NB: Michigan State University is denoted as MSU below, while the University of Waterloo is denoted as UW.

ICM Temperature Inhomogeneity, MSU, 2002-2008, M. Donahue

To more accurately weigh galaxy clusters, how secondary dynamical processes (*e.g.* mergers and AGN feedback) alter cluster observables must first be quantified if cluster temperature or luminosity are to serve as accurate mass proxies. It has been demonstrated that spatial cluster substructure correlates well with dynamical state, and that the most relaxed clusters have the smallest deviations from mean mass-observable relations (*e.g.* [1]). But spatial analysis is at the mercy of perspective. If equally robust aspect-independent measures of dynamical state could be found, then quantifying deviation from mean mass-scaling relations would be improved and the uncertainty of inferred cluster masses could be further reduced. The Cavagnolo dissertation confronts this difficulty via temperature inhomogeneity.

If the hot ICM is nearly isothermal in the projected region of interest, the X-ray temperature inferred from a broadband (0.7-7.0 keV) spectrum should be identical to the X-ray temperature inferred from a hard-band (2.0-7.0 keV) spectrum. However, if unresolved cool lumps of gas are contributing soft X-ray emission, the temperature of a best-fit single-component thermal model will be cooler for the broadband spectrum than for the hard-band spectrum. Using this difference as a diagnostic, the ratio of best-fitting hard-band and broadband temperatures may indicate the presence of cooler gas even when the X-ray spectrum itself may not have sufficient signal-to-noise ratio to resolve multiple temperature components [2].

Building on the [2] simulation results, the dissertation investigates the band dependence of the inferred X-ray temperature of the ICM for 192 well-observed galaxy clusters selected from the *Chandra* Data Archive. X-ray spectra from core-excised annular regions of fixed fractions of the virial radius, R_{2500} and R_{5000}, are extracted for each cluster in the archival sample. A comparison is made of the X-ray temperatures inferred from single-temperature fits when the energy range of the fit is 0.7-7.0 keV (broad) and when the energy range is 2.0/(1+z)-7.0 keV (hard). On average, the hard-band temperature is found to be significantly higher than the broadband temperature, and the ratio of the temperatures is quantified as $T_{HBR} = T_{2.0-7.0}/T_{0.7-7.0}$, shown in Figure 1. On further exploration, it is found that the temperature ratio T_{HBR} is enhanced preferentially for clusters which are known merging systems. In addition, cool-core clusters tend to have best-fit hard-band temperatures that are in closer agreement with their best-fit broadband temperatures, shown using symbols in Figure 1. Presuming cool cores and mergers are good indicators of dynamical state, the dissertation concludes that T_{HBR} is a useful metric for further assessing the process of cluster relaxation. The work associated with this part of the dissertation is published in [3].

ICM Entropy Profiles, MSU, 2002-2008, M. Donahue & M. Voit

ICM temperature and density alone primarily reflect the shape and depth of the cluster dark matter potential, but it is the specific entropy of a gas parcel which governs the density at a given pressure [4]. In addition, the ICM is convectively stable when, without dramatic perturbation, the lowest entropy gas is near the core and high entropy gas has buoyantly risen to large radii. ICM entropy can also only be changed by addition or subtraction of heat, thus the entropy of the ICM reflects most of the cluster thermal history. Therefore, properties of the ICM can be viewed as a manifestation of the dark matter potential and cluster thermal history - which is encoded in the entropy structure (*e.g.* [4]). ICM Entropy is therefore a useful quantity for studying the effects of feedback on the cluster environment and investigating the breakdown of cluster self-similarity.

