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A STEEP SPECTRUM RADIO HALO IN MERGING GALAXY CLUSTER-MACSJ0416.1-2403

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Abstract. Steep Spectrum Radio Halos (RH) are very rare diffuse structures existing in the central region of merging galaxy clusters. Due to their steep spectral nature, they are often not detected at higher frequencies and tend to shine only at very low frequencies. They represent a new class of objects that could be either old halos or clusters at a special time of the merger event, when particle acceleration processes have a lower efficiency. The comparison of theoretical predictions with the low frequency observations clearly suggests that there is yet a large population of very faint RHs in galaxy clusters that still remains to be discovered with steep spectrum RHs expected to dominate this undiscovered population. As the number counts of these steep spectrum RHs is scarce, discovery of even a couple of them is important. We present result on cluster $MACSJ0416.1-2403$ (z = 0.396), that host one such steep spectrum RH and emphasize the important contribution of low frequency observations with interferometers like GMRT, MWA, LOFAR, SKA on cluster science and discovery of new population of rare steep spectrum RHs.

Keywords: galaxies: clusters: general, galaxies: clusters: individual: $MACSJ0416.1-2403$: intracluster medium radio halo

1 Introduction

Cluster of galaxies are the largest bound structures in the Universe. They form by mergers with smaller clusters and galaxy groups. These merger events generate shocks, cold fronts, and turbulence within the intracluster medium (ICM), as can be probed by X-ray observations of the intracluster medium (e.g., Markevitch and Vikhlinin 2007; Randall et al. 2008; Zhuravleva et al. 2015). In addition, these merger give rise to diffuse non-thermal radio emission (Giovannini et al. 2009, Feretti et al. 2012, Bonafede et al. 2012, van Weeren et al. 2012, 2014, Giacintucci et al. 2014, Kale et al. 2013, 2015, Ogrean et al. 2015, de Gasperin et al. 2015, Pandey-Pommier et al. 2015). Thanks to X-ray observations, important progress has been made on the study of thermal properties of the ICM and its interactions in galaxy clusters during merger events (Markevitch & Vikhlinin 2007). However, scarce information is available about the non-thermal emitting components in the ICM and their physical properties, that can for example be used to probe the dynamical properties of the cluster (Dursi & Pfrommer 2008; Parrish et al. 2009).

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The combined study of radio along with multi wavelength properties suggests that, radio halos (RHs) form by electrons that are re-accelerated through scattering with magneto hydro dynamic (MHD) turbulence. Radio relics are thought to trace particles accelerated at shocks. RHs and relics should preferentially be found in massive objects undergoing major mergers, since more energy is released into the ICM during these events. At a later stage in the merger, or during less energetic merger events, clusters might give rise to a fainter class of RHs with steep or ultra steep ($\alpha < -1.5$) spectral nature (Cassano et al. 2015). These ultra steep spectrum radio halos (USSRHs) are under luminous at GHz frequencies and tend to shine only in the MHz range. Thus, low frequency radio observation are crucial for the detection of this rare population of steep or ultra steep spectrum RHs.

In this paper, we present results from Giant Metrewave Radio Telescope (GMRT), Chandra and Jansky Very Large Array (JVLA) observations of a merging galaxy cluster: the Hubble Space Telescope (HST) Frontier Fields cluster $MACSJ0416.1-2403$ (z=0.396, Ebeling et al.2001; Mann & Ebeling 2012).

2 Merging galaxy cluster: $MACSJ$0416.1-2403

HST Frontier Field cluster, $MACSJ$0416.1-2403 was discovered by the Massive Cluster Survey (MACS) as an actively merging system with a luminosity, $L_{X,0.1-2.4keV} = 7.43 \pm 0.08 \times 10^{44}$ erg s^{-1}, temperature, $T = 10.06^{+0.50}_{-0.49}$ keV and elongated central region (Ebeling et al. 2001; Mann & Ebeling 2012, Ogrean et al. 2015).

