The power and particle content of extragalactic radio sources in clusters (Part II)

ABSTRACT: X-ray images of galaxies and clusters of galaxies have revealed giant cavities and shock fronts embedded in their X-ray halos. These structures, which are associated with radio sources emanating from the central galaxies, provide a gauge of the total mechanical energy and injection timescales of active galactic nuclei (AGN). How the energy is deposited and heats the gas surrounding the jets and lobes are poorly understood. The solution to these problems is crucial to understanding feedback and galaxy and cluster evolution over cosmic time. Excellent Chandra X-ray observations exist for all of our proposed systems. However, low frequency radio observations of comparable quality, which are vital to this study, are unavailable. We propose to observe 21 clusters of galaxies, 3 in Cycle 16 (done), 5 in Cycle 17 (done), and 5 more in Cycle 18 (rest in 19 and 20), at 3 GMRT frequencies (150, 240 & 610 MHz). The GMRT observations taken together with existing higher frequency VLA data will reveal the content of X-ray cavities, the extent of radio plasma and its relation to the cavities and shock features in the X-ray gas, and will provide the most accurate measurement available of the relationship between jet power and synchrotron power at low frequencies. It will also help us determine the relationship between synchrotron power and jet mechanical power. Finally, this will yield an unprecedented legacy dataset (3 frequencies, full synthesis) for many of the best-studied clusters of galaxies that will benefit all users of the GMRT archives, and for multiwavelength studies involving the Virtual Observatory.

1. Scientific Justification

The understanding of the origin and composition of extragalactic radio jets has remained elusive since their discovery more than a half century ago. Synchrotron emission at radio frequencies probes the relativistic electron and magnetic field content of radio jets and lobes. However, theoretical jet models (Scheuer 1974; Begelman, Blandford & Rees 1984) have shown that the energetics of radio sources are dominated not by radiation but by mechanical energy. Whether the mechanical energy is carried in the form of electrons, protons, positrons, Poynting flux, etc., or some combination of these is unknown. Radio observations do not provide a measurement of the total energy emerging from an AGN. Therefore, the total power and content of extragalactic radio sources cannot be determined from radio observation alone.

X-ray images of clusters and galaxies have revealed giant cavities and shock fronts embedded in their hot halos measuring a few to more than 200 kpc across. X-ray observations provide direct evidence of AGN-driven structure and the mechanical power associated with it (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 A; Birzan et al. 2004 for a survey of cavities in clusters and groups).

The pV work required to inflate X-ray cavities, which is measured straightforwardly using Chandra observations, provides a direct and reliable estimate of the total energy released during a radio outburst. The mean jet power can be found using the ages of cavities based on the (generally well justified) assumption that their dynamics are dominated by buoyancy, and in some instances, using the Mach number and radial extent of their associated shock fronts. The jet power measurements, combined with synchrotron power measurements over a broad frequency range, are able to place interesting limits on the ratio (k) of energy flux carried by protons or other massive particles to that carried by electrons. The ratio of mechanical jet power to synchrotron luminosity shown in the plot of these quantities (Figure 1) provides a measure of their radiative efficiency. Figure 1 shows that the radiative efficiency of radio sources in clusters, groups, and elliptical galaxies ranges between a few and several thousand. Evidently, even weak radio sources can be mechanically powerful and thus profoundly influence their surroundings.

Using samples of central cluster galaxies harbouring prominent cavity systems filled with radio emission, it has been shown (Dunn, Fabian, and Taylor 2005, De Young 2006, Birzan et al. 2008) 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) suggests that the distribution of cavities in clusters is consistent with current-dominated, MHD jets. However, these studies, if at all, primarily make use of VLA observations

$\geq$320 MHz, rather than lower frequencies which are crucial for understanding the content of radio sources and the relationship between mechanical power and low frequency radio power.

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). 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.

