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GMRT 150 MHz follow up of diffuse steep spectrum radio emission in galaxy clusters

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Abstract. It has been recently found that a few galaxy clusters host diffuse radio halo emission with very steep synchrotron spectra ($\alpha > 1.6$), which may be classified as Ultra Steep Spectrum Radio Halos (USSRHs). USSRHs are expected in the turbulence re-acceleration model for the origin of cluster radio halos, and are best discovered and studied at low frequencies. We performed GMRT follow up observations of three galaxy clusters at 150 MHz, selected from the GMRT radio halo survey, which are known to host an USSRH or candidate very steep spectrum diffuse emission. This project is aimed to characterize the low frequency spectrum of USSRHs for a detailed study of their origin and connection with cluster mergers. We present preliminary results at 150 MHz of the cluster A 697.

Key words. Radiation mechanism: non-thermal – Galaxies: clusters: general – Galaxies: clusters: individual: A 697

1. Introduction

Radio halos are diffuse Mpc-scale sources observed at the centre of a fraction of massive galaxy clusters. They have steep synchrotron spectra, with typical spectral index $\alpha \simeq 1.3$-1.4 (in the convention $S \propto \nu^{-\alpha}$). However, recent low frequency observations of a few clusters have revealed the existence of radio halos with much steeper spectra, i.e. $\alpha > 1.6$: A 521 (Brunetti et al. 2008); A 2256 (Brentjens 2008); A 1914 (Bacchi et al. 2003); A 697 (Macario et al. 2010, hereinafter MVB10).

The integrated spectrum of radio halos is a key observable to address the question of their origin. The turbulent re-acceleration model (e.g. Petrosian 2001; Brunetti et al. 2001) provides the unique expectation of spectra much steeper than those found to date, as a consequence of the spectral steepening below GHz frequencies in the spectrum of radio halos generated in less energetic merger events (e.g. Cassano 2009). The detection of radio halos

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with very steep spectrum ($\alpha > 1.6$) would be a major piece of evidence in support of this scenario, and at the same time it would disfavour secondary models (e.g.Blasi & Colafrancesco 1999) for the origin of the emitting electrons which, for the observed steep spectra, requires a very large proton energy budget (e.g.Brunetti 2004). These giant radio halos are best studied at low frequencies, due to their very steep spectrum. Moreover, statistical calculations based on the re-acceleration model predict that their number increases at low frequencies (Cassano et al. 2010).

The prototype of these sources, which we refer to as ultra steep spectrum radio halos (hereinafter USSRH), was discovered in the merging cluster A 521 and has a spectrum with $\alpha \simeq 1.9$ in the frequency range 235-1400 MHz (Brunetti et al. 2008; Dallacasa et al. 2009).

A low frequency follow-up of a few galaxy clusters selected from the GMRT radio halo survey cluster sample (Venturi et al. 2007, 2008) has been recently carried out with the GMRT at 325 and 240 MHz (see Venturi et al. 2009, Giacintucci, this volume; Venturi et al. to be submitted).

An important result of those deep low frequency observations has been the discovery of very steep spectrum diffuse emission at the centre of three clusters. Beyond the USSRH in A 521, another radio halo with very steep spectrum was found in the cluster A 697 (MVB10). Moreover, candidate very steep spectrum radio emission has been found at the centre of A 1682 (Venturi et al. 2008, 2009).

For these three clusters, deep GMRT follow-up observations at 150 MHz were performed, in order to constrain the low frequency end of the spectra of the two USSRH and to carry out an appropriate study of the steep spectrum diffuse emission in A 1682.

2. GMRT 150 MHz observations

In Table 1 we report the main parameters of the GMRT 150 MHz observations. In order to achieve high sensitivity and to ensure an appropriate uv-coverage, each cluster was observed for a total time of 10 hours. All the observations were performed recording only one side-band, in the default spectral line mode, with the 8 MHz band divided into 128 channels, each 62.5 kHz wide.

In this paper we present the data analysis and preliminary images for A 697. Data reduction of the other observations is in progress.