The dissertation studies feedback using radial entropy profiles of the ICM for a collection of 239 clusters taken from the *Chandra* Data Archive, presented in Figure 2. It is found that most ICM entropy profiles are well-fit by a model which is a power-law at large radii and approaches a constant entropy value at small radii: $K(r) = K_0 + K_{100}(r/100\text{ kpc})^{\alpha}$, where K_0 quantifies the typical excess of core entropy above the best fitting power-law found at larger radii and K_{100} is the entropy normalization at 100 kpc. Discussion is presented in relation to theoretical models (*e.g.* [5]) explaining why non-zero K_0 values are consistent with the process of energy injection from AGN feedback. Further, it is shown that the K_0 distributions of both the full archival sample and the flux-limited, unbiased primary *HIFLUGCS* sample of [6, 7] are bimodal with a distinct gap centered at $K_0 \approx 40$ keV cm^2 and population peaks at $K_0 \sim 15$ keV cm^2 and $K_0 \sim 150$ keV cm^2 (Figure 3). It is suggested that the bimodal distribution may result from the effects of ICM thermal conduction and cluster-cluster mergers. The results from this work are presented in [8]. We are also making comparisons between entropy scaled as a function of cluster mass, temperature, and luminosity with expectations from large-scale structure models. The results of this additional work is being presented in [9].

ICM Entropy-Feedback Correlations, MSU, 2002-2008, M. Donahue & M. Voit

Also of interest is how cluster core entropy state is associated with AGN feedback and star formation in the galaxy which resides at the center of a cluster. As an extension of the radial entropy analysis, the dissertation delves into exploring the relationship between some expected by-products of ICM cooling – *e.g.* gaseous instabilities, star formation, and AGN activity – and the K_0 values of clusters. To determine the activity level of feedback in cluster cores, the readily available observables Hα and radio emission are selected as tracers.

Utilizing the results of the archival study of intracluster entropy, the dissertation goes on to show that Hα and radio emission from central cluster galaxies are much more pronounced when the cluster's core gas entropy is $\lesssim 30$ keV cm^2. The prevalence of Hα emission below this threshold indicates that it marks a dichotomy between clusters that can harbor multiphase gas and star formation in their cores and those that cannot. The fact that strong central radio emission also appears below this boundary suggests that feedback from an AGN turns on when the ICM starts to condense, strengthening the case for AGN feedback as the mechanism that limits star formation in the Universe's most luminous galaxies. The results of this work are presented in [10]. The dissertation results also suggest that the sharp entropy threshold for the formation of thermal instabilities in the ICM and initiation of processes such as star formation and AGN activity arises from thermal conduction. A discussion of this topic is presented in [11].

RBS 797, UW, 2008-present, B. McNamara & M. Gitti

The most powerful AGN outbursts in the Universe are useful for placing constraints on possible fueling mechanisms for the AGN. Systems such as MS 0735.6+7421, Hercules A, and Hydra A stress the limits of cold gas accretion models (such as Bondi accretion), and open the door to new mechanisms such as black hole spin [12]. The galaxy cluster RBS 797 is another system which has undergone a cluster-scale AGN outburst. R797 has a pair of X-ray cavities which suggest the AGN outburst in the system is of order $\sim 10^{45-46}$ erg s^{-1}, making it one of the most powerful outbursts ever observed. I have undertaken the detailed analysis of this peculiar system using X-ray, radio, infrared, optical, and UV data. The results of this work are being published in a first author paper [13].

AGN Jet Power-Radio Luminosity Relation, UW, 2008-2010, B. McNamara & C. Carilli

A long-standing problem in observational and theoretical studies of energetic feedback from supermassive black holes as it relates to large-scale structure formation is estimating the total kinetic output from an active galactic nucleus. These estimates have historically been made using models of AGN jets and their impact on the surrounding environment. However, the ICM has proven to be a robust bolometer for measuring jet power courtesy of X-ray cavities. Using a sample of clusters, groups, and isolated giant ellipticals with cavities I have completed a project which measured and calibrated jet power versus radio luminosity. This was an extension of the oft-cited [14, 15] work. For the project, I observed 13 gEs (39 hrs. total) at P-band (327 MHz; 90 cm) using the new EVLA system, and analyzed > 50 archival observations for 21 additional objects at a variety of frequencies (1.4 GHz, 5 GHz, and 8 GHz). We found that jet power scales with radio luminosity to the 0.7 power with a normalization of $\sim 10^{43}$ erg s^{-1}, in accord with current jet models. Our results have implications for galaxy formation, black hole growth, and the mechanical heating of the universe. The results are being published in a first author paper [16]. We are using the results of this study to explore the AGN kinetic luminosity function over cosmic time, and to analyze a subset of peculiar FR-I radio galaxies in more detail.