The second but related goal of this large proposal is to determine the relationship between radio synchrotron power at low frequencies and the mechanical power of the jets (e.g. Merloni & Heinz 2007). Birzan et al. (2008) found a relationship scaling as $P_{\rm jet} \propto L_{\rm radio}^{\beta}$, where β is ~ 0.35 at 1.4 GHz but steepens to ~ 0.6 at 320 MHz (e.g., Fig. 1). Thus the dependence of jet power on radio power is a strong function of frequency. Low frequency radio observations are crucial in nailing down a reliable relationship between these quantities because they are most sensitive to the history of AGN activity over timescales $> 10^8$ yr. High frequency observations are most sensitive to the instantaneous jet power, which changes rapidly with time, giving rise to much of the observed scatter (Birzan et al. 2008). Establishing the low frequency relationship using GMRT and Chandra data will lay the foundation for future studies of galaxy evolution and feedback.

The most powerful applications will come with new wide field, low frequency radio (eg., GMRT, LOFAR) and optical (eg., Sloan II, LSST) surveys of clusters and galaxies over large volumes of space and time. X-ray observations with existing and planned facilities are unable to probe the environments of galaxies and clusters at high resolution beyond $z \sim 1$. X-ray observations are unable to detect jet-induced cavities and shock fronts in distant systems. However, radio observations are able to detect galaxies throughout the observable universe. The GMRT-based jet power–radio luminosity relation will eventually be used to evaluate the mechanical contribution to jet power in distant galaxies. This important relation will provide the fundamental basis for understanding the role of AGN feedback during the growth of galaxies and supermassive black holes, the growth of clusters of galaxies and their hot halos, and the development of large scale structure. An example of how such a relationship may be applied is given in Best et al. (2006), who used the early 1.4 GHz relation of Birzan et al. (2004, in which many of us were involved) to probe feedback in Sloan survey galaxies.

The GMRT is uniquely placed to address these questions, as can be seen in a composite X-ray and radio image of Hydra A, which is shown in Fig. 2 (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.

The need for a large and varied sample: Finally, even though a handful of systems have been studied in detail, we emphasize the need for a varied sample for this systematic study. To begin with, in a single system, the value of k and the radiative efficiency can be different from a general trend, since several conditions like the age of the source, the degree to which it is confined etc. can be important. Furthermore, there are only a limited number of systems where cavities have been clearly detected in high resolution X-ray images (one needs to remember that features like cavities are only detectable by Chandra, and there won't be a similar Observatory in the foreseeable future), in which such measurements can be made. For this project, we need to sample a broad range of radio and jet power, which requires a large sample in various bins of radio power and age. We have chosen in this sample almost all of the clusters with known cavities that can be studied with the resolution of the GMRT. This necessitates the clusters to be mostly closer than a redshift of 0.2, unless the cavities are enormous (e.g. MS0735+742).

2. Observing plan

We have chosen 21 targets from the sample of Rafferty et al. (2006) and Birzan et al. (2008), **which compile clusters that exhibit the best evidence of cavities in Chandra X-ray observations**, and have evidence of higher frequency VLA observations of radio-emitting plasma filling these cavities. Of these, two clusters, 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 explore the extensive data available in the GMRT archives for the Perseus cluster to check whether they are adequate for our purposes, else we will propose at a later cycle.

In Cycle 18, we propose to observe these clusters at 150, 240, 610 MHz (single frequencies) 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 hours (according to availability of source), at each of these frequencies, 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, 14SGa01, 15-064, 16-051, 16-265, 17-016) informs us that the integration times will be adequate to reach flux densities of 0.3 and 0.2 mJy/b at 240 and 610 MHz respectively.

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 Cycles 16 and 17, we had targetted a few clusters of our sample at 150 MHz and 240/610 Mhz dual frequency mode. Dtaa reduction is ongoing- our preliminary data reduction onsome objects indicate that we could significantly increase our S/N and dynamic range if, instead of the 8 MHz BB-bandwidth afforded by the dual frequency mode, we could increase our base BW to 16 MHz. Thus we are applying in this Cycle for single frequency observations.

An average integration of 8 hours each is requested at each of three frequencies 150, 240 and 610 MHz per source. In Cycle 18, we are asking for observations of 5 sources- this amounts to 120 hours.

