

## Diffuse bubble-like radio-halo emission in MRC 0116+111: Imprint of AGN feedback in a distant cluster of galaxies

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**Abstract.** We report the discovery of a luminous, mini radio halo of  $\sim 240$  kpc dimension at the center of a distant cluster of galaxies at redshift  $z = 0.131$ . Our optical and multi-wavelength GMRT and VLA observations reveal a highly unusual structure showing a twin bubble-like diffuse radio halo surrounding a cluster of bright elliptical galaxies; very similar to the large-scale radio structure of M87, the dominant galaxy in Virgo cluster. It presents an excellent opportunity to understand the energetics and the dynamical evolution of such radio jet inflated plasma bubbles in the hot cluster atmosphere.

### 1. Introduction

Recent X-ray observations with *Chandra* and *XMM-Newton* have revealed a surprising aspect of cooling flows in clusters; they showed far less cooling below X-ray temperatures than expected, altering the previously accepted picture of cooling flows (Peterson & Fabian 2006). Unless gas is thermally supported, radiative cooling leads to a ‘cooling catastrophe’, i.e. inexorable inflow of cold gas onto the central galaxy. To prevent this, some heating mechanism was required to raise gas temperature above  $\sim 2$  keV, suppressing the cooling flow. Although several such mechanisms were discussed, the most effective heating process is the energy injected into the intra-cluster medium (ICM) by radio jets from AGNs of central galaxies of clusters and groups (Binney & Tabor 1995; Churazov et al. 2001). Almost all cool-core clusters harbour powerful central AGNs (Burns 1990) which suggests that they are fuelled by accretion of cooling gas (Bagchi & Kapahi 1994; Allen et al. 2006), with the flow rate itself regulated by AGN-heating (Churazov et al. 2001). Many details of how this AGN-ICM feedback process works are still far from clear. Radio jets from a central AGN would inflate two bubble-like lobes of non-thermal plasma, filled with relativistic particles and magnetic field, and thus become visible in radio observations (Gull & Northover 1973). Such non-thermal bubbles are visible in radio and X-ray observations; such as those in clusters MS0735.6+7421, Hydra-A, and others,

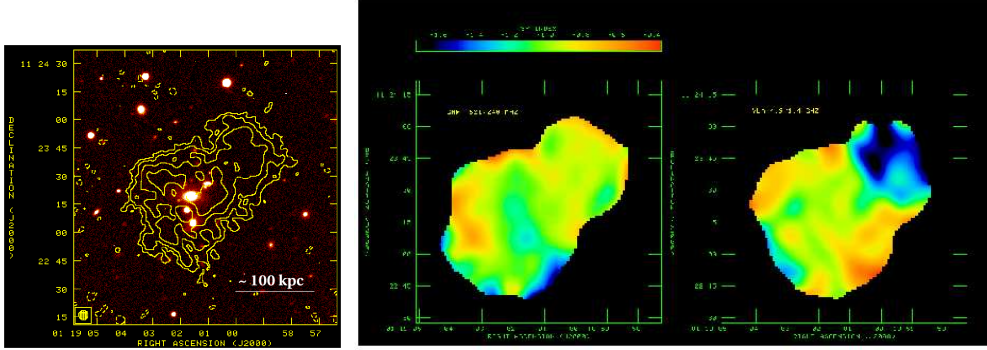


Figure 1. **left:** GMRT 1.28 GHz map of MRC 0116+111 (contour levels:  $\pm 0.24, 0.48, 0.96, 2, 4, 8$  mJy/beam, beam FWHM:  $5''$  circular) overlaid on IGO R-band image. No AGN (radio core) is visible down to  $\sim 1$  mJy/beam flux density limit, and no radio jets or lobes are detectable. **right:** Low and high frequency spectral index maps of MRC 0116+111 from combining the GMRT maps at 240 and 621 MHz (on left) and VLA maps at 1425 and 4860 MHz (on right). Both pairs of maps have the matched resolution of  $12''$  (FWHM). Only pixels  $\sim 3.5$  times above the noise level were included by giving cut-offs at values 4 mJy/beam, 0.5 mJy/beam, 0.27 mJy/beam and 0.15 mJy/beam on 240, 621, 1425 and 4860 MHz maps respectively.

showing an unusually large and energetic pair of radio emitting, X-ray dark cavities (e.g., McNamara et al. (2000, 2005); McNamara and Nulsen (2007)). These synchrotron plasma bubbles are responsible for the mechanical (PdV) work on the ICM for heating it, which is one of the suggested mechanism of AGN-ICM feedback. Therefore, observations of bubble-like, diffuse radio sources near cluster centres can provide crucial data for understanding this important astrophysical process.

