Constraining the evolution of AGN feedback in cluster cores over the past 7Gyr - a targeted VLASS survey

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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). 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 or what is referred to as a 'cooling flow'. While cold molecular gas is found in many systems (Edge 2001; Salome & Combes 2003) much less is detected than would be expected if cooling dominated (McNamara et al. 2004), and only in a fraction of all clusters (15–30%). In addition, X-ray observations indicate that less gas than expected is present at intermediate temperatures in the most rapidly cooling systems (Peterson et al. 2003) and that giant cavities are present in the ICM created by buoyant radio lobes (McNamara & Nulsen 2007). There is a growing consensus that these disparate observations can be understood if clusters with a high central gas density (and hence short radiative cooling times) are heated through the input of mechanical and cosmic ray energy from a central AGN in regular "outbursts". These energetic events can in principle provide the required heating to reconcile the X-ray observations and the cold gas acts as the fuel required to trigger these outbursts.

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. Also, what is the power output of the supermassive black hole in between outbursts while in its "quiescent" state? Do these sources remain "active" or can they become dormant?

We have been 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. Our 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). 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 "quiescent" periods (where the AGN is fuelled at well below the Eddington limit, possibly through Bondi accretion) 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 large 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, broad-band spectrum and morphology change dramatically. Therefore, we are drawn to the conclusion that all BCGs in rapidly cooling cluster cores are constantly "on" but at a level below that required for heating to balance the cooling of the ICM. This is in stark contrast to the BCGs with no optical line emission where only 155 of the 565 BCGs are similarly radio bright and most are extended at FIRST resolution.

We have investigated the radio power of all the BCGs in these X-ray flux limited surveys using all-sky ∼1 GHz surveys (NVSS, SUMSS, First) and can determine simple statistics for the sample such as the fraction of BCGs with a certain radio power split on the properties of the BCG (Fig 1, Hogan et al. 2014, in prep.). The two X-ray samples, eBCS in the North (Ebeling et al. 2000) and REFLEX (Böhringer et al. 2002) in the South, show very similar trends that the BCGs with optical emission lines are on average at least an order of magnitude more powerful in the radio than those without line emission. The chance to repeat this this analysis with an 'NVSS-like' survey with the JVLA, at say 2–4 GHz, with an order of magnitude improvement in flux sensitivity is a very exciting one as the statistic of BCG radio power can be applied to clusters selected using many different methods (optical, NIR, SZ, X-ray, weak-lensing) and compare the properties of their BCGs. In particular, eROSITA will dramatically increase the number of X-ray selected clusters over the next 5 years. Ensuring that clusters with strong, flat-spectrum radio cores are correctly identified as clusters and not AGN (BLLacs or flat spectrum radio galaxies) will be essential to ensure the best selection of clusters to recover cosmological parameters from the eROSITA sample. This is perhaps best illustrated by the Phoenix cluster (aka SPTJ2344-4243 at z =0.59) that is the most X-ray luminous cluster known but was only identified as a cluster due to it's strong Sunyaev-Zel'dovich effect (McDonald et al. 2012). The BCG contains a moderately luminous AGN (3×10^{45} erg s^{-1}) but an unprecedentedly large star-formation rate (∼800 $M_\odot yr^{-1}$) suggesting that the system is close to the limit expected for a cooling flow that has not been suppressed. There are other clusters with well-studied AGN in their BCGs, IRAS0910+40 (z =0.44, Iwasawa et al. 2001), 3C186 ($z = 1.06$, Siemiginowska et al. 2010) and E1821+64 (z =0.30, Russell et al. 2010), so the ambiguity in the nature of these systems is more than just a technical issue but may reveal the links between the cluster, cooling and AGN feedback and their joint evolution.