2.1 Dynamic range issues: We are aware that in some of these sources, the presence of very bright central sources will cause problems in mapping the diffuse fainter emission, due to the limited dynamic range available. In our extended sample, this issue will arise with Abell 85, Hercules A, Abell 2052 and Hydra A. We have already obtained the data for A2052 in Cycle 16, and have been attempting various methods to dealing with this issue. The availability of the software correlator from Cycle 17 seems to be very important for us since this will certainly provide a wider dynamical range. We therefore request the use of the GSB in our observations, and in this cycle, a repeat observation of A2052 (observed in Cycle 16) with the GSB.

2.2 RFI issues: 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 (RFIX, 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.

2.3 Why we need three frequencies: Examination of radio images at multiple frequencies in the 200–600 MHz range is particularly important for us, as the progressive loss of particle energy causes the spectral index to steepen, and a break in the spectrum occurs mostly in this range (or lower) for the range of targets that we are interested in. It is not possible in most cases to detect the break with two frequencies even if VLA observations are available at > 1GHz. Spectral index maps involving 3 low frequencies will enable us to measure spectral ageing, and comparing these to independent age estimates from X-ray, shock ages and buoyancy ages will allow us to model the sources to the level of detail we require. The GMRT is uniquely suited for this experiment.

2.4 Previous observations and Legacy value of our sample: We have thoroughly checked the GMRT archives and have found that several of our sources have been observed previously, but none of them exist in a form that are appropriate for our study. There is a reasonable overlap with the sample of 04DAG01 (PI Dave Green) who observed a large number of (cooling flow) clusters for an hour or less each at 610 MHz. Other individual clusters have been observed for similar short periods at one or two frequencies (e.g. Abell 85, 05KBa02). Her A has been observed several times in short exposures for studies of the radiogalaxy. While these observations would yield the luminosity of the central source, lack of u-v coverage would not allow us to make the spectral maps that we need for our project.

We would like to point out that our sample of 21 clusters with full synthesis observations at 3 frequencies will yield an unprecedented legacy dataset. The targets in our sample are some of the best-studied clusters of galaxies that have been studied for a multitude of purposes (lensing, haloes, mergers), and this dataset will benefit all users of the GMRT archives, and for multiwavelength studies involving the Virtual Observatory.

3. Status report on earlier proposals: 12SGa01, 13SGa01, 14SGa01, 16-265; 15-042 and 15-064; 16-051, 16-053

Earlier observations of similar systems at the GMRT have been very successful. PI Raychaudhury, and Co-I Athreya have collaborated on several GMRT observations involving radio haloes and AGN feedback in groups and clusters. From 10SGa01, 12SGa01, 13SGa01, 14SGa01 & 16-265 multifrequency observations of AGN in groups, we have truly spectacular results. Two papers (on AWM04 and NGC5044) have been published (Giacintucci et al. 2008, David et al. 2009) and one, on HCG62, is submitted (Gitti et al preprint, on http://arxiv.org/abs/0912.3013), A long paper summarising all of our 610 MHz results is close to submission. Results were presented, among others, in two talks (Raychaudhury, Giacintucci) at the *Radio galaxies in the Chandra Era* meeting in Boston, MA in July 2008, three talks at LFRU08 in Pune, December 2008, (Raychaudhury, Vrtilek and O'Sullivan, two papers now on astro-ph), two talks at the "Monster's Fiery breath" in Madison, Wisconsin, June 2009 (Giacintucci, Gitti), and one talk and three posters at the Chandra's first decade of discovery meeting (Cambridge MA, Sept 2009). Raychaudhury was invited to give a review talk based on this work at the Marcel Grossmann meeting, Paris, July 2009.

A parallel short survey of spiral-rich groups has started with GMRT observations of Stephan's quintet: one paper (O'Sullivan et al 2009, ApJ 701, 1560), and two more groups were observed as 16-053 in May 2009. These data are being analyzed.

The observations from 15-042 (Co-I Raychaudhury), and 15-064 & 16-050 (PI Raychaudhury), which are of rich clusters with interesting feedback issues (A520 is a recent merger and CL0910+41 has a BCG with an AGN and a massive starburst) are still being analyzed.

Observations for the precursor to this project 17-016, were carried out in December, and analysis of this data is in progress. From this proposal, PhD student Matt Lazell joins this project- he will be involved in observations and data reduction. We are asking for re-obsrevations of Abell 2052 (observed in March 2009), since the use of the GSB, and separate observations at 240 and 610 MHz, is likely to help us with dynamic range issues.

