Summary of Past Research and Future Interests

The general process of galaxy cluster formation through hierarchical merging is well understood, but many details, such as the impact of feedback sources on the cluster environment and radiative cooling in the cluster core, are not. My thesis research has focused on studying these details via X-ray properties of the ICM in clusters of galaxies using a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. I have paid particular attention to ICM entropy distribution, the process of virialization, and the role of AGN feedback in shaping large scale cluster properties.

The picture of the ICM entropy-feedback connection emerging from my research suggests cluster cD radio luminosity and core Hα emission are anti-correlated with cluster central entropy. Following analysis of 169 cluster radial entropy profiles (Fig. 1), I have found an apparent bimodality in the distribution of central entropy and central cooling times (Fig. 2) which is likely related to AGN feedback (and to a lesser extent, mergers). I have also found that clusters with central entropy ≤ 20 keV cm^2 show signs of star formation (Fig. 3) and AGN activity (Fig. 4), while clusters above this threshold unilaterally do not have star formation and exhibit diminished AGN radio feedback. This entropy level is auspicious as it coincides with the Field length (assuming reasonable magnetic suppression) at which thermal conduction can stabilize a cluster core against further cooling and gas condensation. It is possible my research has opened a window to solving a long-standing problem in massive galaxy truncation and cluster feedback: how are ICM gas properties coupled to feedback mechanisms such that the system becomes self-regulating? However, these findings serve to highlight unresolved issues requiring further intensive study.

1) What is the origin of the bimodality in K_0 and $t_{\rm cool}$?

Is it archival bias? Are clusters with $K_0 \sim 70$ keV cm^2 "boring" (and faint) and thus have not been proposed for observation? To explore this possibility I have selected a representative sample of clusters which predictably fill the K_0 and $t_{\rm cool}$ gaps, and will be submitting a Cycle 10 proposal to observe these clusters with *Chandra*. There is also the possibility that bimodality is the physical manifestation of two underlying timescales. The gap may be indicating there is a very short period in a clusters life when AGN activity has boosted the core entropy to the point of being conductively stable ($K_0 > 20$ keV cm^2) and subsequent mergers quickly eliminate $K_0 \sim 70$ keV cm^2 clusters. A possible answer to this problem might be found from analysis of simulations by asking the additional question: what is the timescale for depletion of $\sim 10^{12-13} M_\odot$ subclusters in a full dark matter halo? If this timescale is of the order a few Gyrs, then this likely points to a collusion of AGN feedback and mergers to give rise to bimodality. But ultimately the questions I posed are related with two primary underlying questions: what does the distribution of K_0 for a complete sample of clusters look like? And what does the AGN energy injection distribution look like?

2) What role is star formation playing in the feedback cycle of clusters?

Indications from the literature thus far are that most (possibly all?) cDs in X-ray luminous clusters with $K_0 \leq 20$ keV cm^2 are dominated by star formation. But we can see from Figure 4 that most of these systems contain radio AGN. So one should ask the question: are there any AGN dominated nebular cDs? An interesting project to pursue with the *Spitzer* archive would be to study if the cD galaxy in a carefully chosen sample of clusters is star formation or AGN dominated. This study is quite simple using the Far-IR bands to look for polycyclic aromatic hydrocarbons as definitive signatures of star formation and mid-IR excesses as an indicator of dust enshrouded AGN. An additional constraint on star formation can be made by analyzing archival *XMM* Optical Monitor data for near-UV excess from starlight not reprocessed by dust.

A cross-reference of my thesis sample with the *Spitzer* data archive reveals 150+ clusters have already been observed, with 130+ also having OM data in the *XMM* archive. This large data pool to draw from makes selection of a representative sub-sample immediately possible to answer the question, how is star formation affected by AGN feedback? Currently we do not know. All we know is these two processes are triggered in cluster cDs which reside in low entropy environments. It is important to disentangle these two processes if a cohesive model of feedback is to be built.

3) How is energy generated on the parsec scale from a SMBH deposited uniformly over volumes which are orders of magnitude larger?

The role of AGN feedback in shaping global cluster, group, and galaxy properties is quite complex, and to some extent poorly understood. Models for thermalizing energy from AGN blown bubbles have been proposed, but details of these models (e.g. explaining the thermal inefficiency of jets or finding a low scatter relation between jet power-radio power) still need to be explored. Equally important are models which account for the range of environments we know AGN to be interacting with: spirals, giant ellipticals (gEs), and cDs.

While bubbles are well studied and abundant, a fundamental question still remains unanswered: what's *inside* these bubbles? Are they pressure supported by a very low density non-relativistic thermal plasma, or maybe by relativistic particles like cosmic rays, or even stranger, could they truly be voids in the ICM and ISM? Observational studies of bubbles in clusters have been fruitful, but a corresponding study of bubbles in gEs and galaxy groups has been sorely lacking. An obvious project to pursue with *Chandra* is to replicate the seminal work of Birẑan et al. 2004 where they studied bubbles in clusters, but instead of focusing on clusters, focusing on groups and gEs.