One additional complication to the analysis of the radio detection rate of BCGs is the wide variety of radio spectra they exhibit. Essentially all "classic" radio sources can be found in our sample: FR-I and FR-II sources with relatively weak cores, Giga-Hertz Peaked sources (GPS) dominated by their core emission and Compact Steep Spectrum (CSS) sources. We have chosen to break the radio spectra found into two components - a steep ($\alpha < -0.8$) spectrum, diffuse component that can exhibit a high frequency cut-off due to synchrotron losses which we normalise at 1GHz and a core component that can be self-absorbed normalised at 10GHz and has a substantially flatter spectrum ($\alpha > -0.5$). When the normalisation of these two components is plotted against each other we find a diverse behaviour in the ratio of the two (Fig 2). However, the flux density of the core component is correlated to the [OIII] line flux (Fig 3) and the X-ray flux of any nuclear point source in the core (Fig 4) demonstrating that the core has a direct effect on the properties of the BCG. We have obtained 5 GHz VLBA observations of 76 of the brightest of these targets and these observations show that the majority of the flux of the flatter spectrum core source is recovered on 1–30 mas scales. We have just been awarded 58 hours of filler time to more than double the number of systems with VLBA observations and will concentrate on fainter systems and ones without optical emission lines.

Importantly, if one splits the fraction of BCGs detected above a given radio power (Fig 1) into the two spectral components plotted in Fig 2 then the cooling flow clusters exhibit substantially more powerful radio cores than the non-cooling systems (Fig 5). This illustrates that the fuelling of the core is higher where the supply of cold gas is plentiful.

While the core flux is correlated with the AGN activity, the radio power of the more extended, steeper spectrum emission is more closely related to the X-ray estimates of the power required to inflate the X-ray cavities that are found in the majority of cooling flow clusters (Dunn & Fabian 2006; Hlavacek-Larrondo et al. 2013). Figure 6 shows the AGN power estimated from the cavities and the steeper radio component and the scatter seen can be explained by the spectral ageing of the more extended systems as the steepest spectrum systems (plotted in red) are clearly less radio powerful at 1.4GHz than the more compact, younger systems. There are clearly many additional factors that fold into this scatter, such as previous outbursts and larger cluster radio structures, but the statistical analysis that these

X-ray samples allow can address issues that the detailed study of individual systems can't.

One aspect that our current observations of $z < 0.3$ clusters aren't able to address is the evolution of radio power, and hence AGN feedback, particularly of the core emission. Recent work by Hlavacek-Larrondo et al. (2013) shows that the fraction of BCGs with X-ray detected cores in *Chandra* imaging is higher at $z > 0.3$. Given the close correlation between X-ray and radio core emission we find at lower redshift it is reasonable to presume that there is a commensurate increase in the radio core activity. By selecting clusters of comparable X-ray luminosity over a wide range in redshift it should be possible to directly constrain any evolution in AGN activity. Central to this would be obtaining radio data over a wide range (30 MHz to 40 GHz) to determine the properties of the steeper spectrum and core components.

In the context of VLASS surveys that cover the full sky visible from Socorro, like NVSS, at frequencies below 4 GHz, we propose a focused programme to extend our study to 5–50 GHz for a complete sample of X-ray luminous clusters out to $z = 0.8$. When combined with other VLASS and lower frequency surveys (LOFAR, MWA, WODAN and EMU), this study will constrain the radio SED over three orders of magnitude. This will allow us to constrain the properties of the current activity of the core (from the unresolved, flatter spectrum component) and the activity averaged over the past 1–50 Myr.

Assuming a VLASS S-band survey reaches an rms of 10–20μJy (comparable to the ASKAP EMU and WSRT WODAN surveys at <2 GHz) we will detect sources brighter than 10^{23} W Hz^{-1} out to $z = 0.3$ and 10^{24} W Hz^{-1} to $z = 0.8$. At these limits more than 80% and 50% of BCGs are detected in low redshift samples. However, the detected fraction is much higher for the most massive and more distant clusters. Using available and planned all-sky survey radio data we will be able to address the issue of the radio power of BCGs of the steeper spectrum component at frequencies below 5 GHz. However, these wide surveys will not constrain the higher frequency properties of these sources where the AGN activity dominates. Ideally a JVLA survey of 1,000–5,000 $\square^\circ$ at 15–30 GHz to a depth of 0.5–1.0 mJy would provide the coverage to detect enough BCGs to answer most of these issues at $z < 0.3$ but targeted observations will be necessary to constrain the properties of more distant clusters to address the evolution of BCGs.

