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. 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.

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.

Quantifying Cluster Virialization

The normalization, shape, and 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). If we could identify a parameter possibly reflecting the degree of relaxation in the cluster we could improve the utility of clusters as cosmological probes by parameterizing and reducing the scatter in mass-observable scaling relations.

One study that examined how relaxation affects the observable properties of clusters was conducted by Mathiesen and Evrard 2001. They found that most clusters which had experienced a recent merger were cooler than the cluster mass-observable scaling relations predicted. They attributed this to the presence of cool, spectroscopically unresolved accreting subclusters.

I have followed up their work by studying 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 was to find an aspect-independent measure for a cluster's dynamic state. I thus investigated the net temperature skew of the hard-band (2.0-7.0 keV) and full-band (0.7-7.0 keV) temperature ratio. I have found this temperature ratio is statistically connected to mergers and the presence of cool cores. Having confirmed the predicted effect, 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.

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 $\leq$ 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, 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?

Future Work

Looking ahead, the natural extension of my thesis is to further study questions regarding cluster environments and their impact on galaxy formation and participating in the analysis of large samples of clusters found in SZE surveys and followed up with X-ray observations. More specifically, I'd like to use these samples to measure the evolution of the cluster mass function as a direct means of breaking the degeneracy between Ω_M and σ_8. Combined with complementary surveys (specifically those using the SZE which will yield tens of thousands of cluster candidates) X-ray surveys will help further constrain the fundamental parameters defining the current cosmological model.

But, the detailed analysis of the cluster population at redshifts greater than z $\sim$ 1 will be very difficult, and establishing the self similar model as a reliable tool for calibrating the cluster mass function will lead to better studies of hierarchical structure formation and dark energy. In addition, if we are to use SZE as effectively as desired SZE flux must be calibrated to accurately predict cluster mass. But even calibration is not enough, we must also understand the scatter in scaling relations. And to this end one needs two components: verification of cluster candidates and methods for quantifying deviation from mean mass-scaling relations. But the simple application of existing metrics which have been calibrated to low-z samples or high resolution simulations may begin to breakdown as spatial and spectroscopic information is reduced at high redshifts, or if there is evolution in scaling relations with redshift. I look forward to being a part of generating new, novel solutions to these problems.

With potentially enumerable, unbiased samples of clusters emerging from SZE surveys and low flux, all-sky X-ray surveys, the entropy distribution and signatures of feedback culled from these samples could tell us a great deal about the evolution of clusters and galaxy formation. Many questions remain unanswered in this area, such as: 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 can they be used as an indicator of merger activity and onset of feedback? Also of interest are how accretion onto the cD SMBH is regulated by large-scale ICM properties, what the AGN energy injection function looks like, and how it correlates with cluster environment. It will also be useful to have a low-scatter, universal relation between jet power and radio power – a tool which can then be directly applied to understanding both cluster feedback and could possibly be useful in SZE studies.

There are also exciting theoretical cluster feedback model developments on the horizon which will need observational investigation. Developments such as: how exactly are AGN fueled – through a combination of hot/cold accretion, mergers, and consumption of low entropy gas via cooling; or is there a universal mode underlying all these processes? Does accretion of the hot ICM/ISM proceed via Bondi-eque flows or is it more like Eddington accretion? What is the efficiency of accretion and is energy return from a SMBH really the presumed $\sim$ 10%? Why do we see steep metallicity gradients in the ICM/ISM when some amount of turbulent mixing should take place? How is feedback energy distributed symmetrically throughout the ICM?

Models of cluster formation, evolution, feedback, and dynamics are converging such that use of clusters in high precision cosmology is possible. I have the skill sets necessary to make meaningful and unique contributions both now and in the future of this field.