## 2. Optical & radio observations: physical picture of the source

An early report on a diffuse radio source MRC 0116+111 matching the characteristics of a mini-halo, was presented by some of us, based on VLA and GMRT observations (Gopal-Krishna et al. 2002). Recently, a distant galaxy cluster was reported at the position of MRC 0116+111 (Lopes et al. 2004). Here we report higher sensitivity GMRT observations made at 1.28 GHz, 621 MHz and 240 MHz frequencies using the 128 channel FX correlator. The earlier VLA observations made in C-band (DnC array) and L-band (CnB array) have been reanalysed. Optical broadband ( $B, V, R, I$ ) CCD imaging observations were taken with IFOSC on the 2 mt telescope at the IUCAA Girawali Observatory (IGO). For spectroscopy we used the ESO 3.6 mt New Technology Telescope (NTT) and EMMI (ESO Multi-Mode Instrument). A low resolution slit-spectrum was taken with the grism-3 optics on the EMMI (December 1998) which gave a redshift  $z = 0.1316$  for the brightest central cD galaxy and  $z = 0.1309$  for the second brightest elliptical galaxy  $\sim 15''$  south of cD (Gopal-Krishna et al. 2002).

A radio-optical overlay of GMRT 1.28 GHz radio map and optical CCD image of MRC 0116+111 (Fig. 1) shows a highly diffuse ‘halo’ or ‘bubble’ like

structure which bears close resemblance to so-called ‘radio mini-halos’ (RMH). Mini-halos are  $\sim 100$  kpc scale, low surface brightness amorphous radio sources with a steep spectral index ( $\alpha \lesssim -1$ ,  $S_\nu \propto \nu^\alpha$ ), which are rare objects and found around powerful AGNs at the center of cooling-core clusters (Ferrari et al. 2008). The 1.4 GHz radio luminosity of MRC 0116+111,  $L_{1.4\text{GHz}} = 4.57 \times 10^{24}$  W/Hz, is quite large, comparable to the luminous radio-halos in Perseus and A2390 clusters (Pedlar 1990; Cassano, Gitti and Brunetti 2008). Its bolometric radio luminosity (over 10 MHz - 10 GHz range),  $L_{\text{radio}} = 3.64 \times 10^{34}$  W, would place it amongst the most luminous radio halos known.

Integrated spectrum of MRC 0116+111 shows a ‘break’ near 400 MHz, after which it attains a power-law slope  $\alpha = -1.35$  (Bagchi et al. 2009), signifying an ongoing particle injection, even though no radio core is detected down to 1 mJy level. Spectral index maps show that between 240 and 621 MHz the spectral index distribution is fairly uniform ( $\alpha_{\text{mean}} \approx -1$ ) with no strong steepening or gradients across the source, showing a lack of strong radiative losses at these frequencies (Fig. 1 center panel). However, the high frequency spectral index map between 1.4 and 4.8 GHz shows a very different picture (Fig. 1 right panel). While the south-eastern bubble (Fig. 2) still has the same average spectral index value around -1 ( $\alpha_{\text{mean}} = -1.06 \pm 0.15$ ) - implying a straight synchrotron spectrum between low and high radio frequencies - the north-west bubble, in contrast has developed an extremely steep spectrum ( $\alpha_{\text{mean}} = -1.6 \pm 0.20$ ), suggestive of strong radiative energy loss in this part of the source.

Such a situation might be explained if we assume that the very steep spectrum north-western bubble is buoyantly rising away and then detaching itself from a centrally located mechanism of energy injection, while this source or mechanism is still active and possibly injecting relativistic particles into the flatter spectrum south-eastern bubble. One possibility is AGN activity, though we fail to detect a radio core or jets (Fig. 1). Based on a sample of 5-6 mini haloes, Gitti et al. (2004) have reported a positive correlation between the radio power of the mini-halo and the cooling flow power. From this and because of their estimate of the lifetimes of the radiating electrons falling considerably short of the diffusion time scale, they have inferred that in mini-haloes the cooling flow (through the compressional work done on the ICM and the frozen-in magnetic field) energizes the particle acceleration process through magnetoplasma turbulence acting on relic electron population probably left behind by the past episodes of AGN activity. An alternative proposal is that the radiating electrons in the mini-halos are of secondary origin, created in proton-proton collisions (Pfrommer & Ensslin 2004).

### 3. Remarkable morphological similarity with M87 (Virgo A)

Figure. 2 compares the GMRT 621 MHz radio map with the deep VLA 90 cm image of M87 (Owen, Eilek & Kassim 2000), revealing striking morphological similarities. M87 shows extensive diffuse outer structure extending upto  $\sim 40$  kpc from the nucleus. Two collimated flows emerge from the inner-jet region, one directed north-eastward and the other oppositely directed to the south-west (orientation as shown in the rotated image, Fig. 2). The south-west flow ends in a well-defined pair of edge-brightened torus-like vortex rings. The north-eastern