We propose to make targeted JVLA 4–8 GHz, 18–22 GHz and 36–40 GHz broad bandwidth observations in B, C or D-array for a sample of the most radio powerful ($> 10^{24}$ W Hz^{-1}) at 2–4 GHz from the clusters selected from the ROSAT All Sky Survey from the BCS, eBCS, REFLEX, MACS and eMACS samples. The scope of this study is very flexible as the radio power limit and X-ray luminosity of the parent sample can be adjusted. It would also be possible to extend this to clusters from *eROSITA* or SZ-selection from *Planck* or ACT which should recover clusters at $z > 0.5$ more reliably that ROSAT. The frequency coverage could also be adjusted as the 20 and 40 GHz JVLA observations could be added to (or substituted with) CARMA 30 GHz but the information from the 4–8 GHz JVLA data are vital to best characterise the nature of these sources.

We anticipate that we would only target BCGs with a detection above a certain radio power from any VLASS survey at <4 GHz. Unfortunately, this results in a selection bias against the most self-absorbed cores which are much weaker at lower frequencies. Using either a blind high frequency VLASS survey over a smaller area of the sky or CARMA screening of all clusters at 30 GHz would fill this gap, or at least allow us to quantify how significant it is, without the need to devote JVLA time to observe sources that are undetected at lower frequencies.

The wider implications for this work for radio galaxies in general are very significant given the strong preference for radio galaxies to be found in the most massive galaxies at locally (Best et al. 2005). Establishing the connection between the gas fuelling of the AGN and the environment of the BCG (being at the focus of the gas cooling) would require us to reconsider the usual interpretation that distant, sub-mm selected galaxies are fuelled by gas-rich mergers because the observed gas reservoirs may be generated by the host halo. So the study of cluster cores may be a relatively narrow goal but it has a wider legacy value beyond cluster of galaxies.

Technical justification

We anticipate requesting simultaneous 4–5 and 7–8 GHz observations of 150–200 central cluster galaxies from a parent sample of $\sim$300 X-ray luminous clusters ($L_x > 4 \times 10^{44}$ erg s^{-1}) over all RA, with declinations above -30° and an expected 5GHz flux density of between 0.1 and 100mJy. We require an exposure of 10–40mins on source (depending on redshift) split over four 2.5–10min visits spread over a wide LST range to ensure matched sensitivity for an unresolved source with a flat spectral index ($\alpha = -0.5$), for a 5σ sensitivity limit of 25–50μJy at 4.5 and 7.5 GHz (i.e. 0.1-2% of the total expected 5 GHz flux density and an RMS of 5–10 μJy/beam using 1 GHz bandwidth in the current configuration). Given the redshift distribution of our sample we require 75–90 hours for these observations. These observations can be split into varying sized blocks and can be executed in relatively poor weather so we believe they would be well suited to the JVLA dynamic scheduled queue.

We would also request 20–22 and 40–42 GHz observations in C or D-array for a brighter sub-sample of these sources at 8 or 30 GHz. We anticipate this would require observations of at most 80 sources of 10mins per band or 45hours in total including calibration overheads.

The required data analysis will not require anything more than standard procedures for single pointings. We will concentrate on the properties of the central BCG but we will also determine the radio SEDs and morphologies of all the cluster members within the JVLA beam at 4–8 GHz.

The radio positions obtained from this programme will feed directly into future VLBA and eMERLIN observations, which require $< 0.1''$ positions for best correlation performance, and JWST observations to define the position of the central black hole.

References Best, P.N., et al. 2005 MNRAS 362, 25 • Böhringer, H., et al. 2004 A&A 425, 367 • Cavagnolo, K., et al. 2008 ApJ 683, L107 • Ebeling, H. et al. 2000 MNRAS 318, 1232 • Edge, A.C. 2001 MNRAS 328, 762 • Fabian, A.C. 1994 ARA&A 32, 277 • Hlavacek-Larrondo, J. et al. 2013 MNRAS 431, 1638 • Iwasawa, K. et al. 2001 MNRAS 321, L15 • Mahony, E.K., et al. 2012 ApJ 754, 12 • McDonald, M. et al. 2012 Nature 488, 349 • McNamara, B.R. et al. 2004 ApJ 601, 173 • McNamara, B.R. & Nulsen, P.E.J. 2007 ARA&A 45 117 • Peterson, J.R. et al. 2003 ApJ 590, 207 • Russell, H.R. et al. 2010 MNRAS 402, 1561 • Russell, H.R. et al. 2013 MNRAS 432, 530 • Salome, P. & Combes, F. 2003 A&A 412 657 • Siemiginowska, A. et al. 2010 ApJ 722, 102

