RESEARCH SUMMARY

Intracluster Medium (ICM) Temperature Inhomogeneity: If simple galaxy cluster X-ray observables, *e.g.* temperature (T) or luminosity (L), are to serve as accurate mass proxies, how processes like mergers alter these observables need to be quantified. It is known that scaled ratios of L and T, along with measures of ICM substructure, correlate well with cluster dynamical state, and that the apparently most relaxed clusters have the smallest deviations from mean mass-observable relations (*e.g.* [1, 2]). If a cluster's intracluster medium (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 there are unresolved, cool lumps of gas, the estimated cluster temperature may be cooler in the broadband versus the hard-band. This difference is then another diagnostic to indicate the presence of cooler gas, *e.g.* associated with merging sub-clusters, even when the X-ray spectrum itself may not have sufficient signal-to-noise to resolve multiple temperature components [3]. Cavagnolo et al. 2008 is a study of this band dependence for 192 clusters taken from the *Chandra* Data Archive. We found, on average, that the hard-band temperature was significantly higher than the broadband temperature, and that their ratio was preferentially larger for known mergers. Our results suggest a temperature diagnostic may be a useful tool for further minimizing the scatter about mean mass-scaling relations and obtaining more precise cluster mass estimates.

ICM Entropy: ICM temperature and density mostly reflect the shape and depth of a cluster's dark matter potential – it is the specific entropy which governs the density at a given pressure [4]. Without disturbance, the ICM becomes convectively stable when the lowest entropy gas occupies the bottom of the cluster potential and the highest entropy gas has buoyantly risen to large radii. Further, ICM entropy is primarily changed through heat exchange. Thus, deviations of the ICM entropy structure from the azimuthally symmetric, radial power-law distribution which should result from pure cooling are useful in evaluating a cluster's thermodynamic history [4]. Hence, one reason to study ICM entropy distributions is to better understand the effects of energetic feedback processes, *e.g.* from active galactic nuclei (AGN), on the cluster environment and investigating the breakdown of cluster self-similarity.

In Cavagnolo et al. 2009 [5], the ICM entropy structure of 239 clusters taken from the *Chandra* Data Archive were studied. We found that most clusters have entropy profiles which 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. Our results are consistent with models which predict cooling of a cluster's X-ray halo is offset by energy injected via feedback from active galactic nuclei [*e.g.* 6]. We also showed that the distribution of K_0 values in our archival sample is bimodal, with a distinct gap around a $K_0 \approx 40$ keV cm^2.

If cooling of a galaxy cluster's halo triggers eventual heating via an AGN-centric feedback loop, then certain properties of the ICM may correlate tightly with signatures of feedback and/or indicators of cooling. In Cavagnolo et al. 2008 [7] we explored the relationship between Hα emission from cluster cores, radio emission from cluster central galaxies, and cluster K_0 values. Utilizing the results of the archival study of intracluster entropy, we found that Hα and radio emission are almost strictly associated with K_0 values less than 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. In Voit et al. 2008 [8] we go on to suggest that K_0 bimodality and the entropy threshold may occur as a result of thermal conduction in the ICM. We are currently investigating the self-similiar scaling properties of the entropy distributions for our sample [9].

Details of AGN Feedback: There are still many unknowns regarding the process of AGN feedback, one of which is how much total kinetic energy is released via relativistic jets. Pre-*Chandra*, jet power ($P_{\rm jet}$) estimates were made primarily with jet models [*e.g.* 10]. However, the discovery of ICM X-ray cavities [*e.g.* 11] removed the model dependance by enabling direct measurement of the work an AGN performs on its surroundings [12]. It was then possible to determine how a simple observable like monochromatic AGN radio power ($P_{\rm radio}$) scales with $P_{\rm jet}$ [*e.g.* 13, 14]. One aim of such studies was to hopefully reduce the need for X-ray data to study the heating of the Universe as a function of redshift using large samples of radio galaxies taken from monochromatic all-sky radio surveys. Using a sample of clusters, groups, and giant ellipticals (gEs) with detected cavities, Cavagnolo et al. 2010 presents an updated version of the Bîrzan et al. 2008 $P_{\rm jet}$-$P_{\rm radio}$ relation. We found, independent of radio frequency, that $P_{\rm jet}$ scales as $P_{\rm radio}^{0.7}$ with a normalization of $\sim 10^{43}$ erg s^{-1}, in accordance with several jet models. We also identifies several gEs with unusually large $P_{\rm radio}$ for their $P_{\rm jet}$, all of which have radio sources which extend beyond the densest regions of their hot halos. We suggested that these systems may result from their jets being unable to entrain appreciable amounts of gas.