IRAS 09104+4109, UW, 2009-present, M. Donahue & B. McNamara

The transition from quasar-mode to radio-mode feedback in hierarchical structure formation is a poorly understood process. The transition likely coincides with the formation of dense galactic environments like clusters and groups, in addition to the formation of the most massive galaxies which will become present-day BCGs. But we know this process does not proceed unregulated, lest extremely blue cDs residing in catastrophically cooling cluster cores will form. As a probe of how the BCG assembly and ICM heating process proceeds, we obtained deep *Chandra* imaging of the famous and peculiar ULIRG/QSO IRAS 09104+4109. As suspected, we directly imaged a pair of cavities in the X-ray halo surrounding IRAS09. These cavities contain enough energy to offset $\approx 25-35\%$ of the cooling occurring within the cooling radius of the host galaxy cluster. This result suggests only 3-4 such outbursts are needed to halt cooling in the cluster and freeze-out rapid star formation in the BCG. The line-of-sight nuclear absorber in this system has also (as of our current analysis) changed from optically thick to thin over the course of the last 20 years, making this the first-ever observed changing-look QSO. Even more exciting is the change in beaming direction of the AGN within the last few kyrs which has dredged up cool gas from the core, and is likely forming new stars as a result. This work has produced a first author paper [17].

Steep Spectrum Radio Sources, UW, 2010-present, A. Edge

The cores of galaxy clusters are active environments where thermodynamic balance is struck via AGN feedback energy. Many ongoing and previous studies have focused on systems hosting AGN feedback where radio emission and X-ray cavities directly indicate "active" feedback. Along with Alastair Edge at Durham University, we have acquired 50+ hours of 325 MHz radio data for 14 galaxy clusters where unresolved steep radio spectrum sources have been identified. The expectation is that these sources host radio relics from past AGN activity, or the sources result from a subcluster merger has created a radio halo. This study is a key forerunner to the analysis of large samples of similar sources found with LOFAR.

X-ray Mass Estimates, UW, 2009-present, R. Mandelbaum

I am a member of the Supermassive Cluster Survey and am responsible for the X-ray mass analysis in the project. The study is headed-up by Rachel Mandelbaum and seeks to better understand the scatter between X-ray and weak lensing masses for a sample of 12 galaxy clusters. The project is in its final stages with the mass determinations from the X-ray data currently being performed. The project will produce at least one paper on which I am one of the primary co-authors.

2D Abundance Distributions, UW, 2008-present, C. Kirkpatrick & B. McNamara

Clif Kirkpatrick is a senior Ph.D. student under Dr. McNamara. I have co-authored two papers with Clif [18, 19], and we are working on a series of new papers which present analysis of the 1D and 2D heavy metal distributions for a large sample of galaxy clusters. We are specifically interested in how metal transport is related to the process of AGN feedback, and what we can discern about ICM metal enrichment over cosmic time using these results.

Black Hole Spin, UW, 2009-present, B. McNamara & M. Rohanizadegan

Mina Rohanizadegan is a junior Ph.D. student under Dr. McNamara. We are currently working on the analysis of X-ray data to learn about the instantaneous accretion onto SMBHs at the center of galaxy clusters. The aim is to place constraints on the fueling mechanism which gives rise to the AGN jets which bore cavities into the ICM. Mina is also finishing up a co-authored paper which presents comparisons of models for AGN power generation via cold gas accretion and black spin using the robust jet power measures from X-ray cavities. As a supplement to this work, I am writing a paper which discusses the complications of reorienting the spin axis of a SMBH via mergers. Spin axis reorientation has become somewhat of a "fad" in the last decade to explain the morphology of some radio sources and as an explanation for the distribution of AGN feedback energy beyond the small cross-section of AGN jets. However, spin axis reorientation is exceedingly difficult and requires a very specific set of impact parameters which, as discerned from cosmological simulations, are found to be very rare.

