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LOW FREQUENCY EMISSION IN GALAXY CLUSTERS- $MACSJ0717.5+3745$

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Abstract. Cluster of galaxies being the largest gravitationally bound systems, are the ideal laboratories to study the formation and evolution of large scale structures within the Universe. High sensitivity radio observations of galaxy clusters have helped to investigate the non−thermal emission mechanism (in the form of *relics*, *halos*, *mini − halos*) within the Intra Cluster Medium (ICM) and their interaction during cluster mergers. These non-thermal emissions play an important role in the overall understanding of the physical evolution of the ICM and are closely related to their X-ray properties. We present here the observational properties of diffuse non-thermal sources detected in the galaxy cluster: $MACSJ0717.5+3745$. We discuss their classification, equi-partition magnetic field, radio power and spectral properties based on the new observations acquired with the GMRT down to 235 MHz, as well as the published results in the archive. We discuss in general the statistical properties of non-thermal components within galaxy clusters over a redshift range, $0 < z < 1$ (the epoch of their formation), and outline the important contribution that are expected in this area from sophisticated radio facilities (like LOFAR, SKA, etc.).

Keywords: Cosmology, large−scale structures of Universe, galaxy clusters- $MACSJ0717.5+3745$, radiation mechanisms, non−thermal, radio telescope

1 Introduction

Cluster of galaxies are the largest gravitationally bound systems in the Universe, that are formed by mergers of smaller clusters and galaxy groups, as well as through continuous accretion of gas. They serve as a tool to study the formation and evolution of large scale structures in the Universe and can be used to probe the properties of magnetic fields present within them and in even larger structures: filaments connecting galaxy clusters (Feretti et al. 2012). Important progress in the study of Inter Cluster Medium (ICM) and their interactions in galaxy clusters have been made with multi−wavelength observations (Boselli & Gavazzi 2006; Markevitch & Vikhlinin 2007); however, scarce information is available about the physical properties and the origin of nonthermal diffuse ICM, that also play a vital role in the evolutionary stage of galaxy clusters (Dursi & Pfrommer 2008; Parrish et al. 2009). In fact, deep radio observations have shown that significant diffuse synchrotron emission is present in some clusters at Mpc−scale, and which indicate there are magnetic fields and cosmic rays within the cluster volume (Feretti et al. 2005, Kale & Dwarakanath 2009). This Mpc−scale cluster radio structures are generally divided into *relics* and *halos* depending on their position in the cluster, polarization and spectral properties (Ferrari et al. 2008). Further in the case of few clusters double *relics* structures are also detected (Kale et al. 2012). Furthermore, a magnetic field of μG level has been detected in these Mpc−scale structures with relativistic particles in cluster outskirts. The origin of these relativistic particles is explained by the so−called electron primary model acceleration (Enβlin et al. 1998).

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2 Non−thermal emission and their spectral properties in galaxy cluster: $MACSJ0717.5 + 3745$

In this paper we present results on the study of non−thermal emission in one of the most studied galaxy cluster- $MACSJ0717.5 + 3745$ at redshift $z = 0.5548$. Fig. 1 (Top Panel) shows the deep radio observations on the source down to 0.235 GHz with the Giant Metrewave Radio Telescope (GMRT). This system hosts an elongated centrally placed chair−shaped filament of 853 kpc at 0.235 GHz, and a very low−surface brightness powerful radio *halos* of 1.6 kpc at 0.235 GHz (Pandey−Pommier et al. 2013). The morphology of this source is very similar to the X−ray emission of the cluster, which is related to the thermal intra-cluster component (Fig. 1 Bottom Panel). It is evident from figure 1 that, the non−thermal diffuse emission is brighter at lower frequencies. The halo structure was not detect at 1.4 GHz *FIRST* survey data, due to high noise level. The bottom right panel of Fig. 1 shows the radio contours at 0.61 GHz overlaid on the Chandra X−ray map of$MACSJ0717.5 + 3745$. The Chair−shaped filament is centrally placed between the 4 different clusters involved in collision (marked with C1, C2, C3 and C4) within the ICM. The bottom left panel shows spectral index map between 0.61 and 0.235 GHz with overlaid Chandra X−ray contours.

