SUMMARY OF PAST AND ON-GOING RESEARCH

In a broad sense, my research program focuses on galaxy clusters, both as astrophysical laboratories and interesting structures in their own right. In the case of the latter, it is the properties of the intracluster medium (ICM) which have captivated me, while for the former, I am most interested in feedback from active galactic nuclei (AGN) and the processes which couple AGN activity and the ICM. Some highlights of my research in these areas are presented below.

I. ICM Temperature Inhomogeneity

If simple galaxy cluster observables such as temperature or luminosity are to serve as accurate mass proxies, how mergers alter these observables needs to be quantified. It is known that cluster substructure correlates well with dynamical state, and that the apparently most relaxed clusters have the smallest deviations from mean mass-observable relations [*e.g.* 1]. But, 2D analysis is at the mercy of perspective. If a cluster's 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 temperature of a single-component thermal model will be cooler in the broadband versus the hard-band. This difference is then possibly a 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 [2].

In Cavagnolo et al. 2008 [3] we studied this temperature 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 (Fig. 1). The interpretation of this result is that, indeed, ICM temperature inhomogeneity is detectable via a simple bandpass comparison and, on average, it correlates with cluster dynamical state. Our results suggest such a temperature diagnostic may be useful when designing metrics to minimize the scatter about mean mass-scaling relations in an attempt to obtain smaller uncertainties in cluster mass estimates.

II. ICM Entropy and AGN Feedback

ICM temperature and density mostly reflect the shape and depth of a cluster's dark matter potential – it is the specific entropy ($K \approx kT_{\rm X} n_{\rm e}^{-2/3}$) which governs the density at a given pressure [4]. Ignoring convective instabilities induced by anisotropic conduction, the ICM is convectively stable when the lowest gas entropy occupies the bottom of the cluster potential and the highest entropy gas has buoyantly risen to larger 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 [5]. One key use of ICM entropy is for studying the effects of energetic feedback on the cluster environment and investigating the breakdown of cluster self-similarity [6].

In Cavagnolo et al. 2009 [7], 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: $K(r) = K_0 + K_{100}(r/100\ \mathrm{kpc})^{\alpha}$, 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 (Fig. 2). Our results are consistent with models which predict cooling of a cluster's X-ray halo is offset by energy injected via feedback from AGN [*e.g.* 6]. We also showed that the distribution of K_0 values in our archival sample is bimodal, with a distinct gap around $K_0 \approx 40$ keV cm^2.

If cooling of a galaxy cluster's halo triggers eventual heating via an AGN-centric feedback loop, then certain ICM properties (*e.g.* entropy) may correlate tightly with signatures of feedback and/or indicators of cooling. In Cavagnolo et al. 2008 [8] 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 (Fig. 3), which is near the gap of the K_0 distribution. The prevalence of Hα emission below this threshold indicates that it marks a dichotomy between clusters that can harbor thermal instabilities (*e.g.* multiphase gas, 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 [9], we go on to suggest that core entropy bimodality and the sharp entropy threshold arises from the influence of thermal conduction. This result is one of the key motivating factors for the fellowship proposal that follows, and is discussed in more detail therein.

III. Details of AGN Feedback

A. Properties of Jets: A long-standing problem in observational and theoretical studies of AGN energetics is estimating total kinetic energy output. These estimates have historically been made using jet models built around first principles and observations of how it *appears* jets interact with their surroundings [*e.g.* 10]. However, X-ray observations of clusters have revealed that AGN outflows inflate cavities in the ICM, and these cavities yield a direct measure of the work, and hence total mechanical energy, exerted by the AGN on its environment [see 11, for details]. Hence, any correlation between derived cavity power and associated synchrotron radio power yields a useful device for constraining total AGN energy output when X-ray data or cavities are unavailable. Such relations between jet power ($P_{\rm jet}$) and radio power ($P_{\rm radio}$) for clusters were presented by Bîrzan et al. 2004, 2008 [12, 13]. In Cavagnolo et al. 2010 [14] we appended a sample of 13 giant ellipticals (gEs) to these studies to determine if a single $P_{\rm jet}$-$P_{\rm radio}$ relation extends from clusters down to isolated gEs.