An additional missing piece of the AGN feedback puzzle is what role X-ray coronae may be playing in promoting feedback. Coronae have been seen in groups and some clusters, but their progenitors should also be seen in smaller scale objects. A search for coronae in a sample of radio-loud groups and clusters with moderate to high central entropy would also be very interesting as these systems shouldn't have feedback activity, but sometimes do (i.e. AWM4) because a corona is most likely insulating core gas from the hot atmosphere and allows for low entropy gas to cool.

4) How important is conduction in the feedback loop and how does it couple to the ICM?

Assuming pure free-free cooling, the Field length (the size at which a gas cloud is stabilized against condensation by conduction) is a function of entropy alone, $\lambda_F \equiv K^{3/2}$. Assuming realistic magnetic suppression, $K_0 = 20$ keV cm^2 is the entropy level above which conductive heating wins against cooling (Fig. 5). This would nicely explain the dichotomy in Figure 3, but additional theoretical and observational evidence is needed to support this idea. Mark Voit is undertaking a theoretical study of this topic, and collaborating as observational counterparts would be an excellent project. For example, selecting a sample of clusters which span the $K_0 = 20$ boundary and investigating ICM conductive properties should yield robust differences between clusters above and below this entropy threshold. In addition, a systematic study of cold fronts as surrogates for internal ICM physics (such as origin, strength, and structure of magnetic fields) would be enlightening for better understanding conduction.

5) What about the oddities?

In Figures 3 and 4 there are a total of 12 unique clusters (blue boxes with red stars) which lie below the auspicious $K_0 = 20$ cut-off and *do not* have star formation and/or radio-loud AGN. One must ask, "why the heck not?" Why aren't there stars and/or AGN? I can only conjecture at the moment as a thorough study of these objects does not exist. Imagine an overdense gas parcel buried in a very low entropy medium. As the gas parcel sinks it will reach a region of higher density, stop, buoyantly rise, and dissipate. Reproducing this process over an $\approx$ 10-20 kpc region should result in all gas overdensities being washed out while the overall entropy of the region continues to lower (kind of like a beating heart). The result would be a low entropy core with no overdense regions which could produce stars or SMBH feeding gas streams. But is this process stable? Does it require large magnetic suppression of conduction? How would one even observe this process with existing instruments (this is possibly a good feasibility study for Con-X to help push for higher-res optics)? What are the other possible explanations for this odd class of cluster: are we not seeing the star formation in Hα? Are there AGN and they're just not radio-loud? I'm not sure at the moment, these ideas require much more thought and study.

Looking ahead, the natural extension of my thesis is to further study questions regarding details of feedback and galaxy formation. There are also exciting theoretical cluster feedback model developments on the horizon which will need observational investigation, and for which I am well positioned to study.