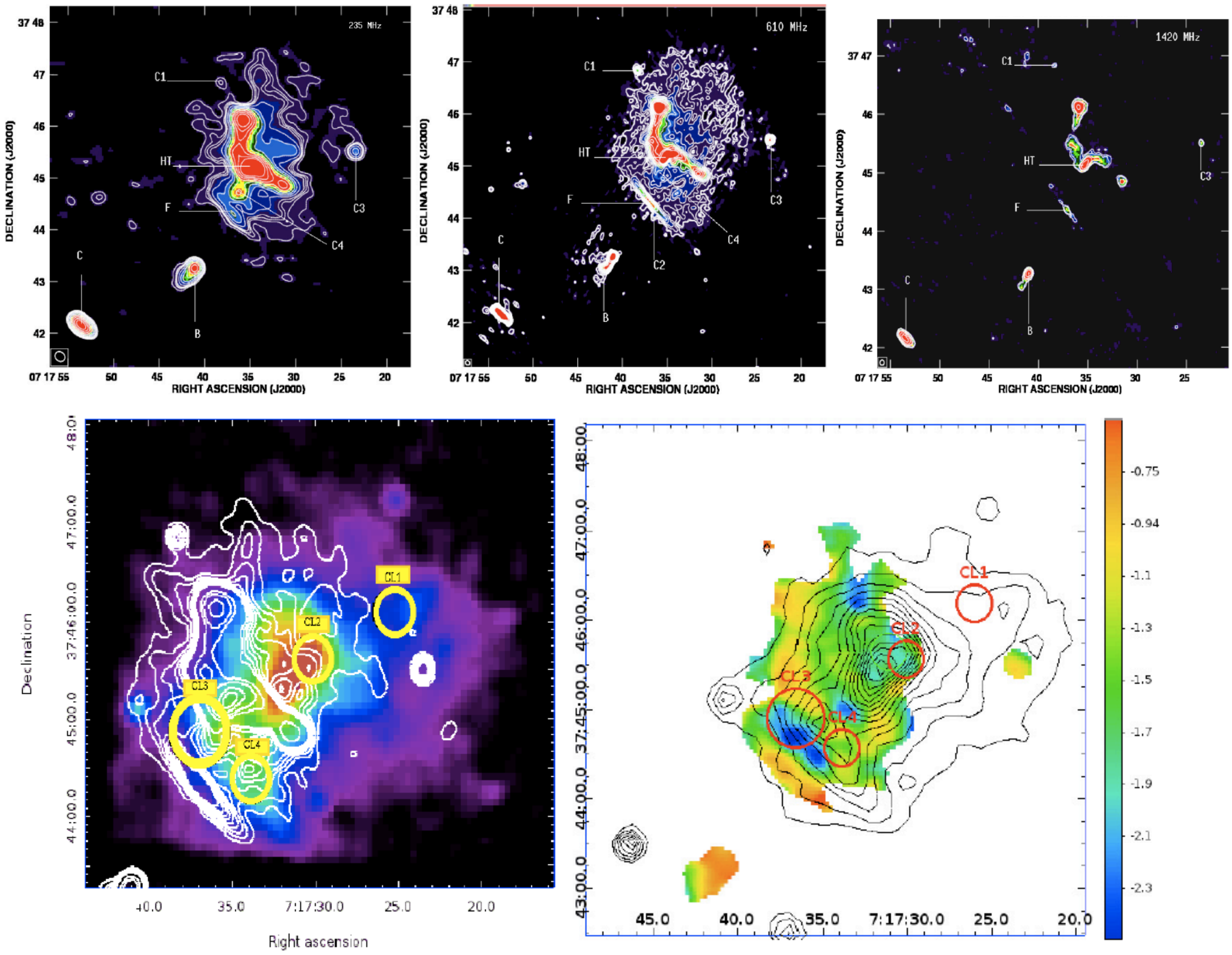

Fig. 1. *from top left to top right - 3 panels* High resolution radio images of massive galaxy cluster $MASCJ0717.5 + 3745$ ($z = 0.5548$) at 0.235 GHz from GMRT (*Top left*) at FWHM beam of $13.46'' \times 10.76''$ resolution, 0.61 GHz from GMRT (*Top middle*) at FWHM of $5.70'' \times 4.82''$ resolution and 1.42 GHz from FIRST survey (*Top right*) at FWHM of $5'' \times 5''$ resolution. Contours start at (3σ) and scale by a factor of $\sqrt{2}$. (*Bottom right*) radio contours at 0.61 GHz overlaid on Chandra image. (*Bottom left*) Spectral index error map between 0.235 and 0.61 GHz image with overlaid Chandra X-ray contours. The red and yellow circles (C1, C2, C3, C4) shows galaxies in 4 different clusters involved in collision-extracted from Pandey−Pommier et al. 2013.

A detailed understanding of the origin of the centrally placed '*Chair-shaped*' filament is still debated (e.g. Pandey−Pommier et al. 2013, Bonafede et al. 2009, van Weeren et al. 2009). The location of the filament being coincident with regions in the cluster having higher temperatures, suggests that the '*Chairshaped*' filament is probably the result of a largescale shock wave within the cluster where particles are accelerated during merger events. The less−steep spectral index of the bright '*Chair − shaped*' filament, $\alpha^{0.61}_{0.235}$= -0.92 to −1.5 further supports this scenario (ref. Fig. 2 Top Panel). The overall radio spectrum of the halo is very steep with typical spectral index ranging from $\alpha^{0.61}_{0.235}$ = -0.85, close to the cluster center, up to about α = -2.3 towards the outer edge, that traces the outer cooler region of the cluster and a mean spectral index of $\alpha^{0.61}_{0.235}$ = -1.17±0.37. Based on the size of the halo and mean spectral index, a standard equipartition magnetic field of 3.43 μG was derived from our observations.