Search for Giant Galactic Cores and Radio-Xray Cross-correlations, UW, 2009-present, B. Whuiska, R. Myers, & B. McNamara

Brad Whuiska and Rob Myers are senior undergraduates working with Dr. McNamara. Brad is measuring the core radius for BCGs in the HST archive. The aim of his study is to find the largest cores and analyze them under the assumption that the large cores were created via scouring (the process of stellar ejection via SMBH mergers). The work is producing results which will be presented in a paper on which I will be a co-author. Rob is undertaking the detection of BCG radio sources in X-ray selected clusters using the NVSS and SUMSS all-sky radio surveys. These sources will then be run through our $P_{jet} - P_{radio}$ relations, and an estimate of the heating resulting from these AGN will be assessed. Rob is also examining the connection with cluster properties such as X-ray luminosity and temperature. Rob's work is also producing results which will be presented in a co-author paper.

References

[1] D. A. Ventimiglia, G. M. Voit, M. Donahue, and S. Ameglio. Substructure and Scatter in the Mass-Temperature Relations of Simulated Clusters. *ApJ*, 685:118–127, September 2008.

[2] B. F. Mathiesen and A. E. Evrard. Four Measures of the Intracluster Medium Temperature and Their Relation to a Cluster's Dynamical State. *ApJ*, 546:100–116, January 2001.

[3] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Bandpass Dependence of X-Ray Temperatures in Galaxy Clusters. *ApJ*, 682:821–834, August 2008.

[4] G. M. Voit, G. L. Bryan, M. L. Balogh, and R. G. Bower. Modified Entropy Models for the Intracluster Medium. *ApJ*, 576:601–624, September 2002.

[5] G. M. Voit and M. Donahue. An Observationally Motivated Framework for AGN Heating of Cluster Cores. *ApJ*, 634:955–963, December 2005.

[6] T. H. Reiprich. *An X-Ray Flux-Limited Sample of Galaxy Clusters: Physical Properties and Cosmological Implications*. PhD thesis, AA(Max-Planck-Institut für extraterrestrische Physik, P.O. Box 1312, 85741 Garching, Germany), July 2001.

[7] T. H. Reiprich and H. Böhringer. The Mass Function of an X-Ray Flux-limited Sample of Galaxy Clusters. *ApJ*, 567:716–740, March 2002.

[8] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Intracluster Medium Entropy Profiles for a Chandra Archival Sample of Galaxy Clusters. *ApJS*, 182:12–32, May 2009.

[9] K. W. Cavagnolo, G. M. Voit, M. Donahue, and M. Sun. Galaxy Cluster Entropy Scaling Relatons. *In preparation for ApJ*, 2010.

[10] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. An Entropy Threshold for Strong Hα and Radio Emission in the Cores of Galaxy Clusters. *ApJ*, 683:L107–L110, August 2008.

[11] G. M. Voit, K. W. Cavagnolo, M. Donahue, D. A. Rafferty, B. R. McNamara, and P. E. J. Nulsen. Conduction and the Star Formation Threshold in Brightest Cluster Galaxies. *ApJ*, 681:L5–L8, July 2008.

[12] B. R. McNamara, F. Kazemzadeh, D. A. Rafferty, L. Bîrzan, P. E. J. Nulsen, C. C. Kirkpatrick, and M. W. Wise. An Energetic AGN Outburst Powered by a Rapidly Spinning Supermassive Black Hole or an Accreting Ultramassive Black Hole. *ApJ*, 698:594–605, June 2009.

[13] K. W. Cavagnolo and B. R. McNamara. The AGN Outburst in RBS 797: One of the Most Powerful Ever Observed. *In preparation for ApJ*, 2010.

[14] L. Bîrzan, D. A. Rafferty, B. R. McNamara, M. W. Wise, and P. E. J. Nulsen. A Systematic Study of Radio-induced X-Ray Cavities in Clusters, Groups, and Galaxies. *ApJ*, 607:800–809, June 2004.