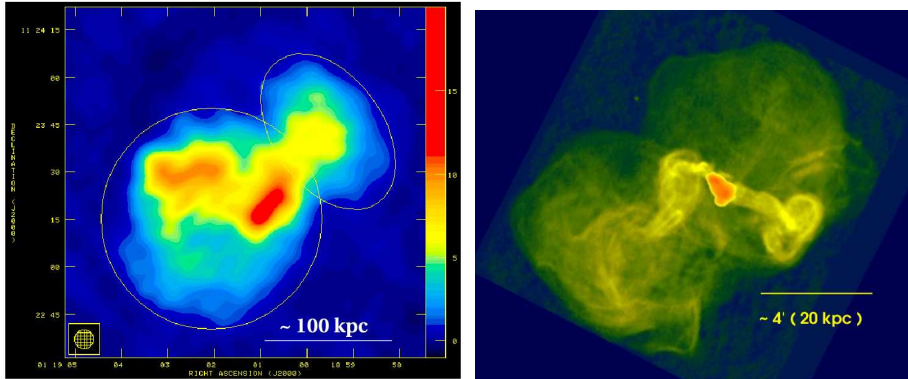


Figure 2. **left:** GMRT 621 MHz grey-scale map of MRC 0116+111 (beam:  $6''$  circular) showing diffuse radio-halo emission and twin bubble-like plasma structures which are delineated by dotted lines. **right:** VLA 90 cm radio image of M87 in Virgo cluster (from Owen, Eilek & Kassim (2000), reflected and rotated by us). A remarkable morphological similarity can be seen in both with twin bubble structures and similar internal outflow patterns.

flow develops a gradual but well-defined S-shaped southward twist, starting only a few kiloparsecs beyond the inner lobes. Finally, both flows are immersed in a pair of giant overlapping radio ‘bubbles’, each extending about 40 kpc from the nucleus. After entering the outer lobes, the flows gradually disperse, filling the entire halo with radio-loud, filamented plasma.

We observe similar flow pattern in the central region of MRC 0116+111: an edge brightened torus-like ‘mushroom’ structure about 40 kpc west of the center, analogous to the peculiar ‘ear-shaped’ vortex structure of M87. Here the flow pattern sharply turns northward and appear to be flowing into the smaller radio bubble to the north-west. We observe an S-shaped flow pattern to the east north-east of the center, which further bends southward, and thus clearly resembles the filamentary structure visible in the southern bubble of M87 (Fig. 2). Both these radio sources are surrounded by a pair of radio emitting ‘bubble’ like lobes. The similarity of large scale radio outflow structures indicates that both sources might have originated in, and their evolution governed by, similar physical process and conditions prevailing in the central regions of their host clusters. Hydrodynamic simulation of Churazov et al. (2001) suggests that twin bubbles in M87 are buoyant bubbles of cosmic rays, inflated by jets launched during an earlier nuclear active phase of the central galaxy, which rise through the cooling gas at roughly half the sound speed. As shown above (section 2), detection of a  $\sim 100$  kpc scale very steep-spectrum radio bubble north-west of center of MRC 0116+111 strongly supports this model. The flattened ‘mushroom’ shape of this plasma bubble resembles a rapidly rising vortex-ring (Fig. 2) into which an initially spherical bubble will naturally transform due to viscosity and drag forces (Gull & Northover 1973; Churazov et al. 2001). Interestingly, at  $\sim 240$  kpc MRC 0116+111 is about three times larger than M87 ( $\sim 80$  kpc; Owen, Eilek & Kassim (2000)). The bolometric radio luminosity of both is about the same,  $L_{\text{radio}} = 3.6 \times 10^{34}$  W, implying that average volume emissivity of MRC 0116+111 is roughly factor 30 times smaller than that of M87.

#### 4. Summary & future directions

We have presented radio and optical observations of MRC 0116+111 showing that it is a  $\sim 240$  kpc scale radio mini-halo source in which huge radio bubbles have been blown by a central AGN, and which are possibly rising buoyantly in the hot atmosphere of a cluster. Such plasma bubbles are precursors of the giant X-ray dark cavities observed in several clusters. A remarkable morphological similarity with radio structure of M87 is found both in twin bubble-like structures and internal flow patterns, suggesting a common origin. The lack of an X-ray image of the present cluster prohibits us from quantifying the energy input rate by the AGN as well as the dynamics of the mini-halo. This gap is in the process of being bridged. Future X-ray imaging with *XMM-Newton* or *Chandra* will probe the intracluster medium, look for a cooling-core and search for signs of radio plasma-ICM interaction: such as X-ray dark cavities, bright filaments and shock heating. Detection of giant cavities will allow calorimetry for estimating the energy injected into the cooling gas by the rising bubbles. It seems also feasible to search for non-thermal inverse-Compton X-ray emission of radio bubbles from lower energy electrons (with Lorentz factor  $\gamma \sim 600 - 3000$ ) up-scattering the CMB photons. Combination of the observed non-thermal X-ray and radio fluxes will determine the volume averaged magnetic field of intra-cluster medium in cluster core, which is currently unknown.

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