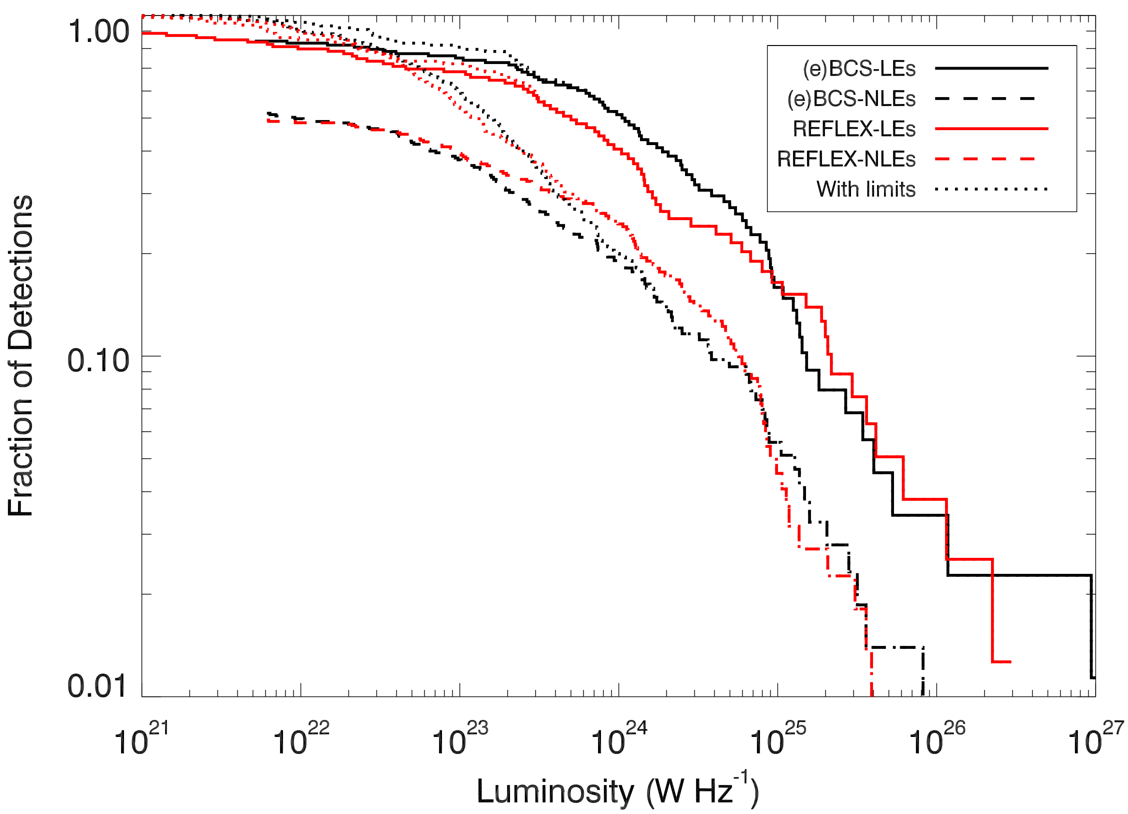

Figure 1: The cumulative function of the 1.4GHz radio power of BCGs in the combined BCS/eBCS (black) and REFLEX (red) X-ray selected cluster catalogs split on whether the BCG exhibits optical line emission (LE, solid lines) or not (NLE, dashed lines) which is an excellent proxy for whether the cluster is a cooling flow or not. The dotted lines mark the maximum possible contribution of each BCG by assuming a detection just below the detection limit.