[15] L. Bîrzan, B. R. McNamara, P. E. J. Nulsen, C. L. Carilli, and M. W. Wise. Radiative Efficiency and Content of Extragalactic Radio Sources: Toward a Universal Scaling Relation between Jet Power and Radio Power. *ApJ*, 686:859–880, October 2008.

[16] K. W. Cavagnolo, B. R. McNamara, C. L. Carilli, C. Jones, W. R. Forman, P. E. J. Nulsen, L. Bîrzan, and S. Murray. A Relationship Between AGN Jet Power and Radio Luminosity. *In preparation for ApJ*, 2009.

[17] K. W. Cavagnolo, M. Donahue, B. R. McNamara, G. M. Voit, and M. Sun. Cavities and Changing-Look QSO in the ULIRG IRAS 09104+4109. *In preparation for ApJL*, 2010.

[18] C. C. Kirkpatrick, B. R. McNamara, D. A. Rafferty, P. E. J. Nulsen, L. Bîrzan, F. Kazemzadeh, M. W. Wise, M. Gitti, and K. W. Cavagnolo. A Chandra X-Ray Analysis of Abell 1664: Cooling, Feedback, and Star Formation in the Central Cluster Galaxy. *ApJ*, 697:867–879, May 2009.

[19] C. C. Kirkpatrick, M. Gitti, K. W. Cavagnolo, B. R. McNamara, L. P. David, P. E. J. Nulsen, and M. W. Wise. Direct Evidence for Outflow of Metal-enriched Gas Along the Radio Jets of Hydra A. *ArXiv e-prints*, ApJL Accepted, September 2009.

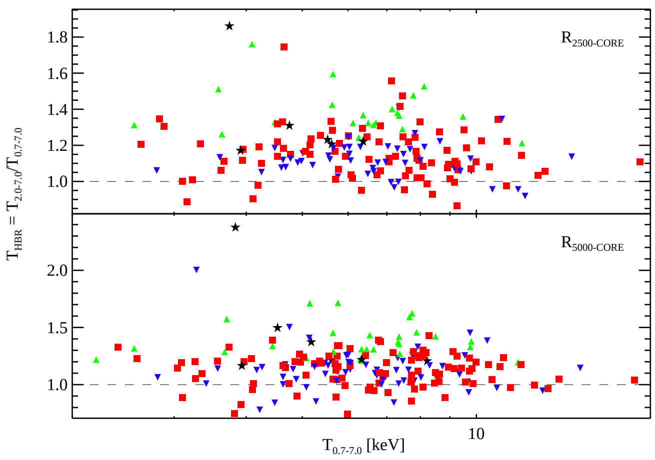

Figure 1: T_{HBR} vs. $T_{0.7-7.0}$. The dashed line is the line of equivalence. Symbols and color coding are based on two criteria: 1) presence of a cool core (CC) and 2) value of T_{HBR}. Black stars are clusters with a CC and T_{HBR} significantly greater than 1.1. Green upright-triangles are NCC clusters with T_{HBR} significantly greater than 1.1. Blue down-facing triangles are CC clusters and red squares are NCC clusters. It is found that most, if not all, of the clusters with $T_{HBR} \gtrsim 1.1$ are merger systems.

