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. Mergers and feedback activity are interesting for two reasons: they potentially compromise the use of clusters for cosmological studies, and there is a tremendous amount of interesting astrophysics going on. My thesis research has focused on studying the details of feedback and mergers via X-ray properties of the ICM in clusters of galaxies. I have paid particular attention to ICM entropy distribution and the role of AGN feedback in shaping large scale cluster properties. Additionally I have examined the quantification of cluster virialization via aspect-independent metrics, with emphasis on understanding temperature inhomogeneity as a surrogate for cluster dynamic state.

Mining the CDA

My thesis makes use of a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. This massive undertaking necessitated the creation of a robust reduction and analysis pipeline which 1) interacts with mission specific software, 2) utilizes analysis software (i.e. `XSPEC`, `IDL`), 3) incorporates calibration and software updates, and 4) is highly automated. Because my pipeline is written in a very general manner, adding pre-packaged analysis tools from missions such as *XMM*, *Spitzer*, and *VLA* will be straightforward. Most importantly, my pipeline deemphasizes data reduction and accords me the freedom to move quickly into an analysis phase and generating publishable results.

Quantifying Cluster Virialization

Cluster mass functions and the evolution of the cluster mass function are useful for measuring cosmological parameters. Cluster evolution tests the effect of dark matter and dark energy on the evolution of dark matter halos, and therefore provides a complementary and distinct constraint on cosmological parameters to those tests which constrain them geometrically (e.g. supernovae and baryon acoustic oscillations).

Empirically, the relationship of mass and some observable properties is well-established. However, if we could identify a set of parameters – possibly reflecting the degree of relaxation in the cluster – we could improve the utility of clusters as cosmological probes. The work of Mathiesen and Evrard 2001 found an auxiliary measure of substructure which does not depend on perspective and could be combined with power ratio, axial ratio, and centroid variation to yield a more robust metric for quantifying a cluster's degree of relaxation.

I have studied this auxiliary measure: the bandpass dependence in determining X-ray temperatures and what this dependence tells us about the virialization state of a cluster. The ultimate goal of this project is to find an aspect-independent measure for a cluster's dynamic state. To this end, I have investigated the net temperature skew in my sample of the hard-band (2.0_{rest}-7.0 keV) and full-band (0.7-7.0 keV) temperature ratio for core-excised apertures. I have found this temperature ratio is statistically connected to mergers and the presence of cool cores. The next step is to make a comparison to the predicted distribution of temperature ratios and their relationship to putative cool lumps and/or non-thermal soft X-ray emission in cluster simulations. This will be carried out by a fellow graduate student as part of his thesis and funded by a successful *Chandra* theory proposal by Dr. Mark Voit which was motivated by my work. In addition, this project has produced a first author paper which has been submitted to the ApJ (in fact, I was informed it was sent to you for dissemination to a referee).

Cluster Feedback and ICM Entropy

The picture of the ICM entropy-feedback connection (Fig. 1) emerging from my work suggests cluster radio luminosity and Hα emission are anti-correlated with cluster central entropy ($K = T_X n_e^{2/3}$). There also appears to be a bimodality in the distribution of central cooling times (Fig. 2) which is likely related to AGN feedback (and to a lesser extent, mergers). I have found that clusters with central entropy ≤ 20 keV cm^2 exhibit star formation (Fig. 3) and AGN activity (Fig. 4) in the BCG 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, λ_F, (assuming reasonable suppression) at which thermal conduction can stabilize a cluster core. It is possible we have opened a window to solving a long-standing problem in massive galaxy formation (and truncation): how are ICM gas properties coupled to feedback mechanisms such that the system becomes self-regulating? However, this result serves to highlight unresolved issues requiring further intensive study.

1) What is the origin of the bimodality in K_0?