3. The very steep spectrum radio halo in A 697

Abell 697 is a rich and massive cluster at z=0.282. It is hot (kT $\simeq$ 10 keV) and luminous ($L_X \simeq 10^{45}$ erg s^{-1}) in the X-ray band, and is part of the ROSAT Brightest Cluster Sample (BCS; Ebeling et al. 1998).

Observational evidence shows that A 697 is far from dynamical equilibrium: substructures in the galaxy distribution and in the gas have been detected through optical and X–ray analysis (Girardi et al. 2006, MVB10). Also, the absence of a cool core in the cluster was reported (Bauer et al. 2005). These studies suggest that A 697 is in a complex dynamical state, and it is probably undergoing multiple merger/accretion of small clumps (Girardi et al. 2006).

Diffuse radio emission at the centre of A697 was first suggested inspecting the NVSS and WENSS (Kempner & Sarazin 2001). GMRT observations at 610 MHz, as part of the GMRT radio halo survey, allowed to confirm the presence of a giant radio halo.

In MVB10 we studied the spectral properties of the radio halo, by using deep 325 MHz GMRT observations, together with the 610 MHz GMRT data and VLA archival observations at 1.4 GHz. Our multifrequency analysis showed that the integrated radio spectrum of the halo is very steep, with $\alpha_{325\ \mathrm{MHz}}^{1.4\ \mathrm{GHz}} \approx 1.7-1.8$.

4. Data reduction and preliminary results at 150 MHz

The 150 MHz dataset of A 697 was reduced and analysed using the NRAO Astronomical Image Package (AIPS). Sources 3C 147 and 3C 286 were observed at the beginning and the the end of the observing run, respectively, and were used as flux density and bandpass calibrators. The source 0735+331 was used as

Table 1. Summary of GMRT 150 MHz observations

Cluster name	RA_J2000	DEC_J2000	z	Obs. Date	ν (MHz)	$\Delta\nu$ (MHz)	Obs. time (hours)
A 0521	04 54 09.1	-10 14 19	0.2475	2009, Aug 16	151	8	10
A 1682	13 06 49.7	+46 32 59	0.2260	2009, Aug 17	151	8	10
A 0697	08 42 53.3	+36 20 12	0.2820	2009, Aug 30	151	8	10

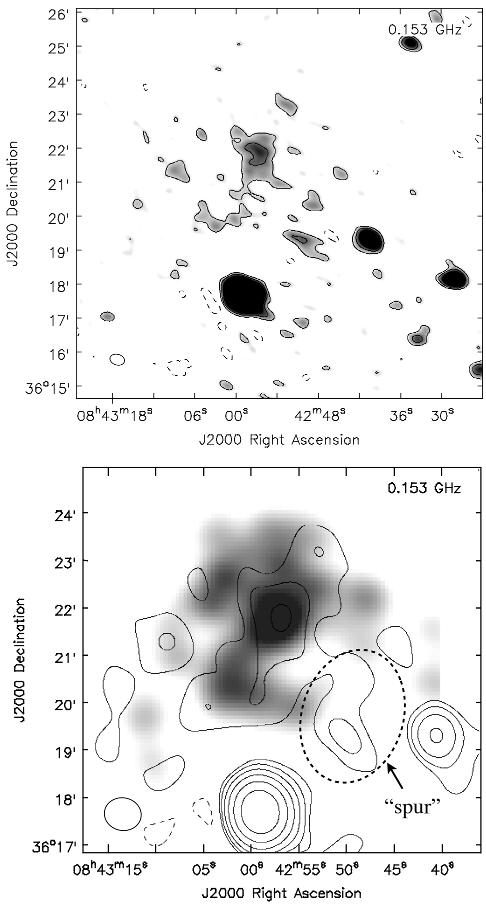

Fig. 1. *Top panel* GMRT 150 MHz image of the central field of A 697. The resolution is ~ 26″ × 19″. Contours are spaced by a factor 2, starting from ±3 σ level (i.e. ~ 3 mJy b^{-1}). *Bottom panel* GMRT 150 MHz contours of the radio halo in A697, overlaid on the GMRT 325 MHz image (grey scale); the two images has the same restoring beam (~ 47″ × 41″). Contours starts from ±2.5 σ level (i.e. ~ 5 mJy b^{-1}), and are spaced by a factor 2.

