CHANDRA OBSERVATIONS OF THE COOL CORES WITH THE MOST CURRENTLY ACTIVE AGN

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, Perseus-A, Cygnus-A and Hydra-A, and these cluster sources range from canonical FR-Is (e.g. 3C31) to the lowest redshift FR-IIs (e.g. Cygnus-A and Hercules-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 central regions of a cluster (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, Wise & Murray 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 comprehensive, multiwavelength campaign to study the largest available sample of X-ray selected clusters of galaxies within a redshift of 0.5 to directly tackle the joint questions of the AGN duty cycle and energetics. This all-sky sample has been drawn from the four largest ROSAT All-Sky Surveys, BCS, eBCS, REFLEX and MACS, and totals over 850 clusters. Of these we have optical spectra for the Brightest Cluster Galaxy (BCG) in 780 of them and of these 215 show optical emission lines (principally Hα), a property which is very closely related to the central cooling time in the cluster core (see Cavagnolo et al. 2008, ApJ 683, 107). Radio observations play a vital role in this study 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 well below the Eddington limit) the characteristic radio properties will be many orders of magnitude less luminous. Interestingly, of the all-sky sample of clusters we are using all but 4 of the 215 we believe are likely to be cooling significantly (on the basis of line emission in their optical spectrum) are detected in the NVSS or SUMSS surveys (>3mJy at 1.4GHz). Of these detections in the FIRST survey region ($\sim$60 of the 215 clusters), the majority (>70%) are unresolved at the FIRST resolution limit ($4''$). This implies that radio emission is found at all stages of the AGN feedback cycle but its power and morphology change dramatically. This is in stark contrast to the BCGs with no optical line emission were only 155 of the 565 BCGs are similarly radio bright and most are extended at FIRST resolution.

The archival and survey radio data do not have sufficient resolution to determine what radio morphology the lower power, "quiescent" systems have. Are they compact sources dominated by emission from the vicinity of the supermassive black hole or low power analogs of the more powerful sources with strongly truncated lobes and jets? Can we apply the workof Merloni & Heinz (2007, MNRAS 381, 589) on the connection between the radio core luminosity, jet kinetic power and Bondi accretion toa sample of a complete sample of clusters? We have recently obtained VLT VIMOS observations that show that in the majority of BCGs there is some apparent rotation in the ionized gas and the axis of this rotation matches the radio jet axis. We have also compared the [OIII] line strength and X-ray point source flux with the 5GHz core radio flux density (see Figs 1 and 2). Both comparisons show that the core radio flux density is related to two other canonical measures of AGN strength. The number of points in Figure 2 is relatively small as only a small fraction of the targets have both VLBA and Chandra observations. We have obtained VLBA observations of 24 systems in the past 3 months and request Chandra observations to match them to expand this under investigated issue.

One important factor in this is that the presence of a >100 mJy flat-spectrum radio source in the core of a cluster has frequently been attributed to a strong X-ray emitting AGN/BLLac in the core and hence the cluster has been overlooked. An striking example of this is RXJ1350.3+0940, $z = 0.13$, that on the basis of its X-ray flux should have been in the BCS (Ebeling et al. 1998, MNRAS 301, 881) or NORAS (Böhringer et al. 2004, A&A 425, 367) samples. However, it contains a 300mJy radio source that was assumed to be a BLLac. However, inspection of the SDSS spectrum of the BCG of the cluster shows that it has all the "classic" features of a strong cooling flow system (Fig 3). In September 2009, we obtained a CO(1-0) detection of the BCG with the IRAM 30m indicating that it shares the properties of many strong cooling flows (Edge 2001, MNRAS 328, 762). This cluster is our highest priority target is this system comparable to A1068 and is one of the very few clusters with a BCG with an Hα luminosity in excess of 10^{42} erg s^{-1} (e.g. A1068, A1835, A2204 and Zw3146).

To this cluster, we request observations of 4 more clusters (A1348 (core of 154mJy at 5GHz), RXCJ0132.6-0804(213mJy), S555 (84mJy), A3378 (330mJy)) to both determine the X-ray properties of the nuclear source (flux and, for the brighter detections, a spectrum) to compare directly with recent radio data (VLBA and/or ATCA) and study the properties of the ICM surrounding the BCG (density, temperature, presence of cavities, etc.). The latter is vital to determine if these systems are potentially dense enough that the observed AGN can be powered by Bondi accretion alone (Allen et al. 2006, MNRAS 372, 21). While we cannot resolve close to the Bondi radius, the density profile on 1–20 kpc should scale between clusters so we will compare the central density profiles from these bright radio-cored systems to others in the Chandra archive that are fainter.