At optical wavelengths the cluster is known to show strong lensing properties based on the HST data (Postman et al. 2012) and hosts numerous strongly lensed galaxies (refer Fig. 1; Zitrin et al. 2013; Richard et al. 2014, Schirmer et al. 2014; Jauzac et al. 2014; Zitrin et al. 2015; Grillo et al. 2015). Further the HST data also reveal a highly elongated mass distribution, typically seen in merging systems with two mass concentrations associated to two main subclusters involved in the merger, plus two smaller X-ray-dark mass structures north east (NE) and south west (SW) of the cluster center (Jauzac et al. 2015). The combined analysis based on shallow, archival Chandra X-ray data (with poor count statistics) and Dark Matter (DM) distribution map using lensing data by Jauzac et al. (2015), suggested that there exists an offset between the DM and the thermal gas components for the SW subcluster and a good DM-gas alignment for the NE subcluster. Jauzac et al. (2015) concluded that- there are two possible scenarios for the merger event in $MACSJ$0416.1-2403$-$ one pre-merging (lack of offsets) and one post-merging (significant offsets). However, with the recent deep Chandra observation, better constraints (within the uncertainties) on the peak of the X-ray position co-located with the DM centers, was derived, favouring the possibility of $MACSJ$0416.1-2403 being a pre-merging cluster, but the possibility of $MACSJ$0416.1-2403 being a post-merging cluster was not ruled out.

3 Non-thermal emitting components and their spectral properties in $MACSJ$0416.1-2403

Low frequency radio observations are good tracers (in the form of RHs and relics) of the dynamical state of massive galaxy clusters. In the case of most massive merger events, RHs show a typical spectral index of , $\alpha < -1.1$ (where, $S_\nu = \nu^\alpha$, Feretti et al. 2012) and may scale up to Mpc size as seen in the case of $MACSJ0717.5 + 3745$ (Pandey-Pommier et al. 2013).

At the later stage of major mergers, USSRHs are expected to be formed, that are under luminous at higher frequencies (i.e., above a GHz), due to the energy losses involved. They should still shine brightly at lower frequencies giving rise to a steep spectrum ($\alpha < -1.5$). In the turbulent re-acceleration model (Brunetti et al. 2008, Cassano et al. 2006, Donnert et al. 2013), less energetic merger events, often occurring in less massive systems, are also expected to produce USSRHs. This is caused by an energy cutoff in the particle spectrum because the re-acceleration is inefficient. Less energetic mergers in less massive systems are more frequent than major mergers in the Universe, however, high sensitivity observations are required to detected USSRHs in these less energetic events, due to their faint nature.

In the case of $MACSJ$0416.1-2403, a RH of size 0.65 Mpc and was detected down to 610 MHz (refer Fig. 2 and 3). The halo has an elongated shape and seems to be associated to both the NE and SW subclusters (Ogrean et al. 2015). Using JVLA and GMRT data, a spectral index- $\alpha^{1500MHz}_{610MHz} = -1.6 \pm 0.5$ was estimated with a radio power of $P_{1.4GHz} = (1.3 \pm 0.3) \times 10^{24}$ W Hz^{-1}. The VLA Low Band Ionospheric and Transient Experiment (VLITE) data at 340 MHz also detects the halo at a flux density level of 14.6$\pm$7.0 mJy giving a spectral index of $\alpha^{1500MHz}_{340MHz} = -1.5 \pm 0.8$. Given the location of $MACSJ$0416.1-2403 on the $L_x - P_{1.4GHz}$ relation for RHs, it is possible that $MACSJ$0416.1-2403 is either hosting a normal RH or possibly an USSRH formed due to the turbulent re-acceleration in less energetic mergers (refer Fig. 3; Brunetti et al. 2008; Cassano

