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Diffuse radio emission from merging and cool-core galaxy clusters

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Abstract. Many dynamically disturbed galaxy clusters exhibit diffuse radio emission, which takes the form of cluster-wide synchrotron giant radio halos and peripheral Mpc-sized radio relics. Smaller-scale, diffuse radio sources – called mini-halos – are found in the cool cores of a number of relaxed clusters. Halos and relics reveal a population of ultra-relativistic electrons coexisting with the intra-cluster thermal gas. The origin of these electrons is one of the most debated problems of cluster astrophysics. Significant improvement in our understanding of the properties of giant halos and of the physical mechanism behind their formation has been possible thanks to dedicated and extensive statistical studies such as the *GMRT* Radio Halo Survey and its ongoing extension. Because of their rarity, mini-halos are still poorly understood. Detailed radio spectral studies help to discriminate between various physical interpretations of mini-halos, but the information on their spectral properties is still scarce. Our recent spectral analysis of the mini-halo in RXJ 1720.1+2638 – the best-studied object of this class so far – has provided new insights on the origin of the synchrotron-emitting electrons in cluster cool cores.

Keywords : radio continuum: general – galaxies: clusters: general

1. Introduction

Hot, X-ray emitting gas is the dominant constituent of the intra-cluster medium (ICM) in galaxy clusters. The ICM is also permeated by magnetic fields and ultra-relativistic particles, whose energy densities are very uncertain. These non-thermal components

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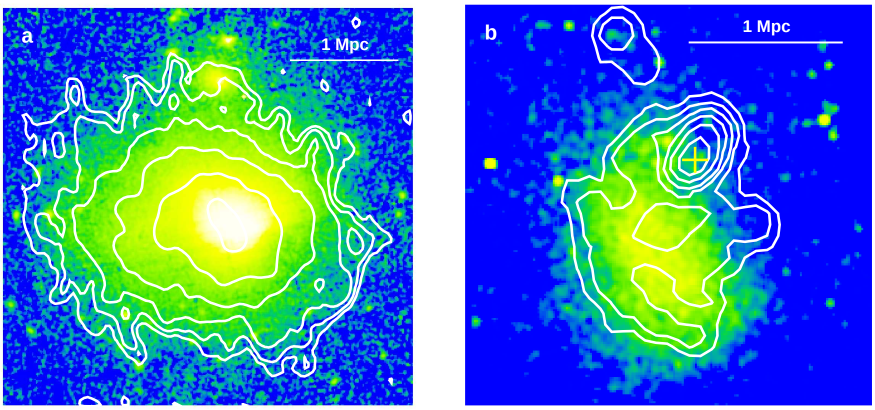

Figure 1. (a) VLA 1.4 GHz contours of the ∼ 3 Mpc-wide giant radio halo in A 2163 (Giacintucci et al. in preparation), overlaid a smoothed *XMM-Newton* X-ray image in the 0.5-2.5 keV band (courtesy of H. Bourdin). Individual radio galaxies have been subtracted. (b) GMRT 327 MHz countours of the giant radio halo in RXC J1514.9-1523 (Giacintucci et al. 2011), overlaid a smoothed *Chandra* X-ray image in the 0.5-5 keV band. The cross marks the position of a head-tail radio galaxy. In both panels, the radio beam is ∼ 50″ and contours are spaced by a factor of 2 starting from 3σ=0.1 and 0.8 mJy beam^{-1}, respectively.

reveal themselves in the radio band as low-surface brightness, steep-spectrum[1] and diffuse *giant radio halos*, smaller-scale *mini-halos* and large peripheral *relics* (Feretti et al. 2012, for a review). How these synchrotron sources form and evolve is still debated, but their existence seems to be closely related to the cluster dynamical state.