The proposed observations will also provide a test of the "mini-corona" model proposed by Sun (2009, ApJ 704, 1586) in which excess Chandra emission is found on very small scales in the cores of cool core clusters. If a direct relationship between the radio core flux and X-ray flux of an unresolved core exists in *all* clusters then many of the proposed "mini-coronae" may be related to an AGN and not an additional component to the ICM. The crucial issue is the combination of high resolution radio data (which we have from VLBA and/or ATCA) and contemporaneous Chandra observations (with 2–3 years).

We have an on-going programme of optical, infrared, far infrared and X-ray follow-up of the potentially cooling clusters which covers VLT, WHT, Gemini, Spitzer, Herschel and Chandra observations. One key element to this follow-up is the optical integral field (IFU) spectroscopy, principally with VIMOS on the VLT and GMOS on Gemini, that now covers 84 systems where extended optical emission lines on scales of 3–12$''$ are found. This dataset offers one of the most direct tests of how the central radio sources interact with the cooler gas (traced by the optical lines) and if this interaction triggers or suppresses star-formation. We have VIMOS IFU data for all our targets except RXJ1350.3+0940 which was not correctly identified at the time of our IFU campaign. The Chandra data for the extended X-ray emission will be used to search for cavities that can be compared to our IFU spectral velocity maps to determine the relative orientation of the gas rotation and AGN jets.

Technical justification

We request 20ks observations of 5 clusters all of which are well detected ROSAT survey sources (BCS or REFLEX, with the exception of RXJ1350.3+0940). Our primary goal is to determine the properties of an X-ray point source that should have a predicted flux of 0.5–1.0$\times10^{-13}$ erg s^{-1} cm^{-2} (0.1–10 keV). We request observations with ACIS-S to ensure the maximum number of detected counts and our interest is focussed on the cluster core ($< 2'$). At these fluxes we expect an ACIS-S count rates of 5–12 counts per ksec for a power law spectrum and galactic absorption. Therefore to obtain at least 100 counts for a point source at a level consistent with the observed trend in Figure 2 but also ensure a detection limit of at least 10^{-14}erg s^{-1} cm^{-2} (i.e. 20 counts required to be detected over the peaked cluster emission) leads us to our requested exposure of 20ksec per cluster.

We also wish to obtain an observation of sufficient depth to constrain the properties of the host cluster. The clusters have intrinsic fluxes from the REFLEX survey of 3.7–9.3$\times10^{-12}$erg s^{-1} cm^{-2} (0.1–2.4 keV) so we expect total cluster fluxes of 1–3 ACIS-S count per second for the expected cluster temperatures (3–6 keV). From our collective experience of the analysis of Chandra data from PI and archival data, obtaining more than 20,000 counts is a bare minimum to stand a chance of detecting the variety of structural features seen in clusters (cavities, cold fronts, shocks, etc.) and to obtain sufficient count statistics to determine temperature and abundance information within the central 500kpc. Establishing whether the cluster structure of the five clusters with strong radio cores is in any way different from clusters without one. The archival data of comparable REFLEX and BCS clusters have an average exposure of around 20ks therefore we believe that our requested exposure is justified in terms of direct cluster comparison and the legacy value of the data. Should any unusual feature be found in our 20ks observation then it can be returned to in later cycles.

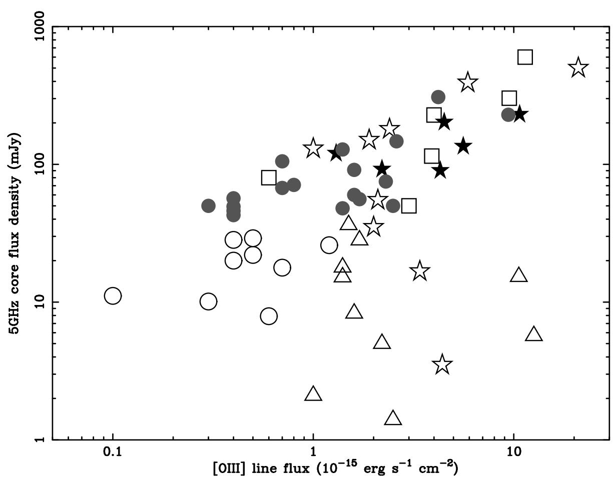

Figure 1: The 5GHz core radio flux density plotted against the flux of the [OIII] line from optical long slit observations from our all-sky sample. The stars are for cores from VLBA observations on milli-arcsec scales. The triangles, squares and circles are the 5GHz flux estimates from FIRST/NVSS/SUMSS observations (assuming $\alpha = -0.7$). The triangles are for systems that are dominated by a MIR starburst (O'Dea et al. 2008, ApJ 681, 1035) as are the two faintest VLBA detections. Note that the systems dominated by star formation lie well below the general trend as the [OII] emission from these sources arises from ionisation by young stars rather than an AGN.

