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 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.

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 tools (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.

Cluster Feedback and ICM Entropy

The picture of the ICM entropy-feedback connection emerging from my work suggests cluster radio luminosity and Hα emission are anti-correlated with cluster central entropy. Following my 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 have no signs of 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 from magnetic fields) at which thermal conduction can stabilize a cluster core against further cooling and gas condensation. It is possible my work has 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.

Looking ahead, the natural extension of my thesis is to further study questions regarding details of feedback and galaxy formation. What are the micro-physics of ICM heating, including the thermalization of mechanical work done by bubbles and the effect of non-thermal sources like cosmic rays? How prevalent are cold fronts and do they play a role in galaxy and star formation? Also of interest are how accretion onto the cD SMBH is regulated by large-scale ICM properties and what the AGN energy injection function looks like and how it correlates with cluster environment.

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. Developments such as: how exactly are AGN fueled? Does accretion of the hot ICM/ISM proceed via Bondi-eque flows? What is the efficiency of the accretion? Why do we see metallicity gradients in the ICM/ISM when some amount of mixing should take place? How is feedback energy distributed symmetrically throughout the ICM?

Cold Fronts in Clusters

As part of my thesis work I have extracted radial surface brightness, temperature, and pressure profiles for well over 220 clusters taken from the *Chandra* archive. Visual inspection of these profiles and the corresponding images of the cluster are an integral step in my analysis, and as other authors have pointed out (e.g. Markevitch and Vikhlinin) cold fronts are a common feature of even the most "relaxed" clusters.

The crux of my thesis is understanding the entropy distribution in the core of clusters as it relates to active feedback (AGN, star formation, etc.), but I often wonder what effect gas sloshing (either from mergers or from AGN bubbles) and "soft" mergers (which result in prominent cold fronts) have had on altering ICM entropy. Currently mergers are viewed as a hammer instead of a scalpel: mergers shock heat the ICM, end of story. But we now know this is most certainly not the case and more sophisticated models of mergers are needed to explain the zoology of cluster substructure. As demonstrated by Ascasibar et al. 2006, accurately generating cold fronts in SPH simulations is possible, and a useful next step would be to analyze these simulations as if they were real data taken with *Chandra*. The research group I am part of at MSU has recently started using software written by Elena Rasia which recasts simulated data as real data. The purpose of the present project (which I do not discuss here) is to better understand the process of cluster virialization. I am gaining invaluable insight and experience in the task of analyzing simulations as real observations and think the undertaking of a similar project to analyze cold fronts in simulations would be fruitful.

Cold fronts in and of themselves are interesting ICM features because they correlate with a number of physical processes (sloshing, mergers, AGN, etc.). But cold fronts are also interesting because one can utilize them as a laboratory for studying the internal physics of the ICM. There are long-standing debates regarding the structure, strength, and origins of ICM magnetic fields, and the properties of cold fronts are sensitive to all three of these features. But cold fronts can also yield information regarding conduction and viscosity in the ICM. These are extremely interesting to me because as I discussed in an earlier section both of these processes are probably very important in transferring feedback energy to the ICM. Conduction is likely the coupling mechanism between AGN feedback, ICM heating, and star formation, while viscosity is likely important in thermalizing bubble and jet energy. But there is a big piece of the puzzle missing: how strong is magnetic suppression and how viscous is the ICM?

I can envision a project where we start with an ensemble of SPH cluster simulations covering a variety of input ICM magnetic fields and viscosities. We then take the ensemble and generate mock observations, meaning proper *Chandra* events files with instrument convolved spectra for each position in the data cube. We then analyze these mock observations using standard observational tools (i.e. `CIAO` and `XSPEC`) to look for and analyze cold fronts. The objective of this approach being quantification of cold front properties as a function of input magnetic and viscosity parameters. The advantage of course is that we know "the truth" about the ICM, and analyzing the simulations as real data will allow us to put constraints on what can be observationally learned about conduction and viscosity. Ultimately the goal would be to use cold fronts as a surrogate for getting at the internal ICM physics so we can build robust models which include conduction and viscosity in the explanation of how feedback mechanisms alter cluster properties like entropy.

There is also a glaring lack of uniformly analyzed cold fronts in the literature. An ancillary project to the one envisioned above is a large observational study of cold fronts. The *XMM-Newton* and *Chandra* archives are replete with enough data to make selection of a representative cluster sample and immediate initiation of such a project possible. There are few people more well prepared to spearhead this ambitious effort than me as I already have the pipeline and analysis techniques necessary to quickly complete the study. The expected results of this project might also be more illuminating when set in the context of my thesis work. The prospect of studying cold fronts in detail as a post-doc is exciting because it expands upon my current work and also might give the results of my thesis greater depth and meaning, and vice versa.