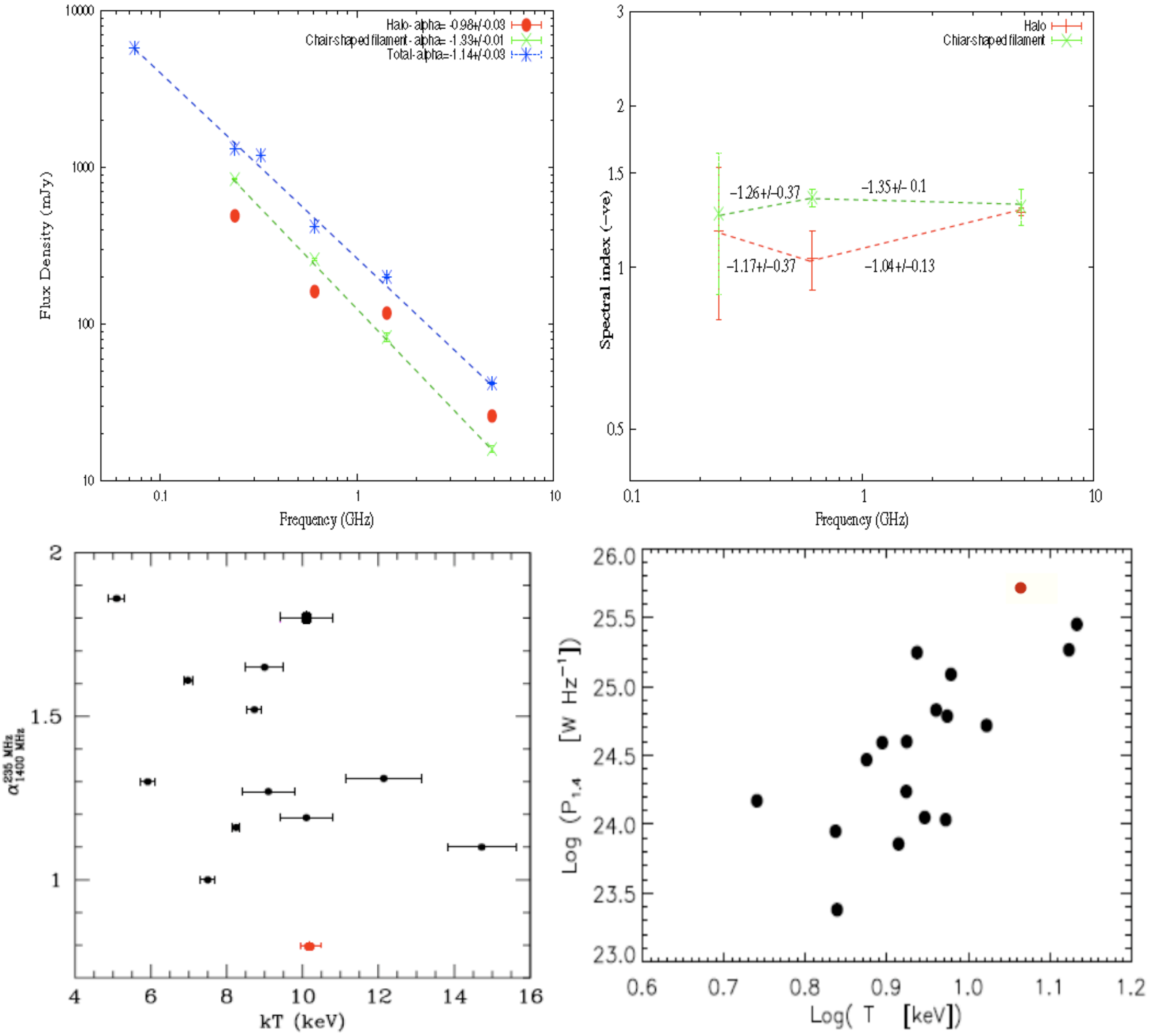

Fig. 2. *Top left panel:* Integrated radio spectra of the halo, '*Chair − shaped*' filament source and total(halo+'*Chair − shaped*' filament source). *Top right panel:* spectral index variation with respect to frequency for the halo and '*Chair − shaped*' filament source (Pandey−Pommier et al. 2013). *Bottom left panel:*Spectral index of radio *halo* in the 235 MHz-1.4 GHz interval as function of the cluster X-ray temperature (adapted from Venturi et al. 2013 and Giacintucci et al. 2013).The red points mark the position of $MACSJ0717.5+3745$. *Bottom right panel:* Radio power in the halo of galaxy clusters with respect to X-ray temperature (extracted from van Weeren et al. 2009). The red point marks the radio power measured in $MACSJ0717.5 + 3745$ with our observations

Giovannini et al. (2009) recently derived a correlation between the radio−halo, integrated spectral index and the average X−ray gas temperature for a large sample of nearby radio *halos* . As per the correlation, hot clusters ($T > 10keV$) show an average spectral index = −1.1 to −1.2, and cold clusters ($T \leq 8$ keV) show steep spectra (average spectral index = −1.7). The radio spectrum derived from our new observations on the present radio halo with $\alpha \sim -1.17$ further confirms the result that $MACSJ0717.5+3745$ is a high−temperature merging cluster, $T = 10.2 \pm 2.4keV$ (Ma et al. 2009) that shows agreement with the correlation