Utilizing the analysis of $>$ 70 multifrequency, archival *VLA* observations and an array of low-frequency radio surveys, we found that the $P_{\rm jet}$-$P_{\rm radio}$ relation is continuous, and has similar scatter, from clusters down to gEs (Fig. 4). We also found that, independent of frequency, $P_{\rm jet}$ scales as $\sim P_{\rm radio}^{0.7}$ with a normalization of $\sim 10^{43}$ erg s^{-1}. Numerous jet models predict a power-law index of $\approx 12/17$, consistent with our results, and normalizations of $\sim 10^{43}$ erg s^{-1} when the ratio of non-radiating particles to relativistic electrons is $\gtrsim 20$ (*i.e.* moderately heavy jets). Our results imply that there does exist a universal scaling relation between jet power and radio power, which would be a useful tool for calculating AGN kinetic output over huge swathes of cosmic time using only all-sky, monochromatic radio surveys. The impact of this result extends into the areas of galaxy formation, black hole growth, and the mechanical heating of the universe.

B. Radio-mode and Quasar-mode Feedback: Galaxy formation models typically segregate AGN feedback into a distinct early-time, radiatively-dominated quasar mode [*e.g.* 15] and a late-time, mechanically-dominated radio mode [*e.g.* 16]. In quasar-mode, it is believed that intense quasar radiation ($> 10^{46}$ erg s^{-1}) couples to gas within the host galaxy and drives strong winds which deprive the SMBH of additional fuel, regulating growth of black hole mass. At later times, when quasar activity has faded and radio mode feedback takes over, SMBH launched jets regulate the growth of galaxy mass through prolonged and intermittent mechanical heating of a galaxy's gaseous halo (*i.e.* the process discussed in Section A). Though AGN feedback models are broken into two generic modes, they still form a unified schema [*e.g.* 17] which predicts a continuous distribution of AGN luminosities. However, the association of the modes, and whether they interact, is still poorly understood. In Cavagnolo et al. 2010 [18] we present a study of the famous & enigmatic massive galaxy IRAS 09104+4109 (IRAS09) which simultaneous exhibits all the characteristics of a system in radio- and quasar-mode of feedback, perhaps implying it is a "transition" object cycling between the modes.

A joint X-ray/radio analysis of IRAS09 reveals cavities in the galaxy's X-ray halo associated with an AGN outflow having $\sim 10^{44}$ erg s^{-1} of mechanical energy and an obscured nuclear quasar with a luminosity of $\sim 10^{47}$ erg s^{-1}. We directly measure, for the first time, that the radiative to mechanical feedback energy ratio for a "transition" object is $\sim$1000:1. Further, the cavities contain enough energy to offset $\approx 25 - 35\%$ of the host cluster's ICM radiative cooling losses. However, how this energy is thermalized remains unknown – which is one aspect of the fellowship proposal which follows. Nonetheless, our results suggest 3–4 similar strength AGN outbursts are sufficient to suppress ICM core cooling and freeze-out rapid BCG star formation. We also unambiguously demonstrate that the beaming directions of the jets and nuclear radiation are indeed misaligned, as previous studies have suggested. Our interpretations of these findings are that IRAS09 may be providing a local example of how the AGN feedback cycle of massive galaxies at higher redshifts evolves, and may also be offering clues as to how the evolution of black hole spin is closely correlated with the feedback cycle.

C. Black Hole Spin: Current models of the late-time feedback loop posit that cooling processes in a galaxy's halo result in mass accretion onto a central supermassive black hole (SMBH), thereby driving AGN activity. While there is direct evidence that halo cooling and feedback are linked [*e.g.* 8], the observational constraints on how AGN are fueled and powered remain loose. For example, what fraction of the energy released in an AGN outburst is attributable to the gravitational binding energy of the accreting matter [19] and the SMBH's rotational energy [20] is still unclear. Mass accretion alone can, in principle, fuel most AGN [*e.g.* 21]. However, there are gas-poor systems which host very powerful AGN (energies $> 10^{61}$ erg) where mass accretion alone appears unlikely as a power source. The importance of these systems in understanding AGN feedback is that either the AGN fueling has been astoundingly efficient, or the power has come from an alternate source, such as the release of angular momentum stored in a rapidly spinning SMBH [*e.g.* 22]. If more such systems can be found, then it may be necessary to incorporate a SMBH spin feedback pathway into galaxy formation models.