4. PhD student: Matt Lazell

Observations from this proposal will form a substantial fraction of Matthew Lazell's PhD thesis. He is about to finish in PhD qualifiers (April 2010), and will go on his first GMRT observing run in Feb 2010. Abstract of his proposed thesis at the University of Birmingham (supervisor: Raychaudhury): "AGN feedback is the most likely source of energy injection into the inter-galactic medium (IGM) of galaxy groups and clusters. This dissertation looks at the differences between radio properties of early-type galaxies belonging to groups and clusters, and those that lie in the field. In particular, it focuses on low-frequency (GMRT) radio properties to estimate the current and past energy injection from active nuclei into the IGM, studied from X-ray observations. Finally, the properties of cluster galaxies at various regions of the e-m spectrum (including several GMRT frequencies) are analyzed using a novel statistical algorithm to find the salient features that distinguish them from field galaxies.".

References

Athreya, R. 2009, ApJ, 69, 885

Begelman, Blandford, Rees 1984, Rev. Mod. Phys. 56, 255; Best, P.N. et al. 2006, MNRAS, 368, L67

Birzan, L., Rafferty, D.A., McNamara, B.R., Wise, M.W.; Nulsen, P.E.J. 2004, ApJ, 607, 800

Brzan, L., McNamara, B. R., Nulsen, P. E. J., Carilli, C. L., Wise, M. W., 2008, ApJ, 686, 859;

Clarke, T.E., Sarazin, C.L. Blanton, E.L., Neumann, D.M., Kassim, N.E. 2005, ApJ, 625, 748

David, L., ... Nulsen, P., ...Raychaudhury, S. 2009, submitted to ApJ (arXiv:0905.0654)

De Young, D. S. 2006, ApJ, 648, 200

Diehl, S., et al. 2008, ApJ, 687, 173;

Dunn, R.J.H., Fabian, A.C., Taylor, G.B. 2005, MNRAS, 364, 1343;

Fabian, A.C., Sanders, J.S., Allen et al., 2003, MNRAS, 344, L43;

Giacintucci, S., Vrtilek, J.M., Murgia, M., Raychaudhury, S., O'Sullivan, E.J.; Venturi, T., David, L.P., Mazzotta, P., Clarke, T.E., Athreya, R.M. 2008, ApJ, 682, 186;

McNamara, B.R., & Nulsen, P.E.J., 2007, ARAA, 45, 117;

McNamara, B. R., Kazemzadeh, F., Rafferty, D. A., Brzan, L., Nulsen, P. E. J., Kirkpatrick, C. C., Wise, M. W. 2009, ApJ, 698, 594

Merloni, A, Heinz, S 2007, MNRAS, 381, 589

Nulsen, P.E.J., McNamara, B.R., Wise, M.W., David, L.P. 2005, ApJ, 628, 629;

O'Sullivan, E., Giacintucci, S., Vrtilek, J. M., Raychaudhury, S., David, L. P. 2009, ApJ, 701, 1560

Rafferty, D. A., McNamara, B. R., Nulsen, P. E. J., Wise, M. W. 2006, ApJ, 652, 216

Raychaudhury S et al. 2009, proceedings of LFRU 2008 eds. Saikia, Green, Gupta, Venturi (ArXiv:0907.0895)

Scheuer, P 1974, MNRAS, 166, 513;

