The morphology of the steepest spectrum radio sources in the cores of clusters of galaxies: Echoes of AGN feedback?

The cores of clusters of galaxies are complex and violent environments that represent a crucial test for many aspects of galaxy formation and evolution. Many of most well-studied radio galaxies are associated with the brightest galaxy in a cluster core, e.g. Virgo-A, Per-A, Cyg-A and Hyd-A, and these cluster sources range from canonical FR-Is (e.g. 3C31) to the lowest redshift FR-IIs (e.g. Cyg-A and Her-A).

One issue that has recently dominated the discussion of cluster cores is the role of AGN feedback on the thermodynamics of the intracluster medium in the cores of clusters (McNamara & Nulsen 2007, ARA&A 45, 117). In the absence of any form of heating, the hot, dense gas in a cluster core should cool and create a substantial mass of cold molecular gas. While cold molecular gas is found in many systems (Edge 2001, MNRAS 328, 762; Salome & Combes 2003, A&A 412, 657) much less is detected than would be expected if cooling dominated (McNamara et al. 2004, ApJ 601, 173), and only in a fraction of all clusters (15–30%). Also X-ray observations indicate that less gas is present at intermediate temperatures in the most rapidly cooling systems (Peterson et al. 2003, ApJ 590, 207). There is a growing consensus that these disperate observations can be understood if the majority of clusters that have mass profiles without a central cusp are heated through conduction (Voigt et al. 2004, MNRAS 347, 1130; Parrish et al. 2009, arXiv:0905.4500) and those with a central cusp, where cooling out-strips conductive heating, are heated instead through the input of mechanical and cosmic ray energy from a central AGN in regular "outbursts". These energetic events provide the required heating to reconcile the X-ray observations and the cold gas acts as the fuel required to trigger each outburst.

One important caveat to this view is that, while the instantaneous power output of the currently active systems can provide enough energy to counteract cooling in individual cases, the uncertainty in how frequently and energetically these injections occur prevents more general conclusions being drawn. We are currently addressing these issues with a campaign to study the largest available sample of X-ray selected clusters with $z < 0.5$ to directly tackle the joint questions of the AGN duty cycle and energetics. This all-sky sample has been drawn from the ROSAT All-Sky Survey and totals over 850 clusters. Of these we have optical spectra for the Brightest Cluster Galaxy (BCG) in 780 clusters and of these 215 show optical emission lines, a property which is closely related to the central cooling time (see Cavagnolo et al. 2008, ApJ 683, 107). Radio observations play a vital role given that the "on" phase of the AGN outburst is most directly traced by radio jets and lobes. However, in the latter stages of an outburst (where diffuse, steep-spectrum emission dominates) and during "quescient" periods (where the AGN is fueled at $< 10^{-5}$ of Eddington limit), the characteristic radio properties will be many orders of magnitude less luminous. Interestingly, 211 of the 215 of our sample of clusters that we believe are cooling significantly on the basis of optical line emission are detected in the NVSS or SUMSS surveys (>3mJy at 1.4GHz). This implies that radio emission is found ubiquitously in the systems which are in the "active" phase of the AGN feedback cycle but its power and morphology vary dramatically.

One additional aspect of the radio sources in cluster cores that has not been very well studied to date is their radio spectral index. This is almost entirely due to the very limited spectral range of existing radio surveys. We have used the only existing large scale survey at frequencies below 200MHz (VLSS at 74MHz) to search for the brightest, steep spectrum radio sources in a sample of 850 X-ray luminous clusters. This comparison recovers many of the best known systems (A2597, Hydra-A, etc) but also recovers a sample of 20 very intriguing but unobserved systems with extreme spectral index ($\alpha < -1.3$) and similar low frequency radio powers. We propose to observe this complete sample of 20 radio spectral index selected sources to make an unbiased morphological study of these sources. The GMRT imaging will identify which sources are the systems that are lobed sources in which the radio emission has spectrally aged and which are examples of radio haloes (or mini-haloes) that are believed to be powered from cluster merger activity. The X-ray and optical properties of the cool core and recent merger clusters are very different; dominated by a single, optically line luminous galaxy and peaked X-ray emission, or having several equally dominant central galaxies and more diffuse X-ray morphology.