In Cavagnolo et al. 2010 [23], we present analysis of the AGN outburst in the galaxy cluster RBS 797 and, because of the extreme energetic demands of the outburst, suggest it may have been powered by black hole spin. We estimate the total energy output and jet power to be of the order 10^{61} erg and 10^{46} erg s^{-1}, respectively. These enormous energies demand that mass accretion alone is an implausible explanation for how the outburst was powered, and we thus suggest that the outburst resulted from the extraction of rotational energy stored in a rapidly-spinning SMBH. We conclude that RBS 797 may be further observational evidence that some AGN are powered by the release of SMBH spin energy.

The model of Garofalo et al. 2010 [24] suggests that the evolution of a black hole's spin state is closely tied to the process of AGN feedback. In their model, during the process of retrograde accretion induced spin-down, a black hole should pass through a state where its spin is ≈ 0. At this point, an asymmetric accretion flow exceeding a mass-dependent critical accretion rate can drastically and quickly reorient a spin axis. This process is the focus of Cavagnolo et al. 2010 [25] as it can possibly give rise to the type of beamed jet-radiation misalignment observed in IRAS09, and can also result in the extraction of extreme jet powers like in RBS 797. In this work, we discuss the complications of re-orienting the spin axis of a SMBH via mergers, which has become a bit fashionable as an explanation for how AGN feedback energy is distributed beyond the small cross-section of AGN jets. In the following fellowship proposal, how AGN feedback energy may be distributed is instead discussed in terms of microphysical ICM processes like conduction, turbulence, and magnetohydrodynamic instabilities.

IV. References

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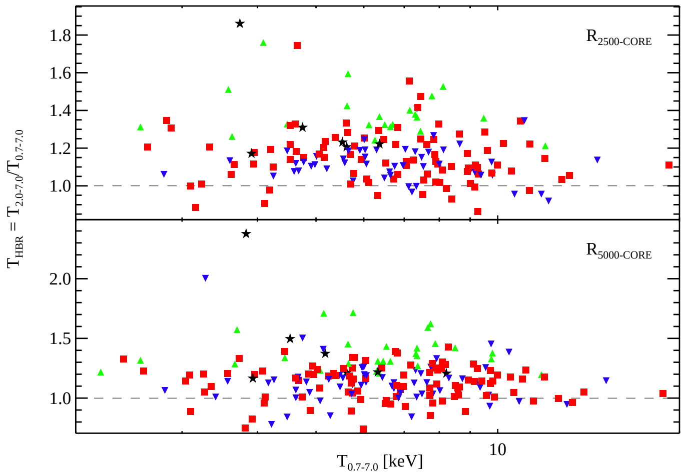

Figure 1: T_{HBR} vs. $T_{0.7-7.0}$. The dashed line is the line of equivalence. Symbols and color coding are based on two criteria: 1) presence of a cool core (CC) and 2) value of T_{HBR}. Black stars are clusters with a CC and T_{HBR} significantly greater than 1.1. Green upright-triangles are NCC 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.

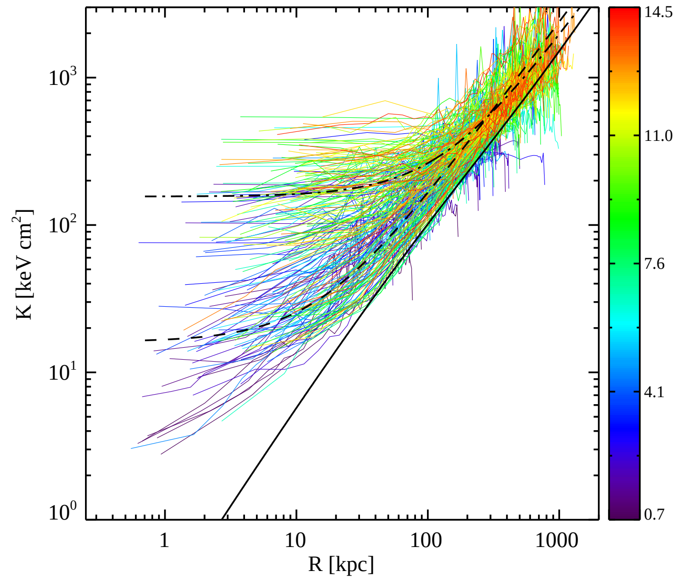

Figure 2: Composite plot of entropy profiles for archival sample. Profiles are color-coded based on average cluster temperature; units of the color bar are keV. The solid line is the pure-cooling model of Voit et al. 2002 [4], the dashed line is the mean profile for clusters with $K_0 \leq 50$ keV cm^2, and the dashed-dotted line is the mean profile for clusters with $K_0 > 50$ keV cm^2.

