The content of giant cavities in the IGM of galaxy clusters

ABSTRACT

X-ray images of the cores of massive clusters of galaxies have revealed giant cavities and shock fronts in the hot gas, revealing evidence of energy injection from active nuclei of the central galaxies. How the energy is injection in the intergalactic medium (IGM) via radio jets and how this energy is converted to heat is poorly understood, and is crucial to the understanding of galaxy evolution. It is interesting to note that though excellent Chandra X-ray observations exist for a number of these systems, comparable radio observations, which are vital to this study, are absent. We propose to observe five clusters of galaxies that have excellent X-ray observations (3 in Cycle 16, 2 in Cycle 17) at 3 GMRT frequencies (150, 240 & 610 MHz), which, together with extant higher frequency VLA data, will reveal the content of these cavities, the extent of radio plasma and its relation to the cavities and shock features in the X-ray gas.

1. Scientific Justification

The origin and composition of extragalactic radio jets has remained enigmatic since their discovery more than a half century ago. By virtue of their synchrotron emission, we know that they are in part composed of relativistic electrons and magnetic fields. Theoretical models of jets (Scheuer 1974; Begelman, Blandford, Rees 1984) have shown that their energetics are dominated not by photons, but rather by mechanical energy. However, the ratio of mechanical energy to synchrotron energy (radiative efficiency) which provides a strong clue to their composition cannot be determined by radio observations alone. Further clues emerge form X-ray observations of the intergalactic medium surrounding these galaxies. X-ay images of the hot inter-galactic medium (IGM) of galaxies and clusters have revealed giant cavities, measuring a few to more than 200 kpc across embedded in their halos. The commonness and variety of bubbles, cavities, and edges observed both in the radio and in X-rays in groups and clusters provides direct evidence of the widespread presence of AGN-driven phenomena (see, e.g., McNamara and Nulsen 2007 for a general discussion of the field; Fabian et al. 2003, Perseus; Nulsen et al. 2005 for shock heating in Hydra; Birzan et al. 2004 for a survey of cavities in clusters and groups).

The pV work required to inflate these cavities, which can be measured in a straightforward way in Chandra observations, gives a measure of the total energy released during a radio outburst. Coupling this with the ages of the cavities based on the well justified assumption of buoyancy and in many cases the ages of shock fronts associated with the cavities, provides a direct measurement (lower limit) of their total mechanical energy and mean jet power. Combining the total energy measurements from X-ray observations with synchrotron power measurements over a broad frequency range is can be used to place interesting limits on the ratio (k) of energy flux carried by protons or other massive particles to that in electrons.

Using samples of central cluster galaxies harbouring prominent cavity systems filled with radio emission, Dunn, Fabian, and Taylor (2005) and Birzan et al. (2008) have shown that on average $k \gg 1$, and in some cases k exceeds several thousand. This implies that the energy flux in jets is dominated by protons, presumably either launched at the base of the jet or entrained from surrounding material as the jet advanced through the IGM. A dramatically different interpretation by Diehl et al (2008) suggest that the distribution of cavities in clusters is consistent with current-dominated, MHD jets. However, none of these studies were based on radio observations below 1.4 GHz (some have shallow VLA 320 MHz observations), which are crucial for understanding the content of radio sources.

Birzan et al. (2008) and Wise et al. (2007) have shown from low frequency radio observations that radio-emitting plasma completely fills X-ray cavities in some systems. When coupled with X-ray observations, low frequency radio observations provide the best tracer to the total energy output of radio jets. Observations below 300 MHz are crucial because they probe the possible existence of a faint, yet energetically important population of electrons that can only be probed below 300 MHz. Earlier estimates of k required extrapolating the synchrotron spectrum below 320 MHz to 10 MHz based on spectral fits anchored at 320 MHz, 1.4 GHz, and 8 GHz, yielding large uncertainties in k (factors of tens).

However, in the aggregate, $k \gg 1$, with values varying from close to unity to several thousand. The proposed observations of clusters with the best jet cavity power measurements from X-ray observations will provide the best constraints available on k, and thus the content of extragalactic radio sources.

Low frequency radio observations will be absolutely crucial in resolving the issue of the content of these cavities, because they are most sensitive to the history of AGN activity over timescales $> 10^8$ yr, while high frequency observations are sensitive to the instantaneous jet power. The GMRT is uniquely placed to address this question, as can be seen in a composite X-ray and radio image of Hydra A, which is shown in Fig. 1 (Wise et al. 2007, ApJ, 659, 1153). Low frequency 320 MHz emission fills the enormous (100-200 kpc across), older ($\sim 10^8$ yr), and more energetic $\sim 10^{61}$ erg cavities, while the 1.4 GHz emission fills the smaller ($\sim$ 20 kpc across), younger (10^7 yr), less energetic ($\sim 10^{59}$ erg) cavities. Thus low frequency radio studies have the potential to detect and evaluate faint, large scale cavity systems of enormous power that might otherwise go undetected in X-ray and high frequency radio observations. Very low frequency radio observations are at the frontier of AGN feedback studies and they will provide crucial clues to the nature of the particles or fields that carry the bulk of the momentum and energy of extragalactic radio sources on large scales.