Giant radio halos and relics. Cluster-wide, centrally-located halos (see Fig. 1 for two examples) and peripheral relics are found in disturbed systems, suggesting that cluster mergers play a role in their origin. In particular, while relics probably trace merger shocks (Brüggen et al. 2012, for a review), giant halos may arise from the reacceleration of pre-existing, low-energy relativistic electrons in the ICM (for instance, injected by cluster radio galaxies and/or hadronic collisions) in the large-scale turbulent wakes of in-falling subclusters (turbulent reacceleration models; see Brunetti & Jones 2014, for a review). As an alternative to reacceleration models, hadronic (or secondary) models propose that appreciable synchrotron radiation can be emitted by secondary electrons continuously generated by inelastic collisions between relativistic cosmic-ray protons accumulated in the cluster and the thermal protons in the ICM (Brunetti & Jones 2014, and references therein). Statistical studies of the properties of giant halos and of their relation to mergers – in particular the 610 MHz GMRT Radio Halo Survey, its extension and lower-frequency follow up (Venturi et al. 2007, 2008; Macario et al. 2013; Venturi et al. 2013; Kale et al. 2013, see also Kale, this

[1] $\alpha > 1$, for $S_\nu \propto \nu^{-\alpha}$.

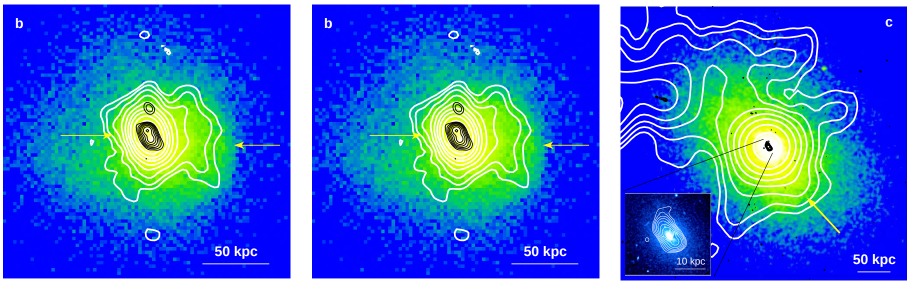

Figure 2. *Left to right*: VLA 1.4 GHz radio contours of the newly detected mini-halos in RX J1532.9+3021, A 2204 and A 478 (Hlavacek-Larrondo et al. 2013, Giacintucci et al. 2014a), overlaid on the *Chandra* X-ray images. The resolution is $3''$, $6''$ and $30''$. Contours are spaced by a factor of 2 starting from 3σ (1σ = 10 μJy beam^{-1}, 30 μJy beam^{-1} and 50 μJy beam^{-1}). Black contours show higher-resolution images of the central radio galaxies, enclosed by the diffuse mini-halos. For A 478, a zoom on the radio galaxy is shown in the inset, overlaid on the optical HST image. Arrows mark X-ray cold fronts, which are possibly confining the mini-halos.

volume) – have significantly improved our understanding of these sources (e.g., Cassano et al. 2013). One of the key outcomes of this survey was the discovery of halos with extreme steep spectra ($\alpha \sim 1.5 - 2$; see Cassano et al. 2013 for a list), whose existence supports turbulent reacceleration and disfavors a secondary origin of the radio-emitting electrons (e.g. Brunetti et al. 2008; Venturi et al. 2013; Giacintucci et al. 2011, see also Venturi, this volume, for a possible new detection).