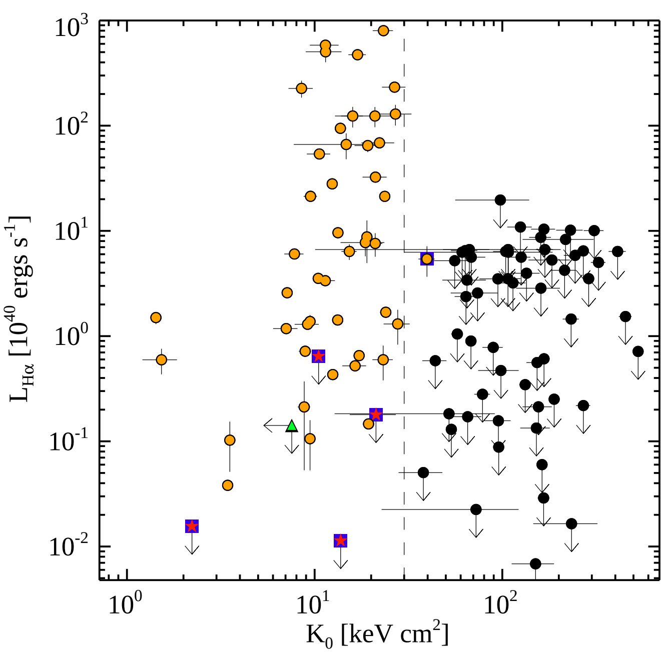

Figure 3: Central entropy vs. Hα luminosity. Orange circles represent Hα detections, black circles are non-detection upper limits, and blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend. The vertical dashed line marks $K_0 = 30$ keV cm^2. Note the presence of a sharp Hα detection dichotomy beginning at $K_0 \lesssim 30$ keV cm^2.

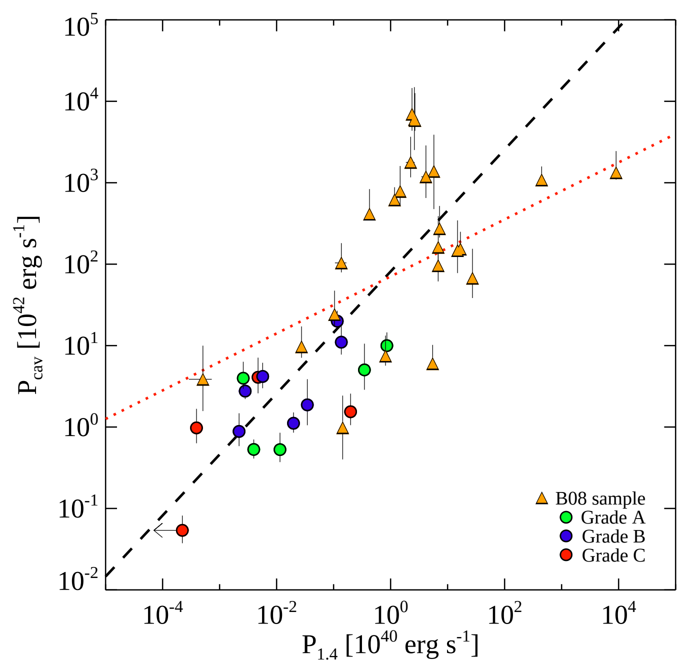

Figure 4: Cavity power vs. 1.4 GHz radio power. Orange triangles represent cluster and group sample of Bîrzan et al. 2008 [13], filled circles are our gE sample, colors represent the quality of cavities: green = 'A,' blue = 'B,' and red = 'C.' Dotted red lines represent Bîrzan et al. best-fit relations. Dashed black lines represent our BCES best-fit power-law relations.