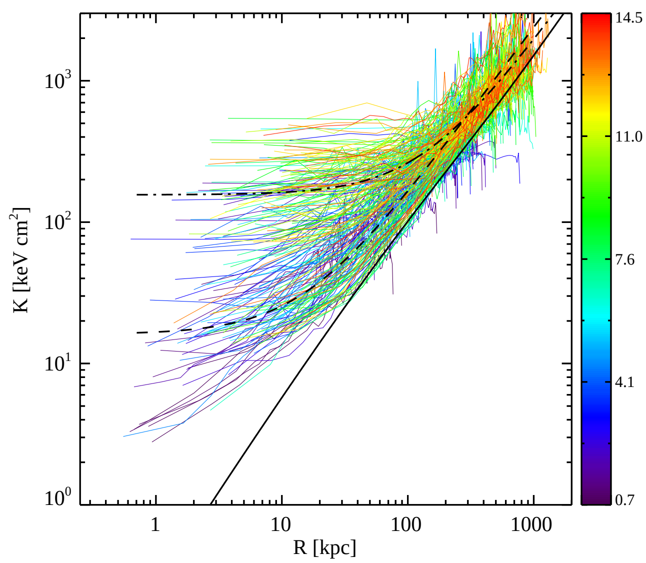

Figure 2: Composite plot of entropy profiles for archival sample. Profiles are color-coded based on average cluster temperature; units of the color bar are keV. The solid line is the pure-cooling model of [4], the dashed line is the mean profile for clusters with $K_0 \leq 50$ keV cm^2, and the dashed-dotted line is the mean profile for clusters with $K_0 > 50$ keV cm^2.

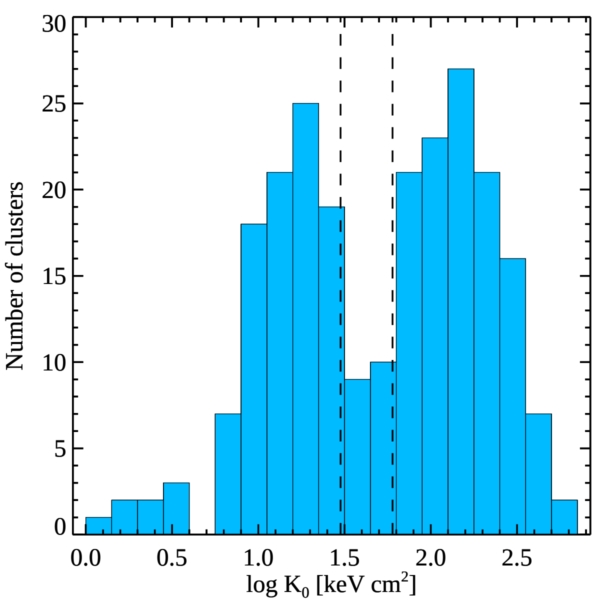

Figure 3: Histogram of best-fit K_0 for all the clusters in the archival study. Bin widths are 0.15 in log space. The distinct bimodality in $K_0$is bracketed by the vertical dashed lines.

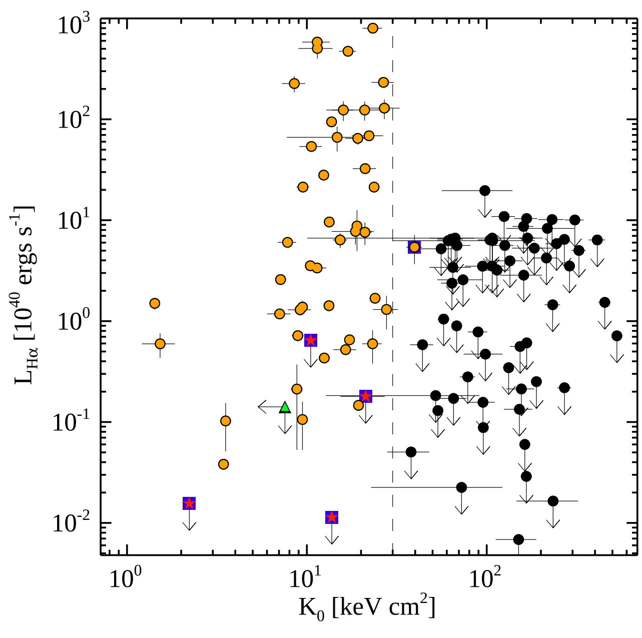

Figure 4: Central entropy vs. Hα luminosity. Orange circles represent Hα detections, black circles are non-detection upper limits, and blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend. The vertical dashed line marks $K_0 = 30$ keV cm^2. Note the presence of a sharp Hα detection dichotomy beginning at $K_0 \lesssim 30$ keV cm^2.