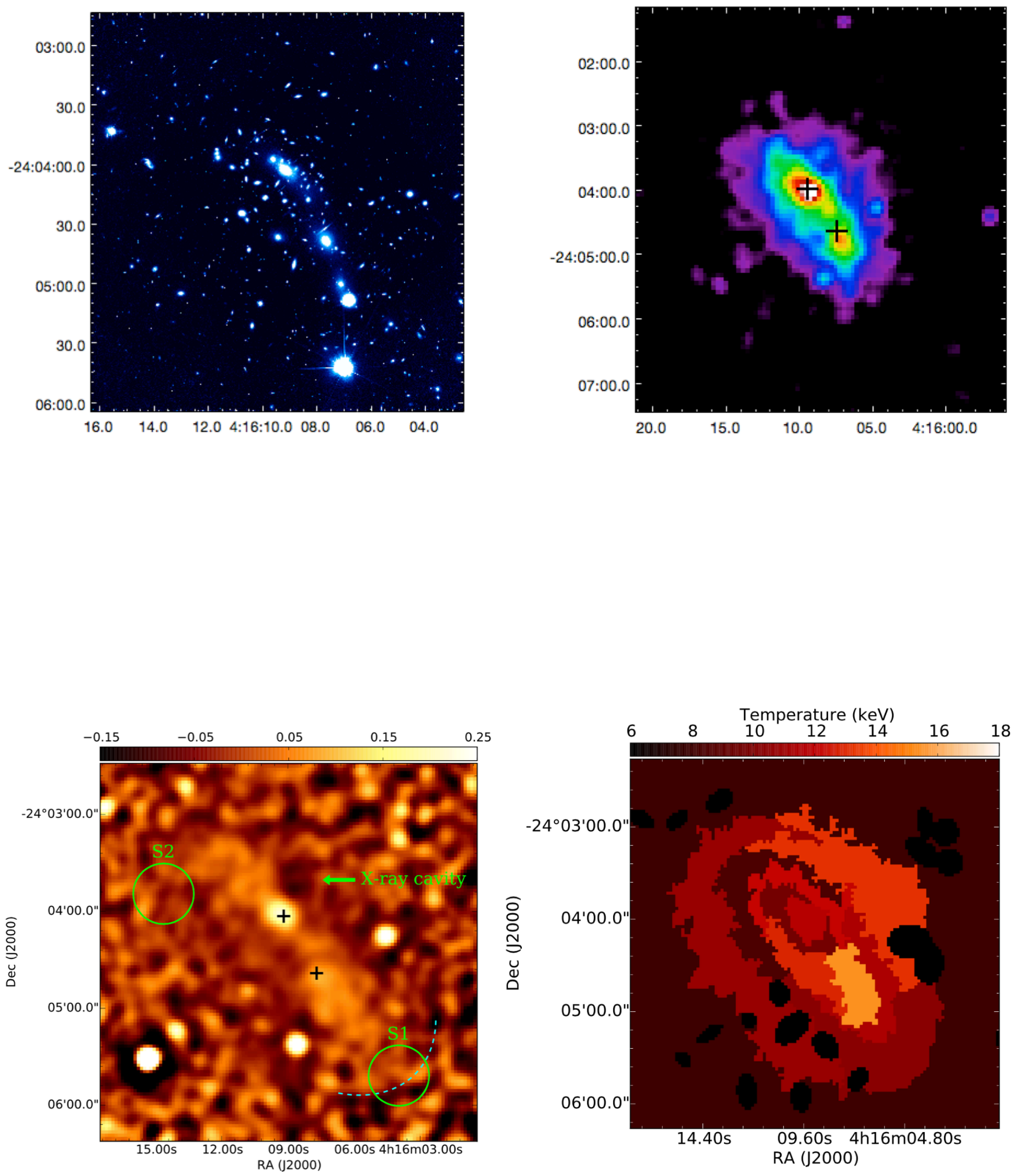

Fig. 1. $MACSJ0416.1$-2403 : *(Top left:)* HST image showing lensed galaxies and elongated mass distribution, *(right:)* Chandra image showing disturbed central region with centers of the DM halos (black crosses) of the NE and SW merging clusters. *(Bottom left:)* Chandra image showing X-ray cavity, positions of the two less massive structures identified by Jauzac et al. (2015) marked as S1, S2. *(right:)* Temperature map showing no strong gradient in the NE and SW merging clusters, (from Ogrean et al. 2015).

et al. 2013; Umetsu et al. 2014). Additional low frequency radio observations (below 610 MHz) are needed to confirm the steepness in the radio spectrum and to establish whether this is an USSRH.