Wise M. et al. 2007, ApJ 659, 1153

Table 1. **Project source list (Cycles 16 onwards)**

Source	RA_{J2000}	DEC_{J2000}	z	Cycle
We are requesting observations for these 5 clusters in Cycle 18				
Abell 2029	15 10 56.0	+05 44 41	0.0773	18
Abell 2052	15 16 45.5	+07 00 01	0.0355	16+18
Abell 2065	15 22 42.6	+27 43 21	0.0726	18
Abell 2218	16 35 54.0	+66 13 00	0.1756	18
Hercules A	16 51 08.1	+04 59 33	0.1540	18
These clusters were/will be observed by us in Cycle 17, in December 2009, data not reduced yet				
Abell 478	04 13 20.7	+10 28 35	0.0881	17
MS0735.6+742	07 41 44.5	+74 14 38.10	0.216	17
Hydra A	09 18 05.7	–12 05 44	0.0549	17
RBS 797	09 47 12.5	+76 23 12	0.354	17
2A 0335+096	03 38 35.3	+09 57 55	0.0349	17
These clusters were observed by us in Cycle 16, re-observation request for A2052				
Abell 2052	15 16 45.5	+07 00 01	0.0355	16
Abell 1835	14 01 02.0	+02 51 32	0.2532	16
Abell 2597	23 25 18.0	–12 06 30	0.0852	16
We will propose for these clusters later in Cycles 19-20				
Abell 85	00 41 37.8	–09 20 33	0.0551	19
Abell 133	01 02 39.0	–21 57 15	0.0566	19
Abell 262	01 52 50.4	+36 08 46	0.0163	19
Abell 496	04 33 37.1	-13 14 46	0.0329	19
Abell 1795	13 49 00.5	+26 3507	0.0625	20
RXJ1720.2+2637	17 20 08.9	+26 38 06	0.1640	20
Abell 2319	19 20 45.3	+43 57 43	0.0557	20
Abell 2390	21 53 34.6	+17 40 11	0.2280	20
Abell 2670	23 54 10.1	-10 24 18	0.0762	20

We request night time observations (IST 2200-0700 hrs) for the minimization of RFI, particularly at 150 and 240 Mhz, which is why we have chosen appropriate targets for each cycle.

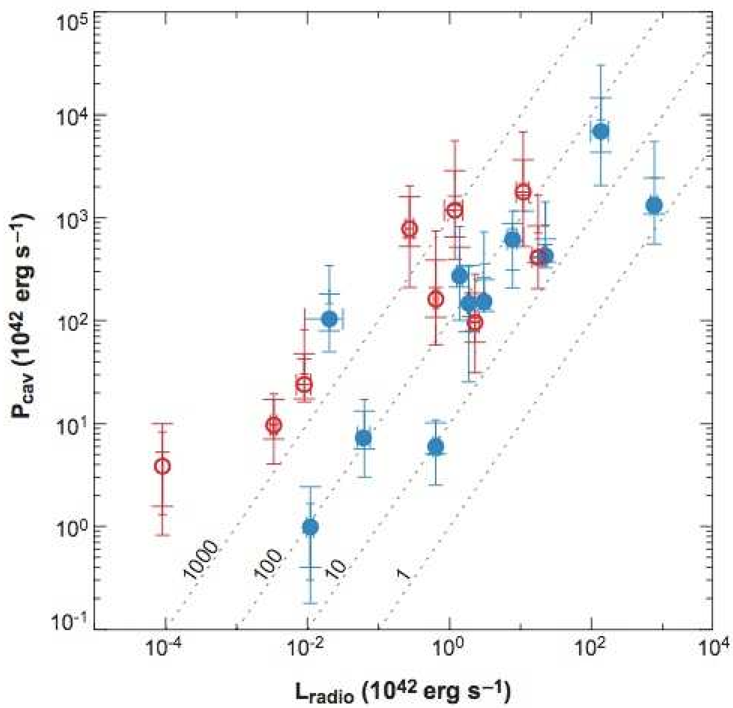

Figure 1: Radio luminosity (10 MHz to 10 GHz) plotted against jet power determined from X-ray cavities in galaxy clusters (McNamara & Nulsen 2007). Open red circles represent so-called "ghost cavities" that are dominated by low frequency radio emission. The blue symbols are filled with high and low frequency emission. The diagonal lines represent ratios of constant jet power to radio synchrotron power. A clear trend is observed but with large scatter. Hopefully the scatter will be reduced with low frequency GMRT observations.