2. Observing plan

We have chosen 5 targets from the sample of Birzan et al. (2008), which are clusters that exhibit the best evidence of cavities in Chandra observations, and evidence of higher frequency VLA observations of radio-emitting plasma filling these cavities. Both MS0735 and A2052 have been awarded >500 ks of Chandra observations to us and our collaborators. the others too have excellent Chandra observations which we have analysed. *These, together with the Perseus cluster, form the best sample from which the issue of the content of cavities can be addressed.*

We propose to observe these clusters at 610/240 MHz (dual frequency) and at 150 MHz to obtain detailed spectral index maps of the radio emission interacting with the hot IGM. For each observation, we ask for a full synthesis of 8 or 9 hours (according to availability of source) to allow adequate u-v coverage for detailed mapping. All short spacings are important since we wish to map extended emission occupying a significant fraction of the field. Our previous experience with observations of groups (e.g. 13SGa01) informs us that the integration times will be adequate to reach flux densities of 0.3 mJy/b at 240 and 610 MHz.

We propose to extend our observations to the lowest available frequency, 150 MHz, motivated by the following considerations:
(1) Broad frequency coverage is essential for the preparation of a useful set of spectral index maps and the reliable interpretation of the radio spectrum; and
(2) The lowest frequencies are needed to show the fullest history of AGN activity, as they show the oldest electron populations, and accordingly often have the greatest spatial extent. In the past, observations at 150 MHz have been limited by nearly-prohibitive RFI. We have recently been encouraged by early tests of an innovative RFI mitigation approach (Athreya 2008), which on an observation of NGC 7626 at 150 MHz has shown remarkable improvements, with sensitivity of 0.5 mJy/beam and a dynamic range of 10^4 (Fig. 4), a factor of 10 better than normally obtained even at higher frequencies and important to many of our observations which contain strong point sources in the field. (The new technique should provide substantial assistance also at 235 MHz.) In addition to furthering the goals of this proposal, the results of our trials with low-frequency RFI mitigation are likely to benefit numerous other observers. The proposed observations represent the first exploration of which we are aware of a broad sample of radio galaxies at this low a frequency, with high angular resolution and sensitivity.

A total of 52 hours is requested.

Table 1. Project source list (Cycles 16 plus 17).

Source	RA_{J2000}	DEC_{J2000}	z
Abell 2052	15 16 45.5	+07 00 01	0.0355
Abell 1835	14 01 02.0	+02 51 32	0.2532
Abell 2597	23 25 18.0	-12 06 30	0.0852
MS0735.6+742	07 41 44.47	74 14 38.10	0.216
Hydra A	09 18 05.7	-12 05 44	0.0549

We request night time observations- so we propose to observe the first three targets in Cycle 16, and the other two in the next Cycle.

3. Status report on earlier proposals: 10SGa01, 12SGa01, 13SGa01, and 14SGa01

Two of us (Raychaudhury, Athreya) have been involved in a survey of feedback in groups of galaxies. The first paper, on AWM 4, from these observations has been published, and a copy is included with this proposal. Since the advent of X-ray data of high quality from XMM, this apparently relaxed group has been puzzling in showing no cooling core, but strong temperature and abundance substructure not reflected in the X-ray intensity maps; arguably we are observing a system reheated by AGN activity (O'Sullivan et al 2005). GMRT data now grant us a new and detailed look into the process: we determine that the radio structure – which we map with high fidelity at three frequencies – is nearly in the plane of the sky, measure the galaxy motion with respect to the surrounding medium, estimate significant physical parameters of the radio source, produce spectral index maps that show a smooth progression of electron aging moving out from the AGN, and determine the source age. The level of detail at which this remarkable source can be understood is indicative of both the strength of the radio and X-ray instrumentation and the scientific synergy obtained from employing them jointly. We have early indications that quite a number of the other sources on our target list will prove equally valuable.

Results from our earlier GMRT proposals have been presented at the following conferences:
(1) "SESTO 2007-Tracing Cosmic Evolution with Clusters of Galaxies: Six Years Later" June 25-29, 2007.
(2) Eight Years of Science with Chandra, October 2007, Huntsville, AL.
(3) American Astronomical Society, HEAD meeting, March 2008, Los Angeles, CA.
(4) "Radio Galaxies in the Chandra Era" July 8-11, 2008, Cambridge, MA.
(5) A summary of our recent results and approaches has been presented in talks at the recent Low Frequency Radio Universe conference (December 2008, Pune, India) by Raychaudhury.