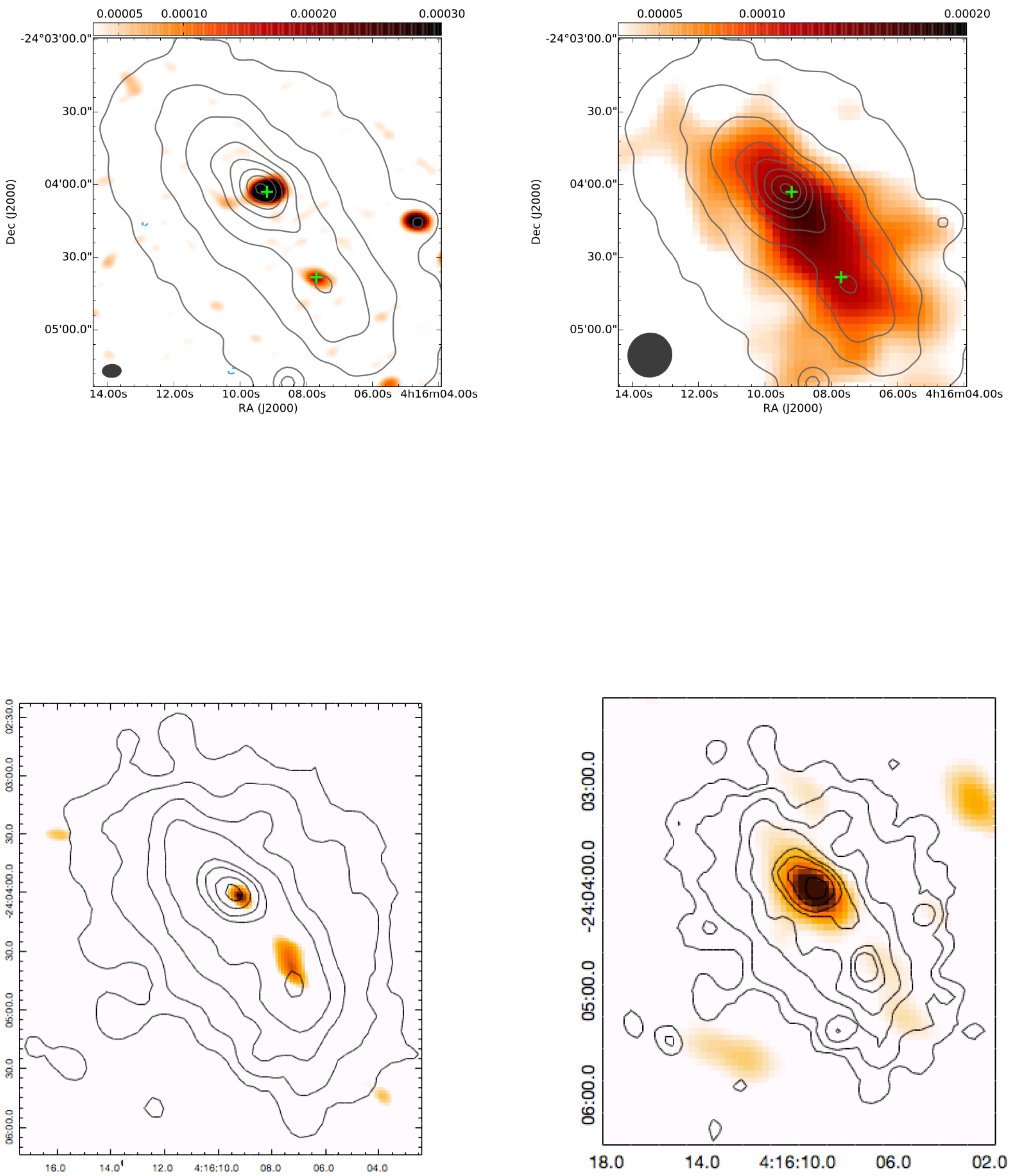

Fig. 2. *(Top left):* JVLA 1-2 GHz high-resolution (7.8 × 5.5 arsec) image showing the compact sources in the cluster region, with the centers of the DM halos marked (green crosses). (*Right:*) 1-2 GHz low resolution image (18 × 18 arsec) of the RH with compact sources subtracted, Ogrean et al. 2015. (*Bottom left:*) GMRT 0.61 GHz high-resolution (7.6 × 4.0 arsec) image showing the compact sources in the cluster region. (*Right:*) low-resolution (20 × 20 arsec) image showing the steep spectrum RH. Chandra contours are overlaid in black.

