basu et al. (2016) studied the integrated spectrum of the relic between 120 MHz to 8 GHz and excluded any steepening up to 8 GHz (Rajpurohit et al. 2020). However, the spectral behavior of the relic remained uncertain between 10-20 GHz. The Toothbrush is known to be highly polarized (van Weeren et al. 2012). Effelsberg observations revealed a high fractional polarization at 8.3 GHz and a strong depolarization and rotation measure (RM) gradient from the brush to the handle (Kierdorf et al. 2017).

The main aim of this paper is to answer the question if the overall spectrum of the Toothbrush steepens in the frequency range between 10-20 GHz. If the spectrum steepens at a high frequency, this would have a tremendous impact on the radio relic formation scenario, since it would clearly be in conflict with the standard scenario for relic formation, which predicts a power law toward high frequencies. A steepening would be difficult to explain within the standard scenario and would favor the re-acceleration scenario. We adopt a flat \( \Lambda \)CDM cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.3, \text{ and } \Omega_\Lambda = 0.7 \). At the cluster’s redshift, \( 1'' \) corresponds to a physical scale of 3.64 kpc.

2. Observations

The radio observations at 14.25 GHz were performed with the Effelsberg 100-m telescope with the new Ku-band receiver in dual polarization mode. The total on-source observation time was 20 hours with a 2500 MHz bandwidth. We obtained 31 coverages of a field of \( 11 \times 7 \text{ arcmin}^2 \) and processed the data with the NOD3 tool (Müller et al. 2017). The data reduction involves radio frequency interference removal and baselevel corrections, like the basket-weaving of two maps with scanning in orthogonal directions (RA/DEC).

The Sardinia Radio Telescope (SRT) observations were performed in a full polarization mode with the seven-feed K-Band receiver centered at 18.6 GHz with a bandwidth of 1200 MHz. The observations were carried out between January and February 2020, for a total of 24 hours. The data were reduced using the proprietary software package Single-dish Spectral-polarimetry Software (SCUBE; Murgia et al. 2016).

The uncertainty in the flux density measurements were estimated as:

\[
\Delta S_f = \sqrt{(f \cdot S_f)^2 + N_{\text{beam}}(\sigma_{\text{rms}})^2},
\]

where \( f \) is the absolute flux density calibration uncertainty, \( S_f \) is the flux density, \( \sigma_{\text{rms}} \) is the rms noise and \( N_{\text{beam}} \) is the number of beams. We assume an absolute flux density uncertainty of 10% for both SRT and Effelsberg.

3. Results and discussion

In Figure 1, we show the Effelsberg and the SRT total intensity images at 70' resolution. The relic is clearly detected at both frequencies. The largest linear size of the relic is \( \sim 1.8 \text{ Mpc} \), similar to those reported below 10 GHz. Contour levels are drawn at \( \sqrt{[2, 4, 8, \ldots] \times 3 \sigma_{\text{rms}}} \), where \( \sigma_{\text{rms},14.25\text{ GHz}} = 0.2 \text{ mJy beam}^{-1} \) and \( \sigma_{\text{rms},18.6\text{ GHz}} = 0.4 \text{ mJy beam}^{-1} \). Right: SRT 18.6 GHz image overlaid with the SRT (gray) and Effelsberg (white) contours. Cyan boxes define the area used for measuring the integrated spectrum of the relic and its subregions. The emission at the top right corner in the SRT image is due to blending of discrete sources.
The radiative lifetime of electrons observed at 58 MHz is about $10^2$ years. According to the DSA theory in the test-particle regime and adopting a constant shock strength and CRe cooling in a homogeneous medium, the “integrated” spectrum is related to the Mach number according to

$$M = \frac{1}{\sqrt{\alpha_{\text{int}} + 1}}.$$  

The radiative lifetime of electrons observed at 58 MHz is about about 160 kpc. The slope of the spectrum down to 58 MHz can only be interpreted as a Mach number, according to Eq. 2, if the physical conditions at the shock do not change significantly on a scale of 160 kpc. This condition is likely fulfilled for the Toothbrush relic, since it is located at a projected distance to the cluster center of about 1.1 Mpc. The index above, therefore, corresponds to a Mach number of $M = 3.7 \pm 0.3$.