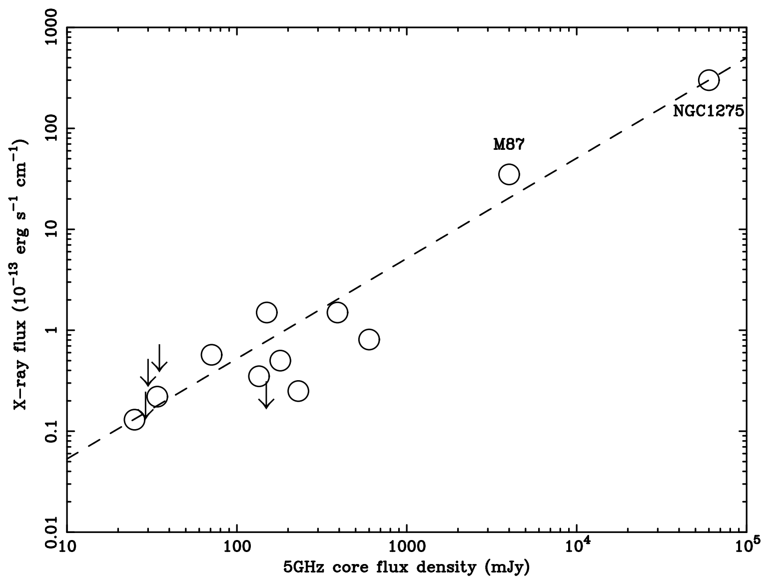

Figure 2: The Chandra point source X-ray flux plotted against the 5GHz core radio flux density for the subset of our sample with both Chandra and VLBA observations. The dashed line denotes a line with the same X-ray/radio flux ratio as NGC1275/3C84. Note our targets all fall in the range of 80–500mJy where a source of $> 5 \times 10^{-14}$ erg s^{-1} cm^{-2} would be expected. This is comparable to the limit achievable in a 20ks Chandra observation over the cluster X-ray emission.

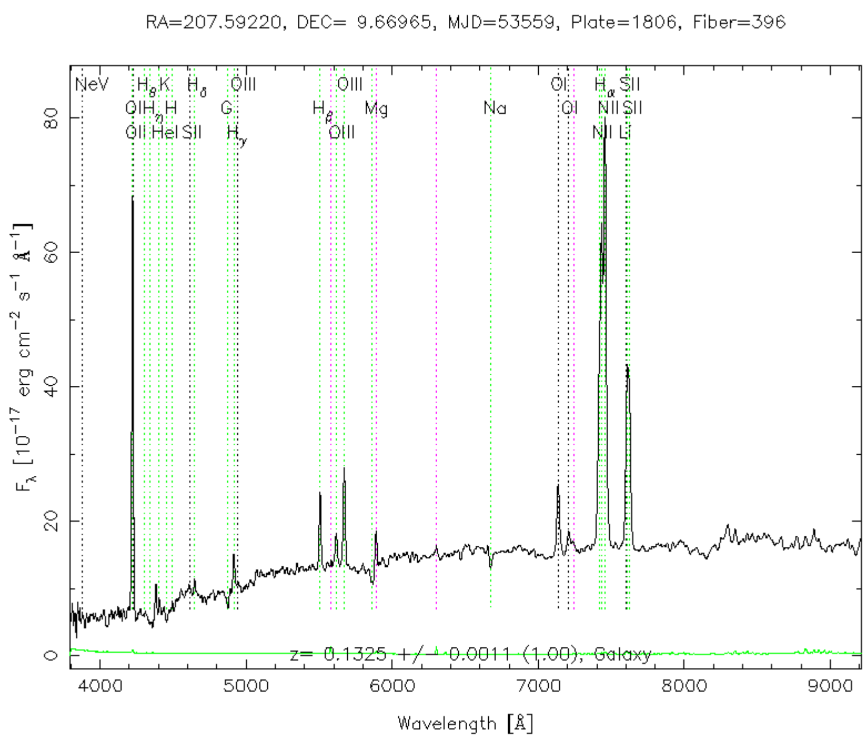

Figure 3: SDSS spectrum of RXCJ1350.6+0940 at a redshift of 0.1325. Note the strong optical lines, especially [OIII].

1 Previous Chandra Programs

PI Edge, GO Cycle 2: "The interaction between radio galaxies and ICM in the cores of clusters". Observation of two potential cavity systems both of which have been published in larger study of Cavagnolo et al. (2009, ApJS 182, 12).

PI Edge, GO Cycle 4: "Probing the mass profile of clusters to 10kpc". Observation of A1201 which has been published in Owers et al. (2009, ApJ 692, 702).