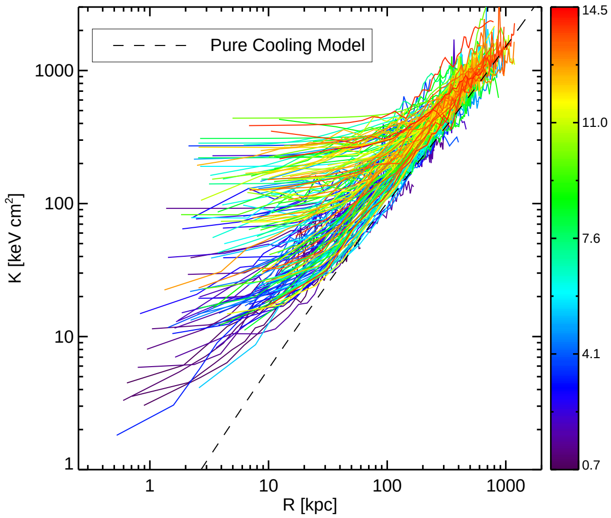

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

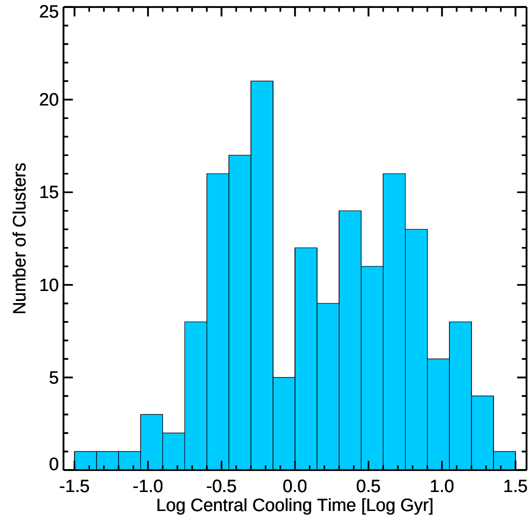

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct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

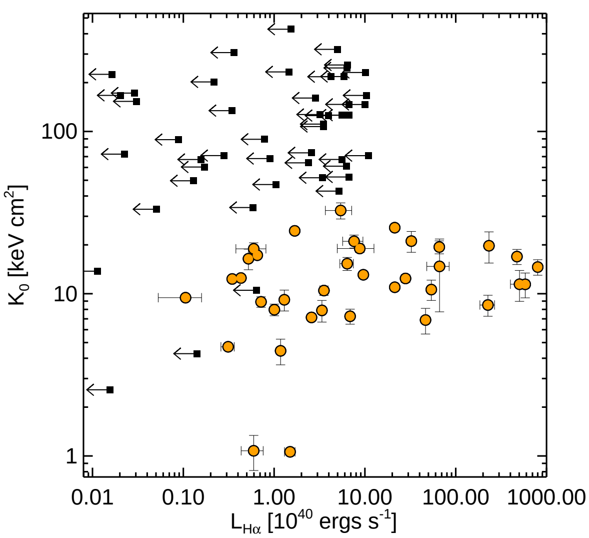

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances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

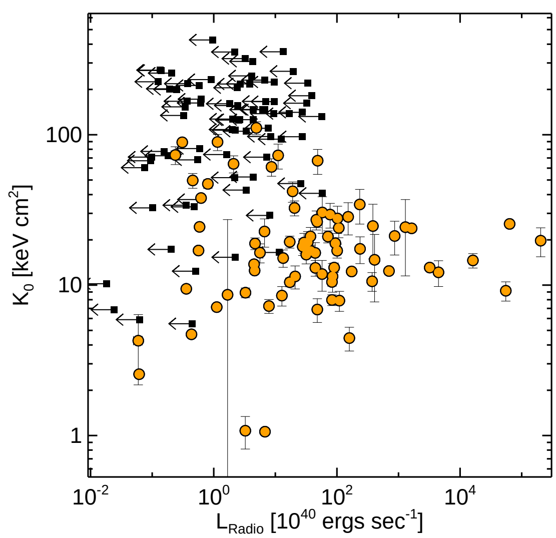

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. There appears to be a dichotomy which might be related to AGN fueling mechanisms: AGN which are feed via low entropy gas, and the smattering of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