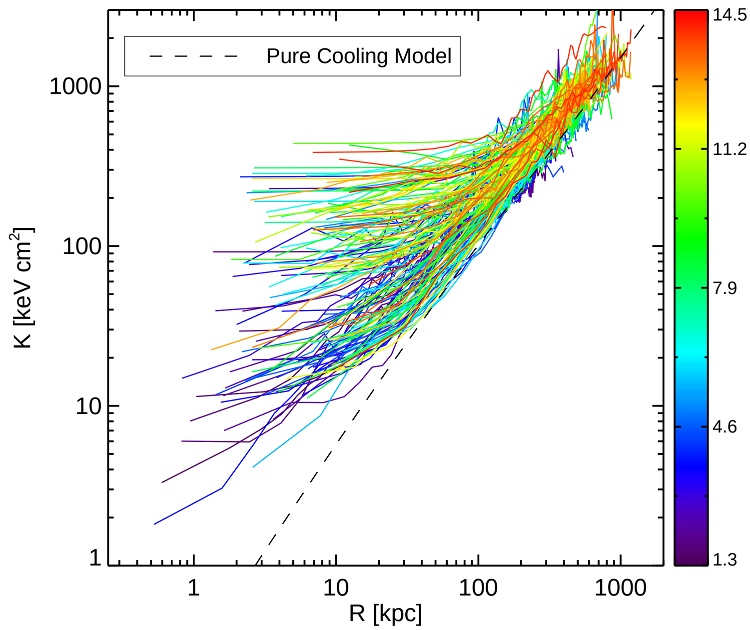

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

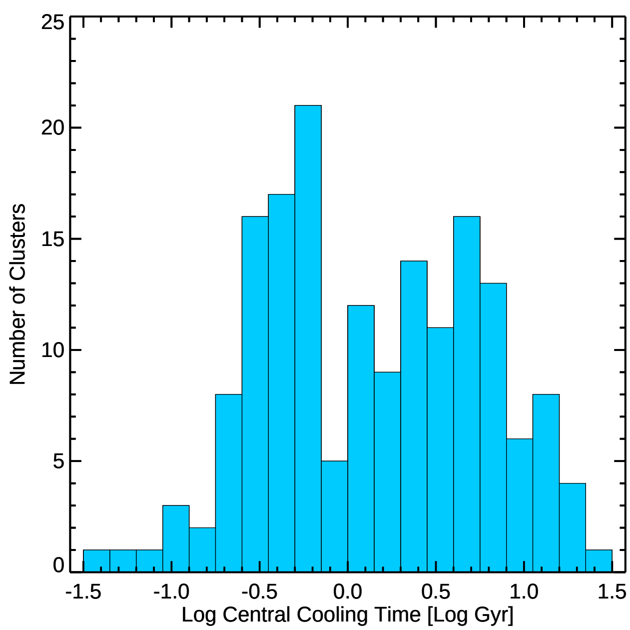

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct gap at $0.6 - 1$ Gyr. An explanation for this bimodality does not currently exist.

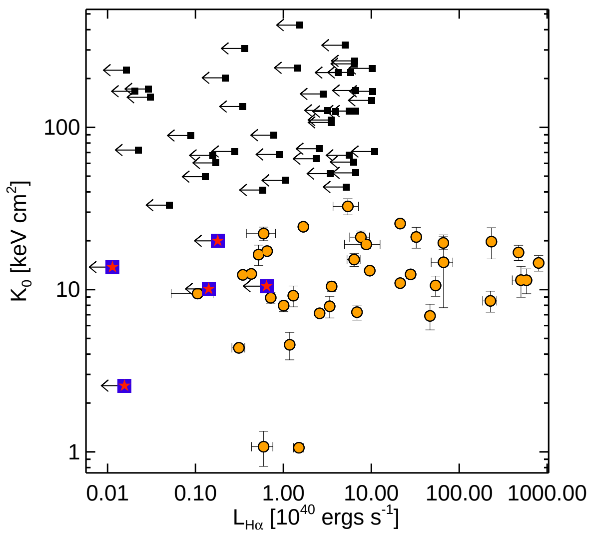

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances radiative cooling and condensation of low entropy gas onto a cD can proceed.

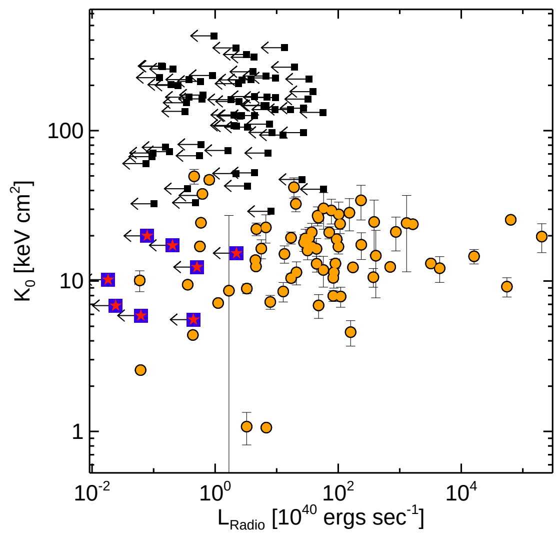

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. There appears to be a dichotomy which might be related to AGN fueling mechanisms: AGN which are feed via low entropy gas, and the smattering of points at $K_0 > 50$ keV cm^2 which are likely fueled by mergers or have X-ray coronae which promote ICM cooling.

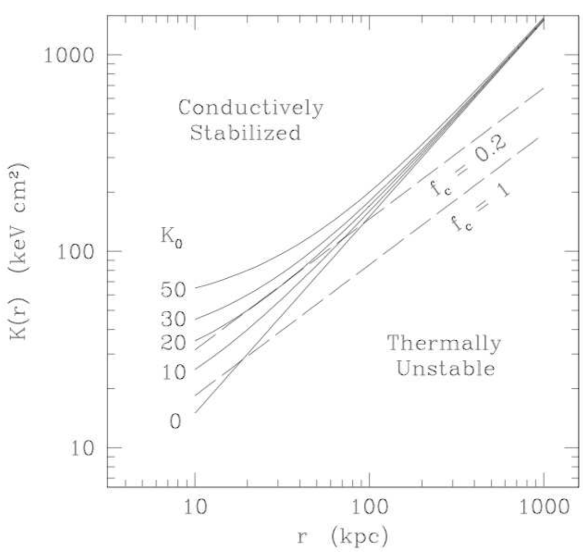

Figure 5: Toy entropy profiles plotted as a function of radius and overlaid with dashed lines representing cooling and conduction equivalence for two suppression factors. Above the dashed lines conduction is effective and condensation cannot occur, the opposite is true below the lines. $K_0 < 20$ keV cm^2 is the break point at which the Field length criterion suggests gas condensation (i.e. star formation and condensation onto a SMBH) can proceed. Reproduced courtesy of Dr. G. Mark Voit.