In summary, we propose to make GMRT observations at 325MHz of a complete sample of steep spectrum radio sources in the cores of X-ray luminous clusters. This study complements the work of van Weeren et al. (2009, in prep, GMRT programme 15HRa01) who studied 26 VLSS-selected, steep spectrum sources but only 4 were in X-ray luminous clusters. It also complements work searching for radio haloes by other groups which have targeted the most X-ray luminous clusters at moderate redshift. The proposed observations select from a much larger sample with a wider range of X-ray luminosity and redshift and will hence uncover the most extreme radio phenomena.

Technical justification

We request 325MHz observations of 20 clusters over all RA, with declinations above -25° and a VLSS flux density of at least 1Jy. We request an exposure of 4hrs on source split over eight 30min visits spread over a wide *uv* coverage to ensure matched sensitivity for an unresolved source with a steep spectral index ($\alpha < -1.3$), with a 3σ sensitivity of 10mJy. Our observing strategy is to determine the morphology of any extended radio emission (most likely on scales of 10–60″ scaling from archival data) for the steepest spectral index emission. We believe this is best done at 325MHz with the GMRT given that the ionospheric phase distortions are less severe at 325MHz compared to 245MHz and the possibility of resolving out emission at 610MHz is minimised. Including a 30% overhead for set-up, pointing and calibration then our total request is 104 hours for all 20 clusters but any award that allows more than 10 clusters to be observed (i.e. doubling the number of suitable targets in the GMRT and VLA archives at comparable resolution) will have a significant impact.

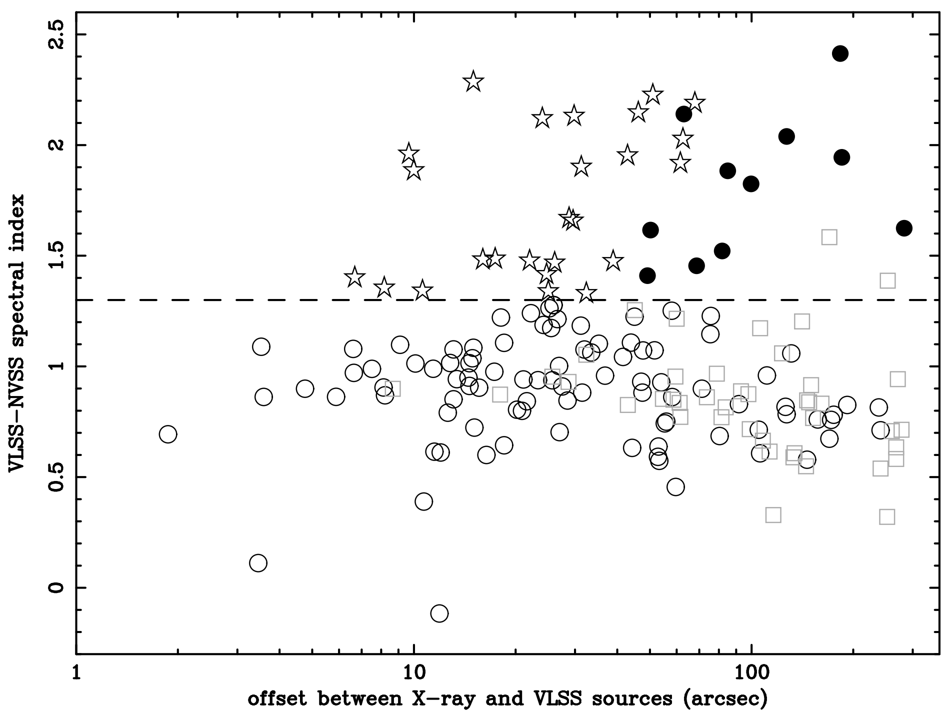

Figure 1: The VLSS-NVSS spectral index for the complete sample of VLSS sources coincident with ROSAT Survey clusters plotted against angular offset between X-ray and radio sources. The stars are the sources that fall within our selection of $\alpha < -1.3$ that are consistent with being within the central 300kpc of the cluster core. The filled circles are candidate radio halo and relics sources that are not the subject of this proposal. The squares are sources consistent with a head-tail source in the cluster. The circles are sources coincident with the BCG. Note that the offset between radio and X-ray position can be large for BCG sources due to a combination of spatial resolution of both surveys and radio extent coupled with the wide range in cluster redshift ($0.01 < z < 0.5$). Note the predominance of head-tails at the outskirts of the clusters and the wide range in spectral index of sources in the cores.