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UNVEILING THE NON-THERMAL RADIO EMISSION IN GALAXY CLUSTERS AND FUTURE PROSPECTS WITH THE SKA

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Abstract. Galaxy clusters are the most massive structures in the universe that are held together by their gravity. They harbor various forms of non-thermal diffuse radio emissions at their cores, including radio halos, mini-halos, relics, and reactivated fossil plasma sources known as 'phoenixes.' The detection of these non-thermal radio emissions at radio wavelengths has been challenging in the past due to their steep spectral nature and low surface brightness. In the last decade, surveys conducted with SKA pathfinder telescopes like LOFAR, uGMRT, and Australian SKA Pathfinder (ASKAP) have revolutionized the study of cluster-scale radio emissions. These surveys have doubled the number of detected radio halos and mini-halos, with masses as low as $\sim 10^{14}\mathrm{M}_\odot$ and up to a redshift of 0.9. These breakthroughs have enabled the development of high-resolution numerical models for radio emissions and advanced our understanding of the cosmic magnetic fields associated with galaxy clusters. In this paper, we present statistical results from surveys conducted in the last decade and highlight the pivotal role of the Square Kilometer Array (SKA) in advancing our knowledge of galaxy clusters, particularly at higher redshifts.

Keywords: galaxies: clusters: general- galaxies: clusters: intracluster medium- non-thermal radio emission

1 Introduction

Galaxy clusters reside at the crossroads of cosmology and the astrophysics of large-scale structure formation and galaxy evolution in the Universe. These dense gravitationally bounded structures provide favorable conditions for collisions, mergers, or interactions between galaxies within their Intracluster medium (ICM). These interactions give rise to turbulence and heating-up of the ICM to temperatures up to tens of millions of degrees (several keV per particle), thereby emitting in the soft X-ray regime via thermal bremsstrahlung radiation. In addition to the thermal emission, the ICM is also known to host non-thermal synchrotron radiation emitting predominantly at MHz-range in the radio regime. Diffuse radio emission has been detected in a considerable number of galaxy clusters and groups, revealing the presence of pervasive cosmic magnetic fields and relativistic particles in the large-scale structure of the Universe. Since the radio emissions in galaxy clusters are faint with steep spectral properties ($\alpha \sim -1.3$), their observations are largely limited by the instrument sensitivity and the frequency of observation, leading to a dearth of information, more so for lower-mass $M_{500} = 10^{14}\mathrm{M}_\odot$ and higher redshift ($z > 0.5$) systems. The recent commissioning or upgrade of several large radio telescope arrays, particularly at the low-frequency bands ($<$ MHz), aided by the development of advanced calibration and imaging techniques, has helped in achieving unparalleled image quality and revolutionized the study of cluster-scale radio emission, thanks to the availability of high-performance computing facilities to handle large survey data set processing. In this paper, we provide a summary of the contributions made by SKA pathfinders, including LOFAR, uGMRT, and ASKAP, over the last decade in uncovering various types of cluster radio sources through dedicated surveys and individual studies. Additionally, we explore the potential of SKA in the discovery of diffuse radio emission in clusters and cosmic web filaments.

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2 Advancements in Radio emission Classification and Detection Statistics in Galaxy Clusters with the SKA pathfinders and prospects with the SKA

Recent advancements in survey sensitivities achieved by SKA pathfinders, reaching levels as low as $\sim$ 0.1 mJy/beam, have opened up exciting possibilities in the study of radio emissions within galaxy clusters. These improvements have led to the detection of a greater number of radio sources at frequencies $<$ 144 MHz, shedding light on a previously unknown population of sources. These discoveries are particularly significant in the context of low-mass galaxy cluster systems, where masses hover around $\sim 10^{14}\mathrm{M}_{\odot}$ as illustrated in Figure 1 (left panel) extracted from (Paul et al. 2023). The compilation of comprehensive datasets from both earlier observations and more recent ones (for a review, see van Weeren et al. 2019 and references therein, Botteon et al. 2022; Cassano et al. 2013; Cuciti et al. 2018; Hoang et al. 2022; Paul et al. 2023) suggests a correlation for $P_{1.4GHz} - M_{500}$ with the BCES bisector slope for ($\alpha_{new} = 3.56 \pm 0.22$). This follows a pattern similar to the previously established correlation ($\alpha = 3.70 \pm 0.56$) by Cassano et al. (2013). With the $P_{1.4GHz} - M_{500}$ correlation plot Figure 1 (left panel), it is apparent that there is a dearth of data points for cluster masses below $M < 4 \times 10^{14}$ $\mathrm{M}_{\odot}$. These results emphasize the need for more extended observation times, preferably exceeding 8 hours, or achieving microJy level sensitivity through advanced arrays like the SKA to probe the properties of radio haloes in clusters at the lower end of the mass spectrum more comprehensively.