between the radio−halo, integrated spectral index and the average X−ray gas temperature. Venturi et al. (2013) further found that, based on the mass, the radio *halos* show different spectral index depending on the energy release into particle re−acceleration during mergers. The most massive hot clusters ($T > 8$ keV) with *halos* show flatter spectra, while moderately massive clusters ($T \sim 5-8$keV) shows *halos* with both steep and flat spectra (Cassano et al. 2006, Cassano et al. 2010). In Figure 2, we report the distribution of spectral index ($\alpha^{235MHz}_{1400MHz}$) in radio−halo clusters versus the X−ray temperature,kT (keV) adapted from Venturi et al. (2013), with the position of $MACSJ0717.5+3745$ shown by a red point (with kT=10.2 ± 2.4 keV). Thus, it is the distant massive cluster with most powerful radio halo showing spectral index, $\alpha^{0.235}_{1.42} = -0.8$, less steep than other hotter clusters, further suggesting its complex nature. $MACSJ0717.5+3745$ cluster hence, is an interesting candidate that provides an upper limit for our understanding of mass−spectral index correlation of giant radio *halos* in distant massive hotter clusters showing multiple mergers. Fig. 2, Bottom Panel also shows the correlation plot of radio power within the halo with respect to X−ray temperature, where $MACSJ0717.5+3745$ is shown to have most powerful radio halo at redshift, $z = 0.5548$, thanks to our new sensitive GMRT observations.