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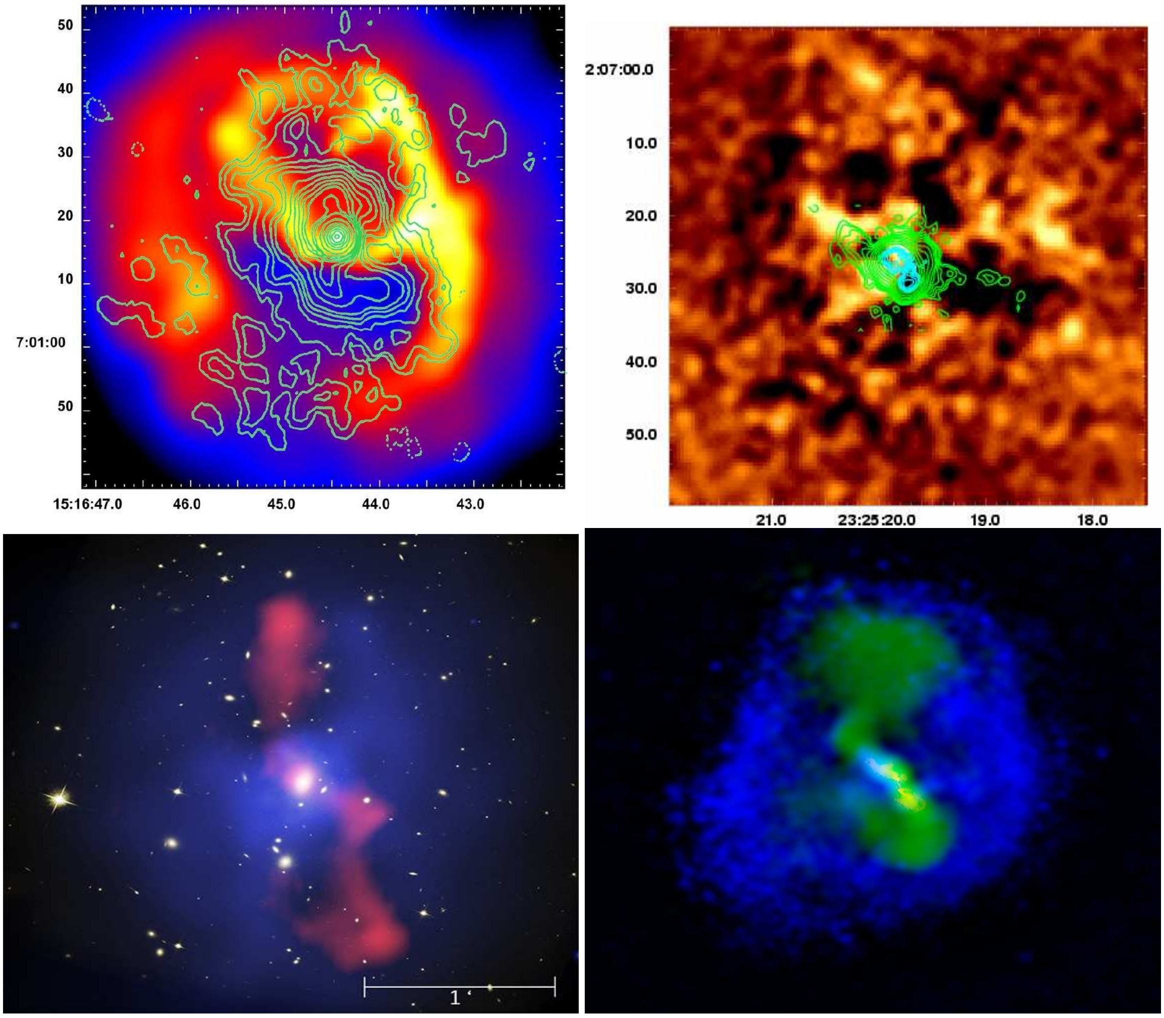

Figure 1: Four clusters from our sample. We propose to observe the top 2 (plus another) in Cycle 16 and the bottom two in Cycle 17 (for night time observations).

(upper left). Adaptive smoothed Chandra X-ray image of the core of the cluster Abell 2052, with 1.4 GHz VLA FIRST survey contours superposed (Blanton et al. 2003). The radio emission seems to fill the inner cavities and extensions go into the apparent cavities to the NW and SE of the cluster centre (latter is better seen in the unpublished Cycle 6 observations). This cluster has been awarded a 500 Ms observation, which will yield a 3 times deeper X-ray image, in the current Chandra cycle.

(upper right). Chandra X-ray image of cluster Abell 2597 (residual with smoothed cluster removed), shown with VLA 1.3 GHz contours in green and 5 GHz in cyan, reveals two large ghost cavities (dark) coinciding with extension seen in the radio images. At GMRT low fruwncies, the true extent of the radio plasma in the cavities will be revealed. (Clarke et al. 2005)

(lower left). HST optical image of the MS0735.6+7421 cluster superposed with the Chandra X-ray image (blue) and VLA 330 MHz radio image (red) shows an enormous pair of cavities, each roughly 200 kpc in diameter filled with radio-emitting plasma. The radio jets inflating the cavities for 10^8 yr have an average power of $\sim 10^{46}$ erg/s. The cavities are well outside the central galaxy. the supermassive BH grew by at leaast $3 \times 10^8\, M_\odot$ during this outburst. (McNamara et al. 2005 Nature, 433, 45, McNamara et al. 2008, arXiv:0811.3020).

(lower right). Composite colour image of the Hydra A cluster that illustrates the close connection between the observed X-ray cavity system (Chandra, blue) and the VLA 330 MHz (green) and 1.4 Ghz (yellow) radio emission. (Wise et al. 2007)