Further, the enhancement in detection statistics has led to more refined source classification schemes based on the intrinsic properties of these sources. These newly identified source populations predominantly consist of radio haloes (larger than 500 kiloparsecs) or mini-haloes (smaller than 500 kiloparsecs), often found in poor clusters, groups of galaxies, and ultra-steep spectrum sources (Botteon et al. 2022; van Weeren et al. 2019). In Figure 1 (Right panel), we present statistics reflecting the increased detection of radio emissions within clusters with respect to the redshift over the last decade, primarily through the use of SKA pathfinders, notably the LOTSS survey initiated in 2014 (Shimwell et al. 2019). Compared to surveys conducted until 2013, there has been a remarkable 54% increase in the number of detected radio haloes and mini-haloes in the last decade. Furthermore, there is a noticeable peak in the formation period of galaxy clusters, occurring at a redshift of approximately $z \sim 0.2$ to $z \sim 0.3$, which is consistent with recent surveys from PLANCK, SPT, and ACT (Bartalucci et al. 2019). In addition, these improved detection statistics have allowed us to identify rare haloes (8) in the $0.6 < z < 0.9$ range and 1 mini-halo up to $z = 0.6$ for the first time. Nevertheless, these detections are scarce, and SKA will significantly contribute to the discovery of thousands of haloes beyond $z > 0.6$ (Cassano et al. 2013). Consequently, the combination of enhanced detection statistics, along with improved theoretical insights, will facilitate the refinement of radio emission mechanisms in galaxy clusters and their classification schemes by incorporating their detailed intrinsic properties.

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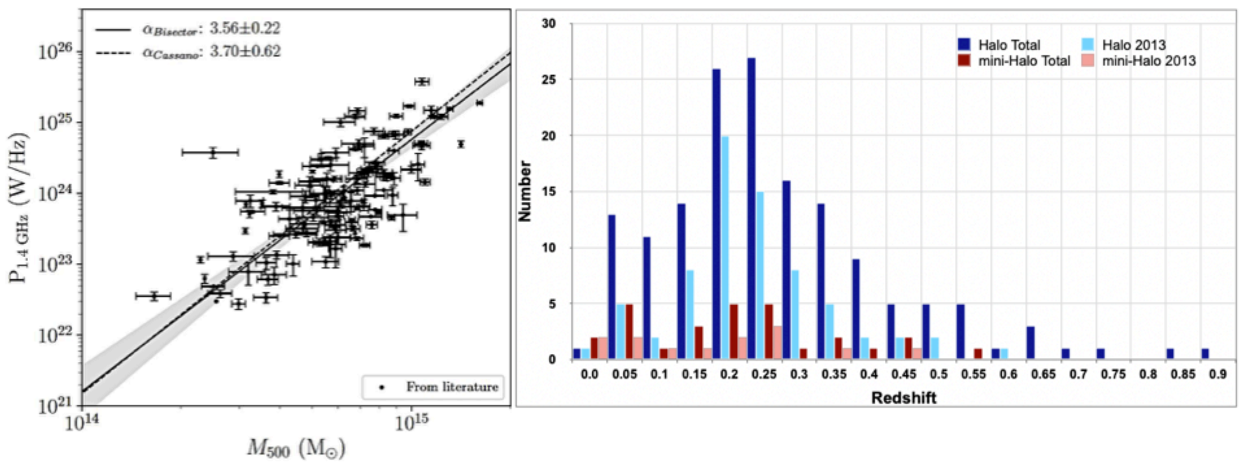

Fig. 1. Left Panel: Radio halo power plotted against mass M_{500} of all the radio halos observed so far and extracted from (Paul et al. 2023). The halo radio power here is scaled to 1.4 GHz, assuming the spectral index of -1.3 wherever no spectral index information is available in the literature. Right Panel: Radio halo and mini-halo detection statistics across redshift: pre-2013 versus recent surveys.