Mini-halos. Unlike giant halos, mini-halos are found at the centers of relaxed, cool-core clusters, where they typically fill the cooling region ($r \sim 50 - 300$ kpc) and encompass – albeit they are not obviously connected to - the radio source associated with the cluster dominant galaxy (Giacintucci et al. 2014a, and references therein; see Fig. 2 for recent detections). As for the larger-scale halos, diffusion of electrons (leaking for instance from the central radio galaxy) cannot explain the few hundred kpc scale of mini-halos, thus requiring a continuous injection or reacceleration in situ of electrons throughout the core volume. Hadronic collisions and/or turbulent particle reacceleration have been considered also for mini-halos (Brunetti & Jones 2014). High-resolution *Chandra* and *XMM-Newton* X-ray images have revealed cold fronts – sharp, arc-like gas density discontinuities – in most, if not all, relaxed cool-core clusters (e.g., Markevitch & Vikhlinin 2007). These features are created by "sloshing" of the low-entropy gas in the cool core in response to a *minor* merger, i.e., interaction with a small subcluster, which does not cause serious disturbance outside the core. A spatial correlation between mini-halo and X-ray cold fronts has been observed in a number clusters, where the radio emission appears contained within the region bounded by the cold fronts (Mazzotta & Giacintucci 2008; Giacintucci et al. 2014a, Giacintucci et al. 2014 in preparation). Fig. 3a shows a striking example of this, in the core of RX J1720.1+2638, where the mini-halo is entirely confined within

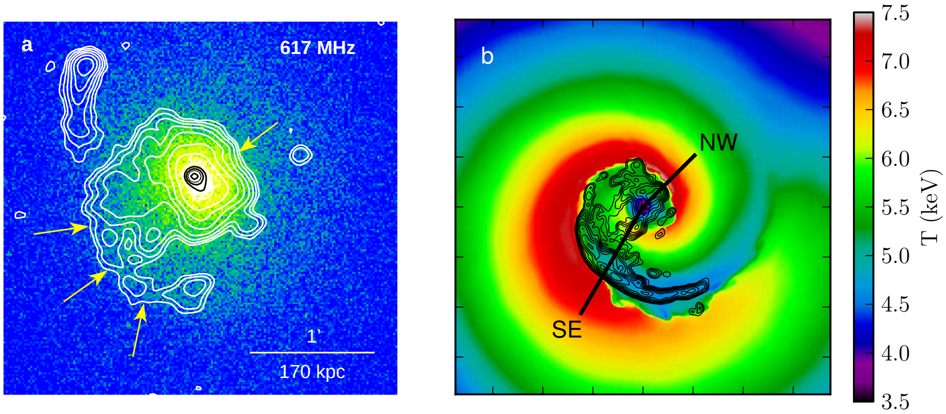

Figure 3. (a) GMRT 617 MHz contours of the central mini-halo in RX J1720.1+2638, overlaid on the *Chandra* X-ray image in the 0.5-2.5 keV energy band. An unrelated head-tail cluster radio galaxy is visible north-east of the mini-halo. A point source (black contours) is associated with the central elliptical galaxy. The resolution is $8'' \times 6''$ and rms noise is $1\sigma = 30$ μJy beam^{-1}. Contours are spaced by a factor of 2 starting from 3σ. Two X-ray cold fronts are indicated by the arrows. The mini-halo is entirely confined to the region bounded by the cold fronts. (b) Contours of synchrotron emission at 327 MHz from a turbulent reacceleration-model simulation, overlaid on the projected temperature map in the z-projection (from ZuHone et al. 2013). Contours increase by a factor of 2 starting from 0.5×10^{-3} mJy arcsec^{-2}. The panel is 750 kpc on a side. Tick marks indicate 100 kpc distances. The simulated radio emission resembles remarkably the mini-halo in RX J1720.1+2638, including the correlation with the cold fronts.

the cold front envelope, as also shown by a comparison of the X-ray and radio surface brightness profiles (Giacintucci et al. 2014b). The observed mini-halo/cold front association has led to the hypothesis that mini-halos are produced by electron reacceleration by sloshing-driven turbulence, coupled with the amplification of the local magnetic field (see simulation in ZuHone et al. 2013; a snapshot of this simulation is reported in Fig. 3b, showing the remarkable resemblance between the simulated synchrotron emission and the mini-halo in RX J1720.1 (b), including the correlation with the X-ray cold fronts).