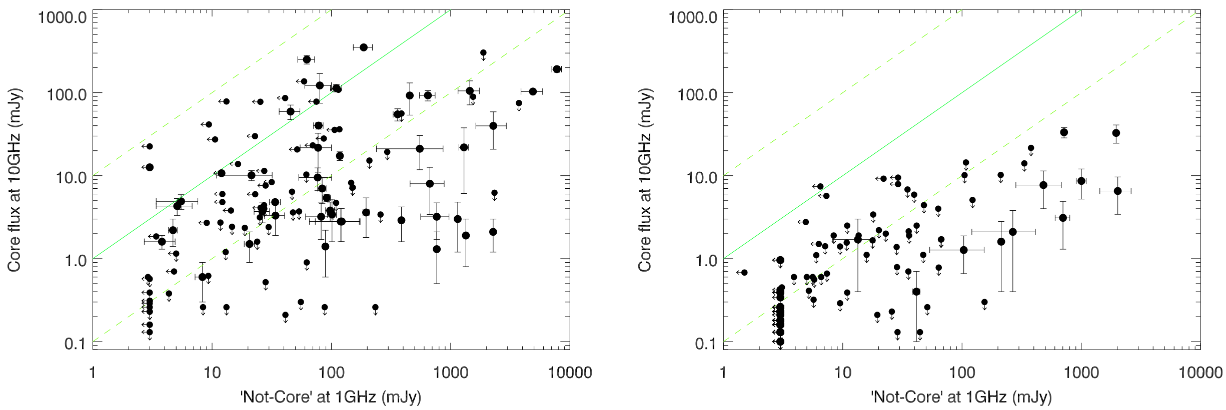

Figure 2: Comparison of the normalisation of two spectral components of the radio spectra of BCGs in X-ray selected clusters in terms of the flux density of a steeper spectrum ('Not-Core') component (normalised at 1 GHz) and a flatter spectrum component (normalised at 10 GHz). On the left is the distribution for BCGs with optical line emission (and hence very likely to be cooling flows) and on the right for BCGs without line emission (non-cooling flows). The green lines mark lines of equal flux density between components (solid) and an order of magnitude either side (dashed). Note the significant fraction of cooling flows with a flat spectrum component of comparable flux density to the more extended, steeper emission that accompanies it.