Is it archival bias? Meaning, are clusters with $K_0 \sim 70$ keV cm^2 "boring" (and faint) and thus have not been proposed for observation? In which case I will select a representative sample of clusters from a flux-limited survey, such as *ROSAT* 400$\square^\circ$, which predictably fill this gap and observe them with *Chandra*. Or, is the gap physically driven? Is the gap representative of 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 have further elevated the ICM entropy to $K_0 > 100$ keV cm^2? A possible answer to this question may be found in 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?

Thus far, indications from the literature are that most (possibly all?) BCGs 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 can ask the question: are there any AGN dominated nebular BCGs? An interesting project to pursue with the *Spitzer* archive would be to examine the shape of spectral energy distributions (SEDs) for all clusters with a BCG and attempt to reveal if the BCG is star formation or AGN dominated. A cross-reference of my thesis sample (which is essentially the entire CDA) with the *Spitzer* data archive reveals 150+ clusters have already been observed by *Spitzer* (combinations of 75+ MIPS, 50+ IRAC, 30+ IRS) covering a broad entropy, luminosity (X-ray, Hα, radio), and mass range. The large pool to draw from makes selection of a representative subsample immediately possible. Does star formation precede/inhibit/enhance/stunt AGN feedback? Currently we do not know. All we know is these two processes are triggered in cluster BCGs which reside in low entropy environments. Surely they are coupled somehow, which is why I highlighted several poor clusters/rich groups in Figures 3 and 4 with blue boxes and red stars. These systems are in the proper regime for feedback, yet they exhibit only one or neither of star formation or AGN. Follow-up of these objects with *Spitzer* and *XMM*'s Optical Monitor to search for polycyclic aromatic hydrocarbon features, UV excess, or dusty AGN would be interesting.

3) How is energy generated on the parsec scale from a SMBH deposited uniformly in the ICM over a few cubic megaparsecs?
The role of AGN feedback in shaping global cluster properties is quite complex and to some extent poorly understood (e.g. Perseus). Models for the process of thermalizing energy in AGN blown bubbles have been proposed, but details of these models still need to be explored. For example, do bubbles contain a very low density non-relativistic thermal plasma or are they truly voids in the ICM? We'd like to know if bubbles are pressure supported, and this could be studied via SZ effects. Radio sources are also being revealed as much more powerful than ever expected now that they have been observed at low radio frequencies (i.e. 330 MHz). Use of surveys such as LOFAR, LWA and EVLA will make study of clusters across a broad radio range a rich field for years to come. Also, what is the contribution of cosmic rays in bubbles? The presence of cosmic rays should be detectable with GLAST using observation of γ-rays from the decay of π^0 in bubble lobes. How do bubbles rise to distances ≥ 100 kpc without being shredded by instabilities? What is the role of $\vec{B}$ fields in stabilizing bubbles? And what is the origin of these fields? This area of cluster feedback studies is littered with more questions than current answers, which makes for an attractive research avenue for a post-doc to write many observing and grant proposals.

I have attempted to highlight without too much depth the areas I have already worked and the directions I would like to go. Most of my experience is with X-ray data, but multiwavelength analysis is the next necessary step in my career, and I hope it will be under your direction at Carnegie.

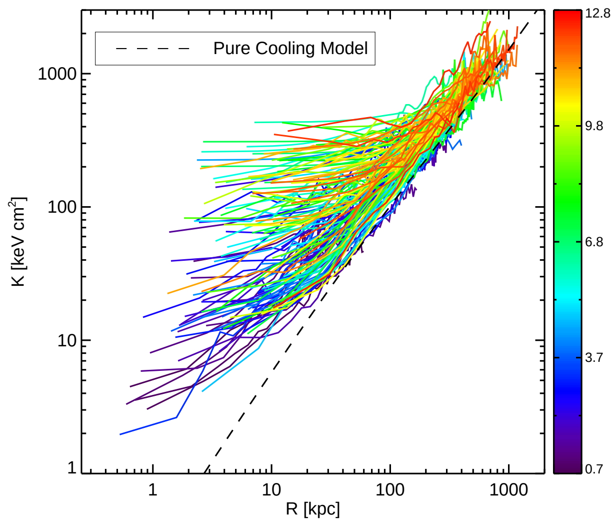

Figure 1: Radial entropy profiles of 143 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