Despite the fact that the brush is about four times brighter than the handle, the entire relic and its subregions follow a power-law behavior and show similar spectral slopes (see Table 1). At face value, this implies that the shock strength remains the same over an ~1.8 Mpc scale. As argued in Rajpurohit et al. (2020), the shock surface indeed shows a distribution of Mach numbers, thus a single Mach number derived above can only roughly characterize the shock. Most importantly, the tail of the Mach number distribution toward high values determines the shock Mach number.

Our finding is basically consistent with the standard scenario for the formation of radio relics if the radio spectral index corresponds to the Mach number of the shock. If the shock would have a strength as low as estimated from the X-ray surface brightness, no radio emission that could be detected with current telescopes is expected (van Weeren et al. 2012; Botteon et al. 2020). If the shock has instead a strength as estimated from the radio spectral index, the standard DSA-based scenario is in agreement with the observations if a strong magnetic field and an efficient electron acceleration is adopted (see, e.g., Fig. 9 in Botteon et al. 2020). We note, however, that even in this situation, a few percent of the kinetic energy dissipated at the shock front needs to be transferred by DSA to the supra-thermal accelerated at the shock front.

### 3.2. Constraints on the downstream magnetic field evolution

It is conceivable that the magnetic field strength downstream of the shock increases, for example, due to a turbulent dynamo pro-
cess driven by the curvature of the shock front, or decreases, for instance, by the expansion of the shock compressed material. Depending on frequency, the observed radio emission probes very different volumes. At the highest frequency, 50% of the emission are emitted from a volume with an extent of about 5 kpc downstream to the shock front. In contrast, the emission at 58 MHz is extended to about 85 kpc. If the strength of the magnetic field would change significantly on these length scales, this would affect the integrated spectrum of the relic.

A nonlinear change in the field strength would either significantly boost the emission at short or at large distances; in both cases, this would result in a curved spectrum (see, e.g., Donnert et al. (2016)). Since the integrated spectrum almost perfectly follows a power law, only a marginal nonlinear increase or decrease in the magnetic field strength seems to be possible on scales probed by the relic.

However, if the field strength changes linearly with distance, the power-law integrated spectrum is preserved, but the relation of Equation 2 does not hold anymore. An increasing field strength would steepen the integrated spectrum, while a decrease in the magnetic field strength seems to be possible on scales probed by the relic. An increasing field scales probed by the relic.

3.3. SZ decrement between 10-20 GHz

The SZ effect contributes a negative signal to the cosmic microwave background for $\nu \leq 220$ GHz. In the case of relics, Basu et al. (2016) show that the SZ effect from the shock downstream also proportionally scales the Mach number squared, producing an even smaller depth of the shock along the line of sight. We emphasize that the quoted values only refer to the contribution to the SZ decrement from the shock discontinuity along the line of sight for the same range of spatial scales responsible for the radio emission. Furthermore, the assumption of a simple planar geometry and the absence of curvature along the line of sight is clearly an oversimplification, which may indeed explain the surprisingly low value of $d_{\text{LOS}}$. Incidentally, such a small SZ decrement may also be explained if the shock responsible for the relic is at a more peripheral location in the cluster. In this case, the density and temperature values suggested by X-ray observations originate from regions which are denser than the one responsible for the radio emission. In this case, Equation 3 would significantly overestimate the pressure jump at the shock, and the requirement on $d_{\text{LOS}}$ would be relaxed.

3.4. Polarization at 18.6 GHz

All of the information on the polarization properties of relics are mainly collected in the frequency range of 1–8.3 GHz. Since the Faraday rotation is expected to be almost negligible at 18.6 GHz, the intrinsic polarization of the relic could be directly mapped by the observations.

