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

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 in a straightforward manner 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 4) provides a measure of their radiative efficiency. Figure 4 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 > 1 GHz (rarely shallow observations at 325 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). 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 (~ 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, in which such measurements can be made (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). 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 Abell 85 and Perseus clusters to check whether they are adequate for our purposes, else we will propose at a later cycle.

In Cycle 19, we propose to observe two clusters, A2390 and A2670 at 150 MHz and 240/610

MHz dual mode to obtain detailed spectral index maps of the radio emission interacting with the hot IGM.

For yet another cluster, A2597, we seek a re-observation of the 235/610 dual mode from Cycle 16, since the larger dynamic range provided by the GSB is crucial in the prsence of a bright central source. Our Cycle-16 observation had 5 antennae missing, and the GSB observation (then in trial mode, Aug 2009) was flawed. The 150 MHz survey observation of this cluster, when available, will be enough for our purposes, since with the limited dynamic range in the presence of a 10 Jy source at 150 MHz, te rms will at best go down to 10-20 mJy/b.

For each observation, we ask for a full synthesis of 8 hours, 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 and clusters (e.g. 13SGa01, 14SGa01, 15-064, 16-051, 16-265, 17-016) informs us that a full synthesis at full resolution will be adequate to reach flux densities of 0.1 and 0.05 mJy/b at 240 and 610 MHz respectively, if not limited by dynamic range (in some of our targets, the limited dynamic range is an issue, but see discussion below §2.1). At 150 MHz, we have been getting down to 1 mJy/b, and even down to 0.5 mJy/b with the use of RFIX (Athreya 2008), but we feel that we can do better in our analysis- this is work in progress.

Observations under 300 MHz are very crucial to our research. 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. Of course, the chance of discovery of new interestig sources within the large primary beam is also an added attraction. In our December 2009 run (Cycle 17), we even tried 16 MHz bandwidth with 150 MHz, and found that after midnight, this is indeed possible- the RFI over a 16 MHz range was unexpectedly low between midnight to 6 am local time.

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 Herc A and Hydra A in Cycles 17 and 18, and have been attempting various methods to dealing with this issue. The availability of the software correlator seems to be very important for us since this will certainly provide a wider dynamical range.

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 at 150 MHz has shown remarkable improvements, with sensitivity of 0.5 mJy/beam and a dynamic range of 10^4 (This 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 Targets: Abell 2390 (z=0.23) is a cluster well-studied by practicioners of gravitational lensing- its straight arc was one of the first of its kind to be found, and an excellent weak lensing map exists (Squires et al 1996). The deep Chandra observation shows very interesting features, at least one large cavity and a possible mini-halo in the core (see Bacchi et al 2003 A&A 400,465). The small scale radio structure for A2390 is well studied with VLBA/Merlin (see Augusto et al 2006, MNRAS 367, 366) but this is dominated by a bright, self-absorbed core with rather indistinct jets. BUT at < 1GHz there is clearly an indication of excess of flux implying some more extended, steeper spectrum emission. **Abell 2670** has a relatively faint central radio source (7mJy at 1.4 GHz but it First shows that it is dominated by one knot that is 12 arcsec offset from the the BCG that is coincident with a faint background galaxy). The Chandra data show that A2670 is a very unusual cluster with a very distorted in falling subcluster. **Abell 2597** (z=0.08) in a canonical ghost cavity system (McNamara 2001) in a cool core cluster, with a blue core indicative on ongoing star formation.

2.5 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 is 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). 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: 14SGa01, 16-265; 15-042 and 15-064; 16-051, 16-053, 17-016, 17-050, 18-015

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 14SGa01 & 16-265 multifrequency observations of AGN in groups, we have truly spectacular results. 4 papers (2 on AWM04, 1 on NGC5044 and 1 on HCG 62) have been published (Giacintucci et al. 2008, O'Sullivan et al 2010, David et al. 2009, Gitti et al. 2010) and another on AWM04 is submitted. 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 in the published proceedings and 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.

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. CL0910+41 was observed at L-band continuum in December 2009, since the need of a higher resolution map was felt necessary to publish results.

Observations for the precursor to this project (17-016) were carried out in December 2009, and analysis of this data is in progress. From this proposal, PhD student Matt Lazell joins this project- he is deeply involved involved in observations and data reduction, and has already spent six weeks at NCRA in the last six months engaged in data reduction.

4. PhD student: Matt Lazell

Observations from this proposal will form a substantial fraction of Matthew Lazell's PhD thesis. He has finished his PhD qualifiers (June 2010). He went for his first GMRT run in February 2010, and in June-July 2010, spent one month at the NCRA attending the SERC summer school and reducing our Cycle 18 GMRT data together with Co-I Dr Ishwara Chandra. 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.".

