The GMRT Radio Halo Survey and low frequency follow-up

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Abstract. The GMRT Radio Halo Survey, carried out at 610 MHz to investigate the statistical properties of cluster radio halos in a complete cluster sample selected in the redshift interval $z = 0.2 - 0.4$, has significantly improved our understanding of the origin of cluster radio halos and relics. Here we briefly summarize the most relevant results of our investigation. A low frequency follow-up is in progress with the GMRT at 325 MHz and 240 MHz on the diffuse sources and candidates found at 610 MHz. We briefly report some preliminary results on these low frequency observations. Cluster radio halos with different radio spectral properties have been unexpectedly found.

1. Scientific background of the GMRT Radio Halo Survey

Thermal and non-thermal components co-exist in clusters of galaxies. Beyond the galaxies and the hot intracluster medium, diffuse extended (up and above the Mpc) emission in the form of radio halos and/or relics is known nowadays in a total of ~ 40 clusters, which prove the existence of relativistic particles ($\gamma \gg 1000$) and large scale magnetic fields (with intensity of the order of the $\mu$G). The steep spectrum of these diffuse sources, with $\alpha \sim 1.2 - 1.4$ ($S \propto \nu^{-\alpha}$) is a signature of their synchrotron origin. Radio halos and relics do not have an obvious optical counterpart, and they are not even the result of blending of individual sources, but they rather permeate the cluster volume, similar to the thermal hot gas responsible for the X-ray emission. These two classes of sources share similar observational properties, such as very low surface brightness (of the order of the $\mu$Jy arcsec$^{-2}$) and steep synchrotron spectrum, while they differ in the location within the cluster – radio halos being centrally located, in good coincidence with the ICM, relics being found in peripheral cluster regions – and in their polarization properties, i.e. radio halos are unpolarized while relics show a high degree of fractional polarization (see Feretti 2005 for a review). The longstanding crucial question concerning halos and relics concerns their origin: the radiative life-time of the radiating electrons is much shorter than the diffusion time necessary to cover the cluster scale volumes, therefore their existence requires some form of particle re-acceleration (see Cassano, present volume).

Among the variety of models proposed so far for the formation of giant (Mpc scale) radio halos, the so-called “re-acceleration model”, whereby electrons are re-accelerated in-situ by MHD turbulence injected in the cluster volume by merger events (Brunetti et al. 2001; Petrosian 2001), has received particular attention. Starting from
the re-acceleration model, a number of statistical predictions (based on Montecarlo simulations) were made on the fraction of clusters expected to develop a radio halo as a function of redshift and mass (Cassano & Brunetti 2005; Cassano, Brunetti & Setti 2006, CBS06; Cassano, this volume). Following those predictions, the bulk of giant radio halos is expected in the redshift interval $z = 0.2–0.4$, where $\sim 35\%$ of massive (i.e. $M > 10^{15} M_\odot$) may host one.

The GMRT Radio Halo Survey was designed to test the statistical predictions derived from the re-acceleration model, in particular the fraction of massive clusters hosting a radio halo and its possible connection with the cluster mass, and at a more general level to investigate the link between cluster mergers and the presence of diffuse cluster sources, or lack thereof.

### Table 1. Clusters with the GMRT at low frequency

| Cluster name      | $z$   | Source type         | $S_{610 \text{ MHz}}$ mJy | $\nu$ MHz | Notes |
|-------------------|-------|---------------------|---------------------------|-----------|-------|
| A 209             | 0.2060| Giant Halo          | 24.0±3.6                  | 325       | (a)   |
| A 521             | 0.2475| Relic+Giant halo    | 41.9±2.1                  | 325, 240  | (b)   |
| A 697             | 0.2820| Giant Halo          | 13.0±2.0                  | 325       | (c)   |
| A 781             | 0.2984| Candidate relic     | 32.0±2.0                  | 325       | (d)   |
| A 1682            | 0.2260| Candidate halo      | ~ 44                      | 240       | (d)   |
| A 1300*           | 0.3075| Giant Halo+Relic    | 325                       | (d)       |
| A 2744*           | 0.3066| Giant Halo+Relic    | 325                       | (d)       |
| RXCJ1314.4–2515   | 0.2439| Halo + 2 Relics     | 325, 240                 | (a)       |
| RXCJ2003.5–2323   | 0.3171| Giant Halo          | 96.9±5.0                 | 325, 240  | (c)   |
| Z 2661            | 0.3825| Candidate Halo      | ~ 5.9                    | 325       | (a)   |