2. Spectral properties of mini-halos

Despite the theoretical efforts, our knowledge and understanding of the physical properties and origin of mini-halos in cool-core clusters and their relation to the core dynamics is limited by the rarity of mini-halos (there are only ~ 15 confirmed detections, Giacintucci et al. 2014 and references therein) and difficulty in separating the faint mini-halo emission from the often much brighter central radio galaxy (e.g., Govoni et al. 2009). For these reasons, spectral information on mini-halos – an important

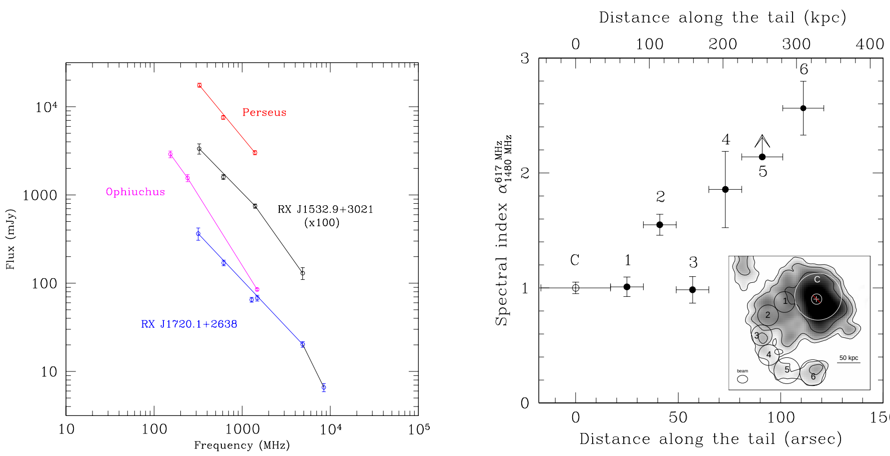

Figure 4. (a) Radio spectra of mini-halos (adapted from Giacintucci et al. 2014a,b). Lines are not fits to the data. (b) Spectral index along the mini-halo in RX J1720.1, computed using the regions shown in the inset (from Giacintucci et al. 2014b).

diagnostics for the origin of the relativistic electrons (Brunetti & Jones 2014) – is very scarse. Until recently, only three integrated spectra were known (Perseus, Ophiuchus and RX J1532.9+3021; Fig. 4a), all consistent with a power law (with $\alpha \sim 1.2$, 1.6 and 1.2, respectively), with hints of a high-frequency steepening in Ophiuchus and RX J1532.9+3021. Such information is not sufficient to differentiate between the models for mini-halos, i.e., a single power-law spectrum predicted by pure secondary models vs. a high-frequency break or cutoff expected in turbulent reacceleration models; obviously, more flux density measurements and a wider frequency interval are needed.

3. New results for the mini-halo in RX J1720.1+2638

A detailed radio spectrum of the mini-halo in RX J1720.1+2638, based on data at six different frequencies between 317 MHz and 8.5 GHz, has been recently obtained by Giacintucci et al. 2014b (also reported in Fig. 4a). This represents the best radio spectral dataset for any mini-halo. The spectrum has a power-law shape with $\alpha = 1$ up to ~ 5 GHz and then it steepens at higher frequencies. A study of the spectral index distribution across the mini-halo revealed that the spectrum of the diffuse emission steepens with increasing distance from the cluster (and mini-halo) center (Fig. 4b). Possible explanations of this steepening that involve relativistic electrons injected in the center and diffusing (or advected) out to the mini-halo periphery are found to be not feasible, as they necessitate implausible high velocities of the gas in the core and/or extreme microphysical conditions (Giacintucci et al. 2014b). The observed steepening, in combination with the high-frequency break in the spectrum, rather favors a turbulent reacceleration interpretation of this mini-halo over other plausible alternatives, such as the secondary models (Giacintucci et al. 2014b).

Future spectral studies of other well-resolved mini-halos will contribute to unveil the origin of the relativistic electrons in cluster cool cores.

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