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The Polarized Handle of a Toothbrush: Low-frequency Radio Relic Polarization with uGMRT

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Radio relics are arc-like, polarized (20-30% at GHz frequencies), diffuse radio emissions typically found at the outskirts of merging galaxy clusters. In polarization, most radio relics show excellent alignment of the electric field position angle (EVPA) with the shock surface, indicating coherent underlying magnetic fields. However, it is still unclear whether this coherence is due to pre-existing large-scale magnetic fields or shock-modified turbulent small-scale magnetic fields. Simulations of both configurations fail to produce coherent structures larger than 250 kpcs, while typical radio relics span around 1 Mpc. The turbulent compression scenario predicts downstream depolarization at the shocks, observed in some cases, notably in the Sausage relic. The magnetic field configuration influences the degree of depolarization at different frequencies. By studying the depolarization spectra, we can infer the underlying magnetic field configurations. Below 1 GHz, depolarization models significantly deviate given the measured and simulated magnetic fields (10-100 rad.m^{-2}). Despite their importance, the low-frequency polarization properties of radio relics remain unexplored due to challenges like beam depolarization, intra-channel depolarization of interferometers, and low polarization signal strengths. However, highly sensitive observations from modern interferometers like the uGMRT make this exploration feasible.

In double radio relics, where the merger occurs in the plane of the sky, the favourable geometry helps avoid intracluster medium (ICM) multipath depolarization effects. To explore this, we used observations of the famous 'Toothbrush' radio relic with the uGMRT band 4 (550-750 MHz). These observations (P.I. Matthias Hoeft, Proposal Code: 34_073) were taken with an integration time of 8 seconds and 2048 channels over a 200 MHz bandwidth. We used 3C286 as our polarized calibrator and 3C147 as our unpolarized calibrator to constrain uGMRT leakages between dipoles. The analysis detected polarization at the tip of the Toothbrush relic's tail, reaching up to ~15% at the outskirts. The RM-corrected EVPAs are consistent with higher frequency measurements and closely follow the shock emission. Depolarization across the shock surface is also consistent with available high-frequency data. The completely depolarized head and body of the Toothbrush relic suggest that these regions are deeper into the ICM compared to the tail, as previously proposed from high-frequency radio and X-ray measurements. This confirms that the ICM is the primary depolarizer for radio relics, making double radio relics promising for studying low-frequency polarization. Alongside the science case, we have demonstrated the use of uGMRT band 4 data for studying low-frequency polarization in extended sources like radio relics. Calibration with refined polarization models below 1 GHz opens a new frontier for studying the polarization of astronomical sources down to 550 MHz with excellent sensitivity and resolution offered by uGMRT, an SKA pathfinder. With validation from the Toothbrush radio relic, we aim to address the long-standing question of whether pre-existing large-scale magnetic fields or compressed turbulent small-scale magnetic fields are responsible for the extraordinary coherence of magnetic fields in radio relics by studying the depolarization trend of a sample of double radio relics using our newly developed calibration approaches with the uGMRT band 4.