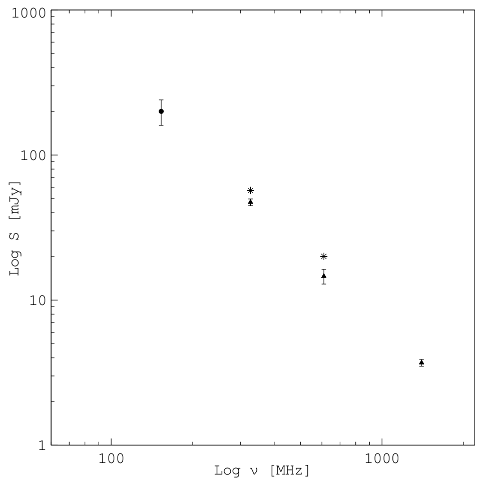

Fig. 2. Integrated radio spectrum of the halo. The flux density values at 325, 610 and 1400 MHz (triangles and stars) are from MVB10; the circle is the preliminary value at 150 MHz. The errorbar represents the upper and lower values given in the text (see Sect. 4).

phase calibrator. We applied a standard calibration procedure to the data. Data were affected by strong radio frequency interference (RFI), which was removed semi-automatically.

In each stage of self-calibration, we used the wide field imaging technique, to minimize the effect of non coplanar baselines. We covered a field of view of ~5×5 square degrees, with 121 facets (each wide ~0.6°). This allowed to remove the sidelobes of strong sources far away from the field centre, outside the GMRT primary beam (~3°). A few rounds of phase-only self-caibration were performed, and further editing of bad data was needed.

Preliminary clean images were then produced. The 1σ rms level reached in the full resolution image is in the range 0.8-1 mJy b^{-1}. However, the presence of strong point sources in the field limits the dynamic range around them. The uncertainty in the calibration of the absolute flux density scale is ~ 15%.

The top panel of Fig. 1 shows the preliminary full resolution (~ 26″ × 19″) contours of the central 12′×12′ region centered on A 697 (~ 3 × 3 Mpc^2, i.e. about the half cluster virial radius; see MVB10). The rms level in the image is 1 mJy b^{-1}. The diffuse radio emission associated with the radio halo is clearly visible around the cluster centre.

In the bottom panel of Fig. 1, a low resolution image of the radio halo is shown as contours (starting from $\pm 2.5\sigma$ = 5 mJy b^{-1}). This is overlaid to the 325 MHz GMRT image (in grey scale), obtained after the subtraction of discrete radio sources (same as in Fig. 2 of MVB10). The two images has the same angular resolution (~ 47″ × 41″). The radio halo at 150 MHz is mainly elongated in the South-East/North-West direction. Moreover, positive residuals of emission indicate an extension in the East-West direction. It is very extended, with largest linear size of ~1.3-1.4 Mpc. Compared to the 325 MHz image, the halo has a similar morphology in the central ~ 1 arcmin, and also shows a similar feature in the southern part. However, an accurate comparison requires subtraction of the discrete sources at the cluster centre. This procedure is in progress.

Although the image is preliminary, and further work is necessary to improve its quality, an estimate of the flux density of the halo at 150 MHz can be given. The contribution of discrete sources embedded into the diffuse halo emission (sources A, D, G in MVB10) is estimated to be ~ 20 mJy at this frequency. This value was subtracted from the total flux density measured by integrating the low resolution image over the halo region. Thus we obtain S_{150MHz} ~ 165-240, depending on whether or not we include the contribution of the south-western "spur" (see Fig. 1). A mean value between these two is reported in Fig. 2, where the integrated spectrum of the halo is shown (same as in MVB10). It is consistent with a steep spectral index $\alpha \sim 1.7$.

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