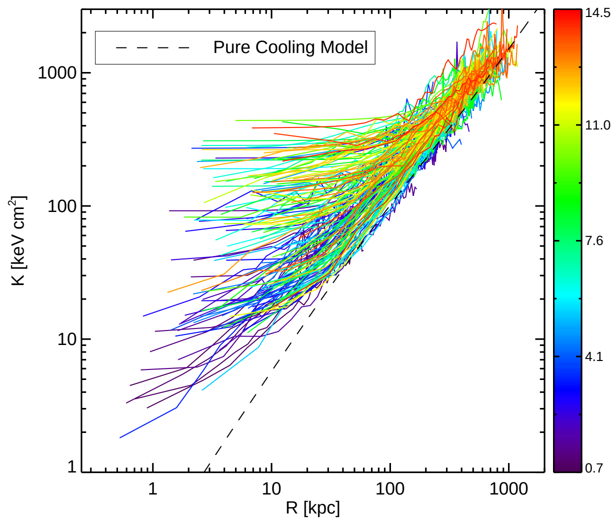

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R$_{2500}$.

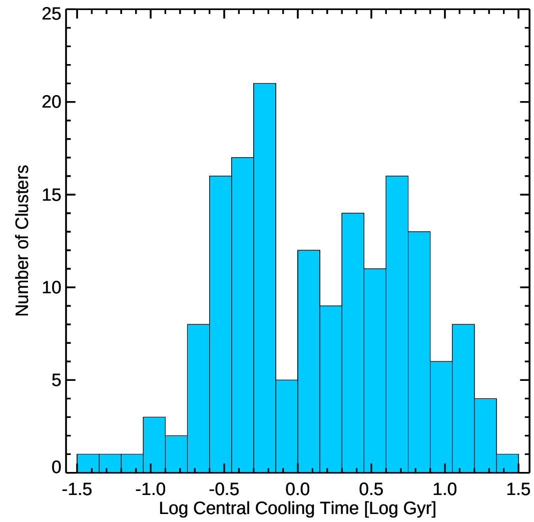

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct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

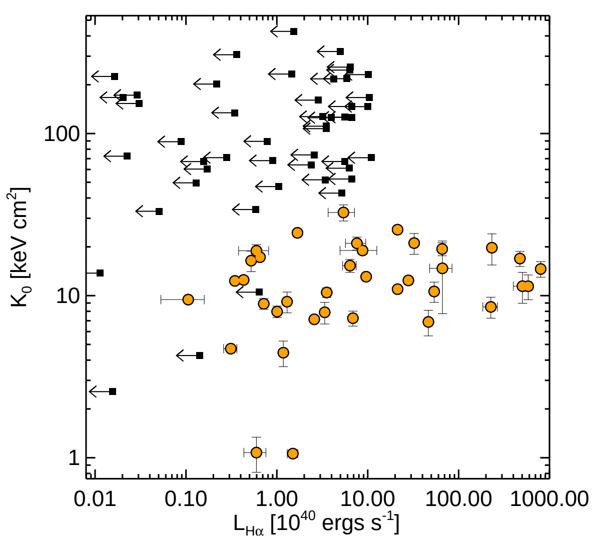

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances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

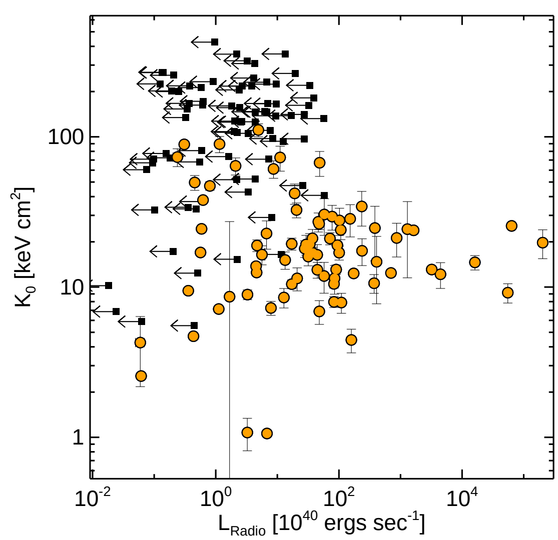

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. There appears to be a dichotomy which might be related to AGN fueling mechanisms: AGN which are feed via low entropy gas, and the smattering of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