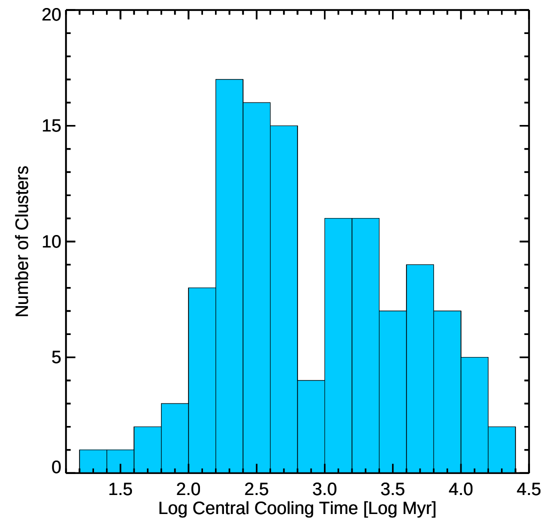

Figure 2: Distribution of central cooling times for an unbiased sub-sample of the clusters analyzed for my thesis. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts.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

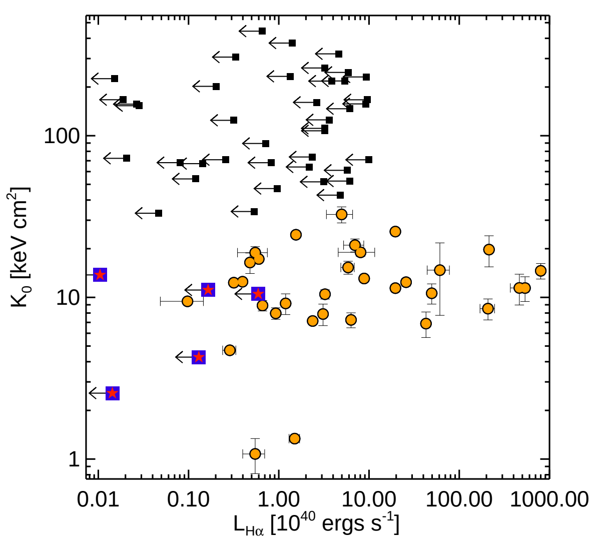

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections, black boxes with arrows are non-detection upper-limits, and blue boxes with red stars are poor clusters/rich groups which do not match the trend. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ 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 BCG can proceed.

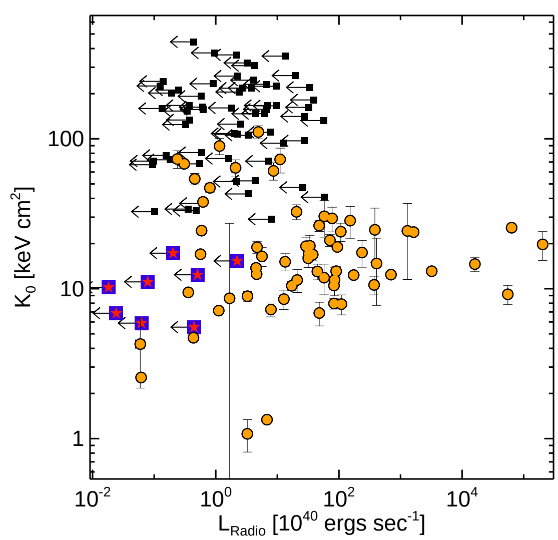

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections, black boxes with arrows are non-detection upper-limits, and blue boxes with red stars are poor clusters/rich groups which do not match the trend. There appears to be a dichotomy which might be related 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.