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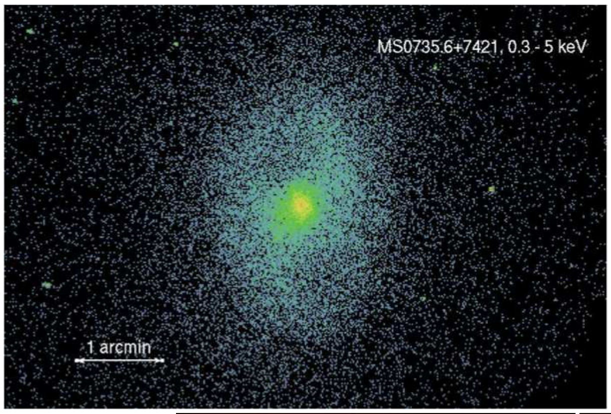
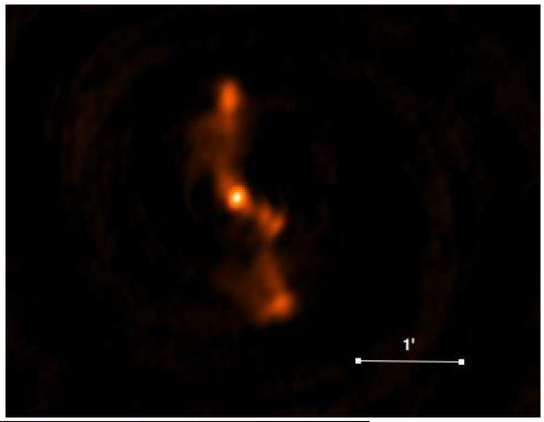
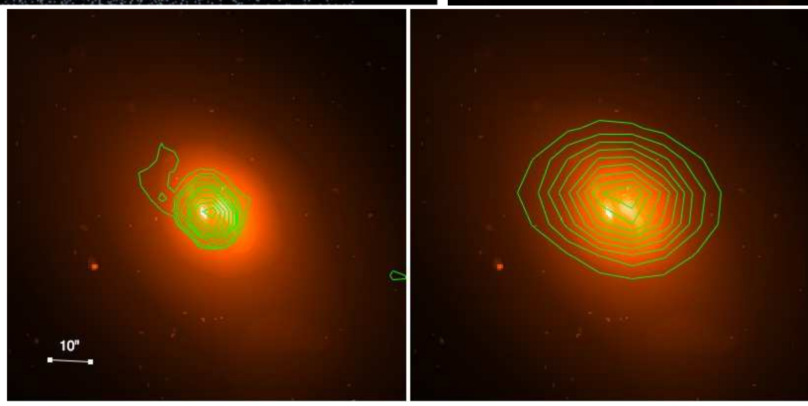
Table 1. Project source list (Cycles 16 onwards)

Source	RA_{J2000}	DEC_{J2000}	z	Cycle	Freq.
We are requesting observations for these 3 clusters in Cycle 19, incl. re-observation at dual mode only for A2590.					
Abell 2390	21 53 34.6	+17 40 11	0.2280	19	150, 235/610
Abell 2597	23 25 18.0	–12 06 30	0.0852	16+19	235/610 only
Abell 2670	23 54 10.1	-10 24 18	0.0762	19	150, 235/610
These clusters were observed by us in Cycle 18, in May 2010, data not reduced yet					
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 observed by us in Cycle 17, in December 2009, data being reduced, see Figs. 1 and 2					
Abell 478	04 13 20.7	+10 28 35	0.0881	17	
MS0735.6+742	07 41 44.5	+74 14 38	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 needed for A2052 and A2597					
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	
Other clusters in sample: we will propose for these clusters later in Cycles 20+					
Abell 85	00 41 37.8	–09 20 33	0.0551	21	Some in archive
Abell 133	01 02 39.0	–21 57 15	0.0566	21	Some in archive
Abell 496	04 33 37.1	-13 14 46	0.0329	21	
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 2029	15 10 56.0	+05 44 41	0.0773	20	
Abell 2052	15 16 45.5	+07 00 01	0.0355	16+20	
Abell 2065	15 22 42.6	+27 43 21	0.0726	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.







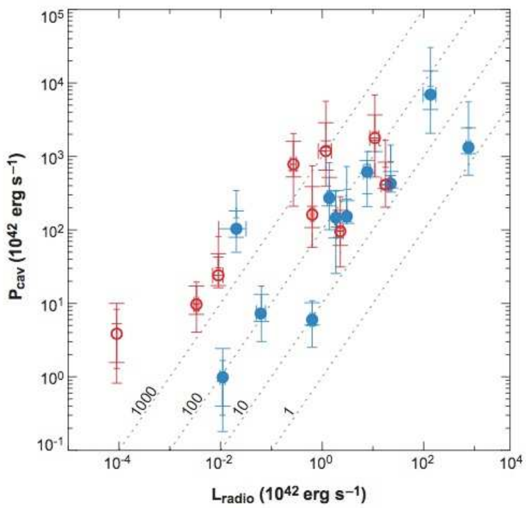


Figure 1: Chandra 0.3–5 keV X-ray image of cluster MS0735.6+7421 revealing the largest giant cavity system known in a cluster of galaxies.

Figure 2: Preliminary map of our own GMRT 610 MHz observation of the same system from December 2009. The rms noise is 85μJy/b, and the flux density of the source is 190 mJy. Some more calibration is required. We also observed this system at 150 and 235 MHz.

Figure 3: The 0.2-2 keV Chandra X-ray wavelet-smoothed image of Abell 478, in colour (Sanderson et al. 2005, showing a pair of cavities. The image is superposed with contours from our Cycle 18 GMRT observation at 610 MHz (left) and 150 Mhz (right), spaced at logarithmic intervals, from 2 times the rms noise upwards. The rms noise obtained at 610, 235 (not shown) and 150 MHz for this source is 0.1 mJy/b, 1.0 mJy/b and 1.6 mJy/b respectively. Some more self-calibration is required, and the offset in the 150 MHz is an artefact that will be fixed.

Figure 4: 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.