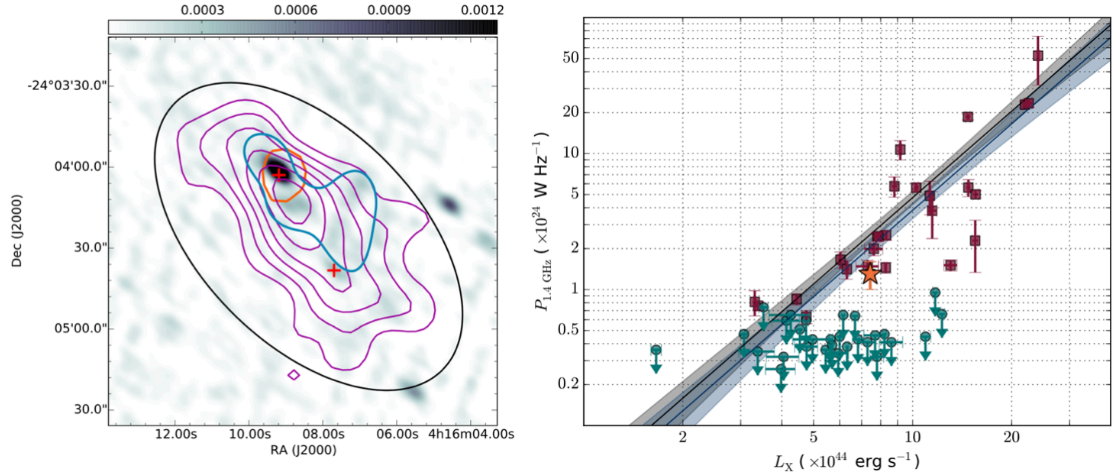

Fig. 3. *(Left):* RH (magenta contours) detected in JVLA data at 1.5 GHz, (blue contours) in GMRT data at 0.61 GHz and in VLITE data (red contours) at 340 MHz for massive cluster $MACSJ$0416.1-2403 overlaid on high resolution JVLA image in grey scale. *(Right)*: $L_X - P_{1.4GHz}$ diagram in clusters with $MACSJ$0416.1-2403 represented in orange star and upper limits on radio halo power in teal (from Ogrean et al. 2015)

4 Properties of USSRHs in clusters

USSRHs are very rare and faint in nature at GHz frequency range. As of now only 7 clusters viz., A697, A521, A1300, A2256, $RXCJ$1514.91523, Z1953 and A1682 are known to host such USSRHs (Venturi et al. 2008; Macario et al. 2010; Venturi et al. 2013, Giacintucci et al. 2011, Kale et al. 2015). They are less luminous in radio and generated in connection with less energetic phenomena, e.g., major mergers between less massive systems or minor mergers in massive systems towards the end of their activity (Cassano et. al. 2015). Thus, considering the energy input required to initiate merger-events, USSRHs are expected to be more common in the Universe, as compared to major massive mergers which require high energy input (Cassano et al. 2015). Evidently, deep low frequency observations at MHz range with high sensitivity are required for their detection. LOFAR (van Haarlem et al. 2013), MWA (Tingay et al. 2013) and SKA are ideal instruments to detect such new population of USSRHs, with number of these sources being larger in SKA1-LOW surveys thanks to its better sensitivity (Cassano et al. 2015). Simulations suggests that SKA1-LOW may be able to detect ∼2600 halos (including Giant RHs), while LOFAR may detect ∼400 RHs (Cassano et al. 2015), thereby providing better test for theoretical models (Brunetti et al. 2008).

5 Summary and Conclusion

We present a combined radio (GMRT, JVLA, VLITE) and X-ray (Chandra) analysis of the massive galaxy cluster $MACSJ$0416.1-2403 (z = 0.396). Low frequency radio observations with the GMRT down to 610 MHz not only confirmed the presence of a faint RH in $MACSJ$0416.1-2403, in the JVLA data but also provided a better constraint on the radio power. Further, the spectral index estimate between JVLA and GMRT data suggests that the RH in $MACSJ$0416.1-2403 has a steep spectral ($\alpha = -1.6$) nature. Thus, these observations not only highlight the importance of low frequency observation to detect rare steep spectrum RHs but also, the expected major contribution of the SKA, MWA and LOFAR in discovering such rare population RHs, thereby probing the dynamical properties of cluster of galaxies.

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