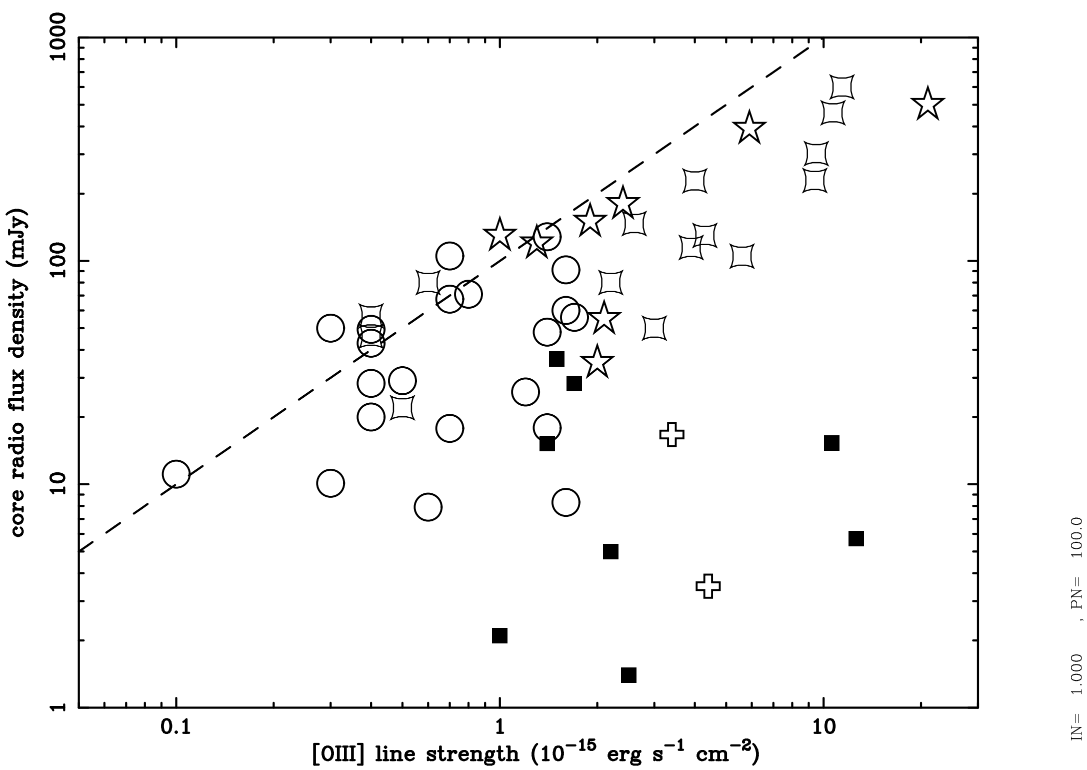

Figure 3: The VLBA recovered core flux density at 5GHz plotted against the observed optical [OIII] line flux for the host galaxy. The stars are from our 2010 VLBA campaign, the circles from our 2013 campaign, the open squares are BCGs that are in the VLBA calibrator list and the solid squares and open crosses are BCGs dominated by star-formation and/or an obscured AGN that dominates the [OIII] emission. Note the strong upper bound to the radio flux for a given optical line flux.

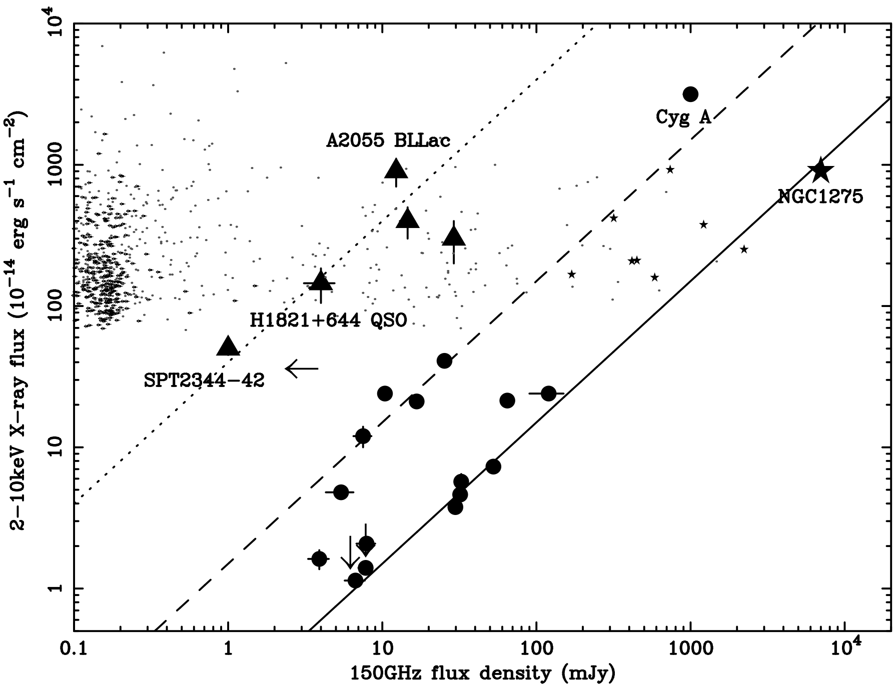

Figure 4: *Chandra* point source X-ray flux plotted against the 2mm flux from IRAM 30m GISMO observations of BCGs. The solid circles are BCGs with narrow optical emission lines and significant compact, flat spectrum radio cores. The solid triangles are BCGs known to be dominated by an AGN component, a QSO in the case of H1821+64 and a BLLac in the case of A2055. The larger, solid stars shows where SPT2344-42 should lie if its radio spectrum can be extrapolated to 150GHz and the current position of NGC1275. The small points mark the position of ROSAT-selected AGN studied by Mahony et al. (2012) at 20GHz extrapolated to 150GHz and the *Chandra* band as a comparison. The small stars mark the eight Mahony et al. sources that have a significant Fermi LAT source. The lines denote constant radio/X-ray flux ratio.