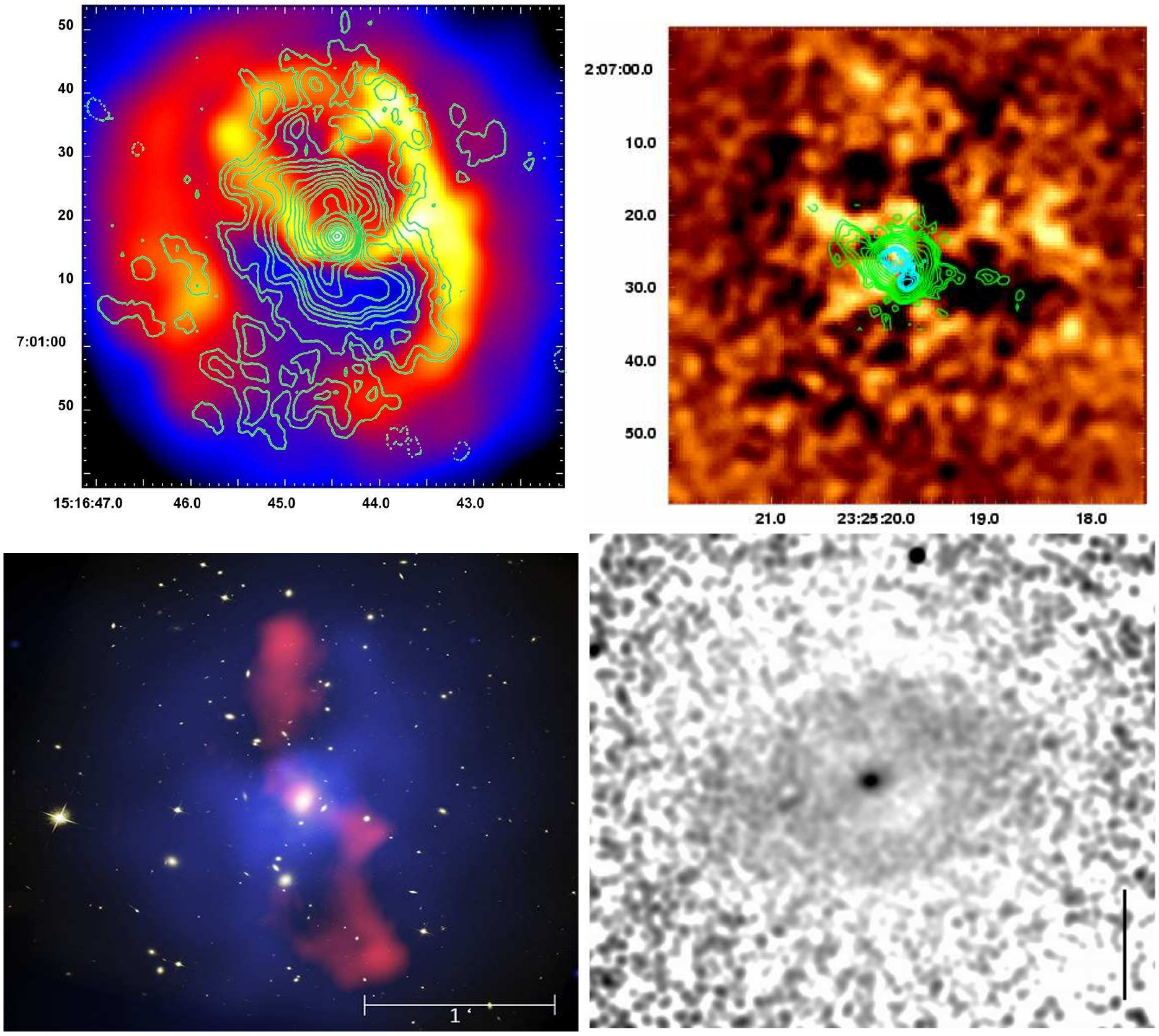

Figure 2: Four clusters from our sample. We have observed the top 2 (plus another) in Cycle 16 and propose to observe the bottom two, among others, in Cycle 17 (for night time observations).

(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 frequencies, the true extent of the radio plasma in the cavities will be revealed. (Clarke et al. 2005)

(lower left). Our 0.37.5 keV Chandra X-ray image of Hercules A. The scale bar in each panel is $1'$ (160 kpc). The bright central region is surrounded by the shock front. The southwest cavity is $\sim 0'.5$ from the central peak. (Nulsen et al. 2005)

(lower right).