3 Statistical properties of non-thermal emission in galaxy clusters

The statistical studies based on observational data from the archive shows that non−thermal emission in the form of radio *relics* and *halos* are known up to now only in a few galaxy clusters (ref. Fig. 3, Feretti et al. 2012), in fact the non−thermal emission being rare is not present in most of the clusters. Theoretical models presented by Cassano et al. 2010, as well as observational data, confirms that diffuse intra-cluster radio sources are generally characterized by steep synchrotron spectra (α = –1.2) and low-surface brightness and hence, best detected at long wavelengths (MHz- regime). Further, at GHz regime, the possible spectral steepening due to electron aging, make them difficult to be imaged at higher frequencies and more easily detectable at the long wavelengths observational facilities like GMRT, LOFAR, SKA etc, and as confirmed by our observations. These instruments are therefore best suited for the discovery of diffuse radio emission in hundreds of massive galaxy clusters up to z = 1 (epoch of formation)(ref. Fig. 3, Cassano et al. 2012). Thanks to its wide frequency coverage, high sensitivity and large field of view (FoV), LOFAR will further open up new radio windows down to 10 MHz, to further study the non-thermal component in large-scale structures within the Universe (Rottgering et al. 2011).

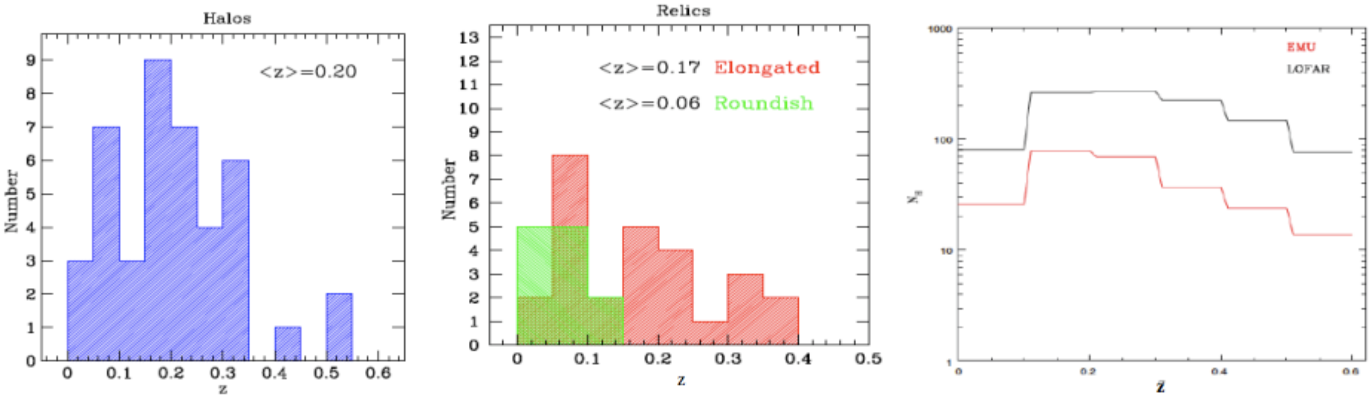

Fig. 3. *Top left panel:* Number count of radio *halos*, *Top middle panel:* Number count of radio *relics* extracted from Feretti et al. 2012 and *Top right panel:* RH distribution in redshift intervals in the Australian SKA Path-finder (ASKAP) Evolutionary Map of the Universe (EMU) survey (red line) and LOFAR (black line) surveys extracted from Cassano et al. 2012

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