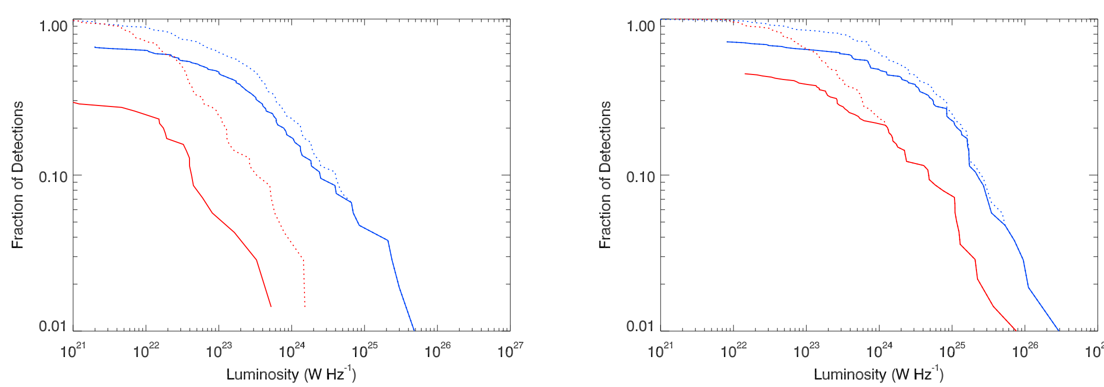

Figure 5: The cumulative luminosity function of BCGs for their cores at 10GHz (left) and their more extended, steeper spectrum emission at 1GHz (right). The blue lines represent cooling flows and red the non-cooling flows. Again the dotted lines mark the maximum possible contribution of each BCG by assuming a detection just below the detection limit.

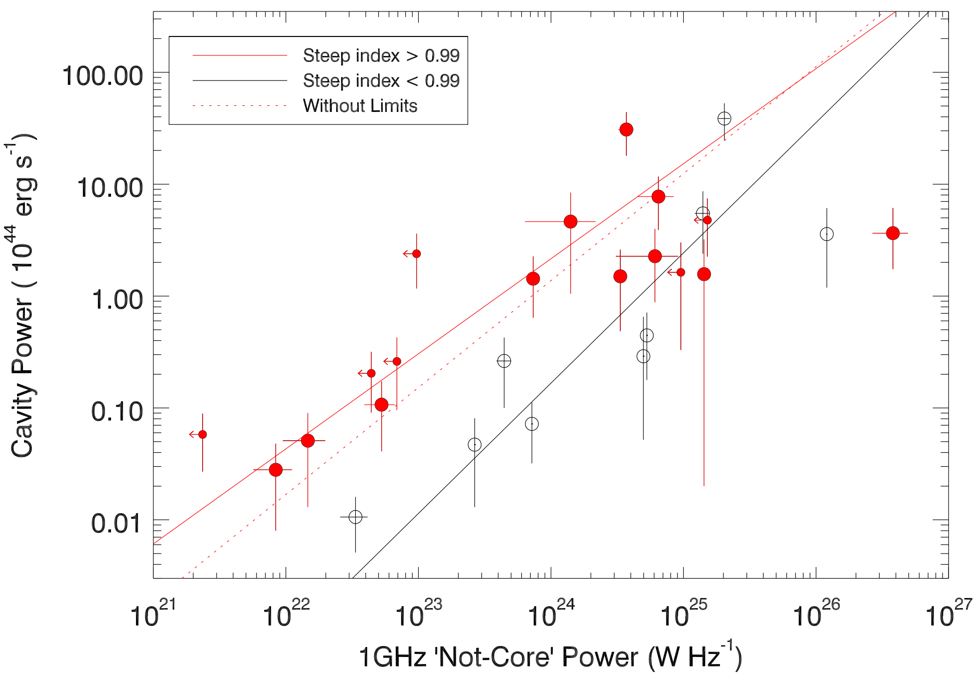

Figure 6: The X-ray-derived cavity power compared to the steeper spectrum ('Not-Core') radio power normalised at 1 GHz for all clusters with suitable X-ray limits. The open symbols are for systems with a spectral index of $\alpha > -1$ and filled red points are for those with $\alpha < -1$ (i.e. steeper spectrum). Note that the flatter spectrum systems have substantially more radio powerful sources for a given cavity power. This difference is expected if the radio source steepens and fades as the cavities expand.