Notes: * halos known from the literature; (a) data reduction still in progress; (b) Giacintucci et al. 2008 and Brunetti et al. 2008; (c) imaging and analysis completed; (d) analysis in progress.

### 2. Sample selection and summary of the results

The galaxy cluster sample for our study consists of 50 clusters, selected from the X-ray REFLEX (Böhringer et al. 2004) and eBCS catalogues (Ebeling et al. 1998 and 2000), imposing the following constraints: $L_X (0.1–2.4 \text{ keV}) > 5 \times 10^{44} \text{ erg s}^{-1}$; $0.2 < z < 0.4$; $-30^\circ < \delta < +2.5^\circ$ (REFLEX) and $+15^\circ < \delta < +60^\circ$ (eBCS). A number of the selected clusters had either archival or literature information, with 7 known radio halos. With the GMRT we observed 34/50 clusters, i.e. those lacking high sensitivity imaging.

The whole observational project is described in Venturi et al. 2007 (V07) and 2008 (V08). The observations were carried out at 610 MHz; each cluster was observed for $\sim 2.5–3.5$ hours, for an average noise in the images of the order of $35–100 \mu$Jy beam$^{-1}$, mainly depending on the presence of strong sources in the field.

A number of new diffuse cluster sources (halos, relics and mini-halos) were found, as well as candidates (see next section and Table 1), but the great majority of the observed clusters (25/34) do not host diffuse emission at their centres. This result in itself confirms that radio halos are rare. Inspection of the X-ray properties of the clusters in
the sample allowed us to conclude that: (a) all clusters hosting halos and relics show evidence of strong merger events; (b) clusters with mini-halos have a cooling core; (c) clusters without diffuse emission may be either dynamically active or relaxed. These results are consistent with the expectations of the re-acceleration model.

The results of the GMRT Radio Halo Survey (both detections and upper limits) were combined with the information from the Northern VLA Sky Survey (NVSS) for the clusters in the redshift interval $z = 0–0.2$ (Giovannini et al. 1999), so as to have a picture of the radio halo phenomenon in the large redshift interval $z = 0–0.4$. It was found that galaxy clusters are either “radio loud”, hosting a giant halo whose power correlates with the ICM X-ray luminosity (CBS06), or “radio quiet”, i.e. they do not host diffuse central emission down to a level which is at least one order of magnitude below the log $L_X – \log P_{1.4 \text{GHz}}$ correlation (Brunetti et al. 2007). Moreover, it was quantitatively shown that the fraction of clusters with a giant radio halo increases with increasing cluster mass (X-ray luminosity), at a statistically significant level (Cassano et al. 2008). The X-ray luminosity threshold is $L_X \sim 10^{45}$ erg s$^{-1}$. All the above results are pieces of evidence in favour of the re-acceleration model by turbulence.

3. Low frequency follow-up of diffuse sources in the GMRT cluster sample

Most of the radio halos and relics known to date have been detected and imaged only at 1.4 GHz (i.e. Bacchi et al. 2003; Govoni et al. 2001 and 2004) and very little information is available on their emission properties at frequencies $\nu \leq 325$ MHz. Therefore we started a GMRT low frequency follow-up of the new cluster sources detected at 610 MHz and of the candidates (V07 and V08), and of the radio halos in the sample with literature information. The list of clusters observed and the frequency chosen are reported in Table 1.

Each cluster was observed for 8 hours, recording both upper and lower side bands. The quality of the data is generally good; the $1\sigma$ rms level reached in the images is in the range $0.1–0.5$ mJy beam$^{-1}$, mainly depending on the amount of editing required as consequence of RFI.