It is well-known that the process of galaxy growth and cluster/group evolution is likely regulated by AGN feedback [*e.g.* 15, 16], lest ultramassive galaxies prodigiously forming stars will emerge in the cores of galaxy clusters/groups which are catastrophically cooling. For simplicity, galaxy formation models divide AGN feedback into an early-time quasar-mode (radiatively dominated feedback) to a late-time radio-mode (mechanically dominated feedback). However, the observational constaints on how systems transition from one to the other are very poor. The importance of this transition is increased because it may coincide with 1) the formation of dense galactic environments which host the poorly studied population of obscured AGN, and 2) the merger of massive galaxies which become present-day brightest cluster galaxies (BCGs).

As a test of these models, we performed a X-ray study of the famous and peculiar ULIRG/BCG IRAS 09104+4109 (I09) which hosts an obscured quasar. We were able image X-ray halo cavities (mechanical feedback) and irradiation of the halo by the central quasar (radiative feedback), making this the first known system where both channels of feedback have been simultaneously studied. We found that the mechanical to radiative feedback ratio is $\approx 100:1$, and that the cavities contain enough energy to offset $\approx 25\%$ of the halo cooling. We argue that I09 may be a local example of how massive galaxies at higher redshift form and evolve, and suggest that other odd properties of the system (*e.g.* the misaligned beaming and jet axes) may be related to evolution of the central supermassive black hole's spin axis.

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 [**?**]. 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 [17].

[18]

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 [19].

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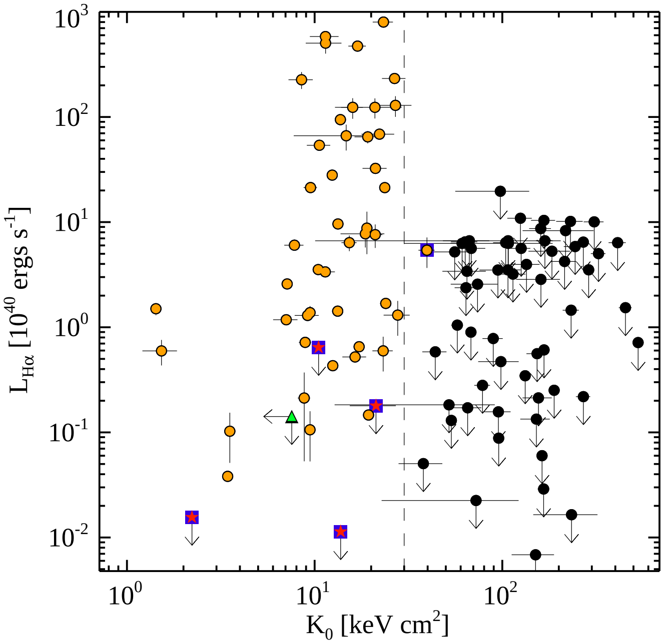

Figure 1: Central entropy vs. Hα luminosity. Orange circles represent Hα detections, black circles are non-detection upper limits, and blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend. The vertical dashed line marks $K_0 = 30$ keV cm^2. Note the presence of a sharp Hα detection dichotomy beginning at $K_0 \lesssim 30$ keV cm^2.

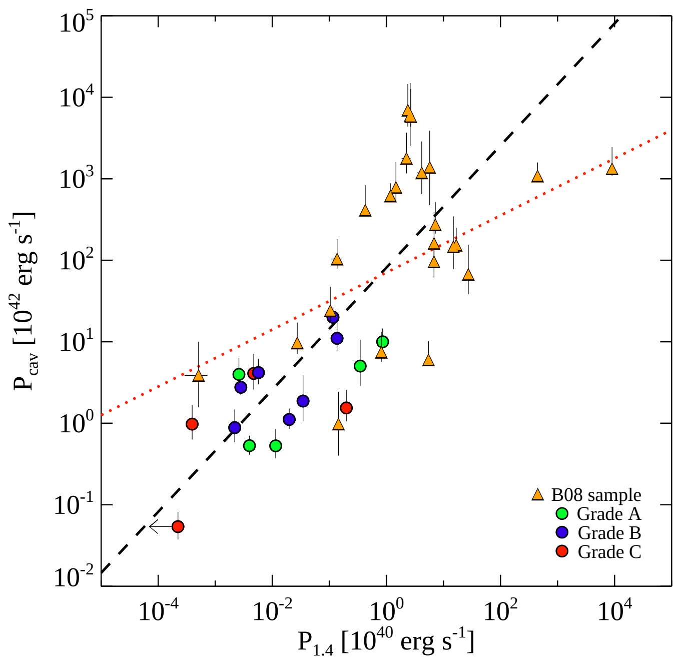

Figure 2: Cavity power vs. 1.4 GHz radio power. Orange triangles represent cluster and group sample of [14], filled circles are our gE sample, colors represent the quality of cavities: green = 'A,' blue = 'B,' and red = 'C.' Dotted red lines represent [14] best-fit relations. Dashed black lines represent our BCES best-fit power-law relations.