For the first time, we detect polarized emission from the relic at 18.6 GHz. We detect polarized emission mainly from the brush region (see Figure 3). The degree of polarization varies along the brush and the magnetic field vectors are mainly aligned to the relic’s orientation. The fractional polarization reaches ~66% in some areas, the average being ~30 ± 7%. We note that these values could be affected by beam depolarization.
We detected polarized emission at 18.6 GHz. Compared to measurements at lower frequencies, the polarization fraction of the brush increases at 18.6 GHz. The high value of $\sigma_{\text{RM}}$ is consistent with $\sigma_{\text{RM}}$ fluctuations of an ICM screen with tangled magnetic fields. This suggests that the brush is located in or behind the ICM.

From the lack of steepening in the relic spectra, we find that either the SZ decrement at the shock along the line of sight is $\lesssim 600$ kpc thick, or the pressure jump associated with the relic is located far behind in the cluster. The latter explanation can also be reconciled with the trends of the polarization fraction for the brush region.

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Fig. 3. B-vectors distribution across the brush region at 51″ resolution overlaid with the SRT total power contours at 3σ. The length of the vectors depict the degree of polarization. The vectors are corrected for Faraday rotation effect. The mean polarization fraction at the brush is (30 ± 7)%.

Previous polarization measurements of the Toothbrush relic have shown that the fractional polarization of B1 decreases rapidly toward lower frequencies. B1 is polarized at a level of about 15% at 8.3 GHz (Kierdorf et al. 2017) and about 11% at 4.9 GHz. The polarization fraction drops below 1% at a frequency near 1.4 GHz (van Weeren et al. 2012). The comparison between 8.3 GHz and our measurement suggests significant depolarization even between 18.6 and 8.3 GHz. Other than the Toothbrush relic, the polarization observations above 4.9 GHz are only available for three relics, namely the Sausage relic, the Toothbrush relic, the polarization observations remain nearly constant at 4.9 GHz and 8.3 GHz.

The standard deviation of the RM, $\sigma_{\text{RM}}$, is a useful parameter to characterize Faraday rotation and depolarization caused by an external Faraday screen. The depolarization induced by an external Faraday screen containing turbulent magnetic fields (Burn 1966; Sokoloff et al. 1998) can be described as

$$p(\lambda) = p_0 e^{-2\sigma_{\text{RM}}^2 \lambda^4},$$

where $p_0$ is the intrinsic polarization fraction. The maps between 4.9 and 18.6 GHz show depolarization of $\Delta \sigma_{\text{RM}} = 0.36 \pm 0.07$ for B1. This enabled us to derive $\sigma_{\text{RM}} = 212 \pm 23$ rad m$^{-2}$. The observed $\sigma_{\text{RM}}$ for the brush is several times higher than for any other radio relic. This indicates that the brush region of the relic experiences Faraday rotation strongly from the dense ICM. The strong depolarization suggests that the emission lies in or behind the ICM, which very likely causes a low Mach number shock detected via X-ray observations (Ogrean et al. 2013; van Weeren et al. 2016).

4. Conclusions

We presented high frequency radio observations of the Toothbrush relic with the SRT and the Effelsberg telescope. We find that the relic follows a close power-law spectrum between 58 MHz to 18.6 GHz, with a slope of $\alpha = -1.16 \pm 0.03$. Our findings indicate that Toothbrush can be consistently explained by the standard scenario for relic formation. The slope of the spectrum disfavors that the strength of the magnetic field significantly changes on scales probed by the radio emission, that is to say about 85 kpc.

From the lack of steepening in the relic spectra, we find that either the SZ decrement at the shock along the line of sight is $\lesssim 600$ kpc thick, or the pressure jump associated with the relic is located far behind in the cluster. The latter explanation can also be reconciled with the trends of the polarization fraction for the brush region.
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