3.1. A 521: the first ultrasteep spectrum radio halo

The low frequency observations of A 521, carried out to study the cluster relic (Giacintucci et al. 2008), led to the discovery of a very steep spectrum ($\alpha \sim 2$) giant radio halo at the cluster centre (Brunetti et al. 2008). The existence of radio halos with very steep spectrum is consistent with the re-acceleration scenario in case of less energetic events, which would not be able to provide enough turbulence to re-accelerate electrons at the energies requested to have GHz emitting radio halos (see also the paper by Cassano, this volume). Given that minor mergers are very common in the Universe, we expect that many more ultra steep spectrum radio halos (USSRH) may be found, when searched for with appropriate cluster selection criteria and observing strategies.

3.2. A 697: a candidate USSRH

The faint radio halo visible in this cluster at 610 MHz (V08) has a flux density $S_{325 \text{ MHz}} \sim 45$ mJy, leading to a spectral index $\alpha_{325 \text{ MHz}} \sim 2$. The cluster largest linear size is of the order of the Mpc, and its morphology is in very good agreement with the underlying
X-ray emission. A detailed study of this cluster is in progress (Macario et al. to be submitted).

3.3. A 781: an intriguing diffuse peripheral source

The diffuse source detected at 610 MHz (V08) is much more extended at 325 MHz, reaching a maximum extent in the North–South direction of \( \sim 1 \) Mpc. The total flux density for this source is 80 mJy. The spectral index is \( \alpha_{610 \text{ MHz}} \sim 1.2, \) if the flux density is integrated over the same area. Such value is not in very good agreement with the value \( \alpha_{1.4\text{ GHz}} \sim 0.78 \) reported in V08, and this could be due to different areas used for the total flux density integration. Consistency checks are in progress.

3.4. A 1682: a very complex cluster

Our 240 MHz observations confirm that the radio emission in this cluster is very complex. The left panel of Fig. 1 reports the 240 MHz radio contours overlaid on the VLSS. We confirm that the S–E ridge has a steep spectrum: \( \alpha_{240 \text{ MHz}} \sim 1.4 (S_{240 \text{ MHz}} = 59 \text{ mJy}) \). The analysis of the E tail and of the N–W ridge is in progress. The most remarkable feature in the 240 MHz image of A 1682 is the detection of diffuse emission with a strong counterpart on the VLSS (see Fig. 1). A detailed study is in progress (Cassano et al. in prep.).

3.5. A 1300 and A 2744

Both clusters, known from the literature, host a giant radio halo and a relic. The radio halo in A 1300, shown in the right panel of Fig. 1, has a largest linear extent of \( \sim 1.3 \) Mpc, much larger than inferred in the MOST image published in Reid et al. (1998). The flux density detected in the radio halo and in the relic are respectively \( S_{325 \text{ MHz}} = 290 \text{ mJy} \) and \( S_{325 \text{ MHz}} = 77 \text{ mJy} \). Using the flux density measurements reported in Reid et
al. (1998) for the candidate relic we obtained $\alpha_{325 \text{ MHz}} \sim 1$. No estimate of the spectral index be given for the radio halo.

Thanks to the better sensitivity of our image compared to those in Orrú et al. (2007), the radio halo in A 2744 is larger than previously imaged at 325 MHz, with a largest linear size of the order of 1.5 Mpc. Its total flux density is $S_{325 \text{ MHz}} = 330$ mJy, while for the relic we measured $S_{325 \text{ MHz}} = 122$ mJy.

### 3.6. RXCJ 2003.5−2323

This giant radio halo (largest linear size 1.4 Mpc) was discovered with the GMRT Radio Halo Survey and has been extensively studied in the radio, X-ray and optical band (Giacintucci et al. to be submitted). It is very powerful, with a single power law spectrum with $\alpha_{240 \text{ MHz}} \sim 1.3$. Our multiwavelength study supports the scenario of a merger-driven formation for this giant radio halo.

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