Summary of Experience and 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 in clusters of galaxies via X-ray properties of the ICM. I have paid particular attention to ICM entropy distribution, the process of cluster virialization, and the role of AGN feedback in shaping large scale cluster properties.

My research 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 (e.g. `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.

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 run-away cooling and ICM condensation. These results are highly suggestive that conduction is very important to solving the long-standing problem of how ICM gas properties are coupled to feedback mechanisms such that the system becomes self-regulating.

The final phase of my thesis is focused on further understanding why we observe bimodality, what role star formation is playing in the cluster feedback loop, refining a model for how conduction couples feedback to the ICM, and examining the peculiar class of objects which fall below the Field length criterion but *do not* have star formation and/or radio-loud AGN (blue boxes with red stars in two of the figures).

There are additional areas of my present research I'd like to expound on in the future:

1. I am proposing *Chandra* Cycle 10 observations for a sample of clusters which predictably fall into the $t_{\rm cool}$ and K_0 gaps to see if bimodality is archival bias or physical.

2. Two classes of peculiar objects warrant intensive multiwavelength study: high-K_0 clusters with radio-loud AGN (e.g. AWM4) and low-K_0 clusters without any feedback sources (e.g. Abell 2107). The former likely have prominent X-ray corona, while the latter may be showing evidence that extremely low entropy cores inhibit the growth of gas density contrasts.

3. At present, I am putting all my reduced data products and thesis results into a static website so they are available to any interested researcher. Long-term however, I plan on submitting an archive grant proposal to convert this site into an interactive database which can be easily used by novices (i.e. undergraduate labs or course instructors), expert X-ray astronomers, and curious theoreticians.

4. Thus far I have only focused on AGN which are radio-loud according to the 1.4 GHz eye of NVSS. But recent work has shown AGN radiate profusely at low radio frequencies (e.g. 300

MHz). I'd like to know what the radio power is at these wavelengths for (ideally) my entire thesis sample and see if the K_0-radio correlation tightens.

5. Using the near-UV sensitivity of *XMM*'s Optical Monitor and the far-IR channels of *Spitzer* I'd like to pursue a joint archival project to disentangle which $K_0 \leq 20$ cDs are star formation dominated and which are AGN dominated. A quick check of these archives shows 130+ clusters have the necessary band data available.

6. I'd also like to pursue a systematic study of AGN bubbles in groups and ellipticals – akin to the seminal work of Birẑan et al. 2004 – but with the focus of this project being adaptation of existing cluster feedback models to smaller scale objects.

In another part of my thesis research I studied 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 of a cluster's dynamic state. Prompted by the work of Mathiesen & Evrard 2001, I investigated the net temperature skew of the hard-band (2.0_{rest}-7.0 keV) and full-band (0.7-7.0 keV) temperature ratio for core-excised apertures of my entire CDA sample. I found this temperature ratio was robustly and significantly connected to mergers and the absence of cool cores. This project touched on quantifying and reducing the scatter in mass-observable relations to bolster the utility of clusters as cosmology tools. I am eager to keep this area of my work alive as we get closer to having access to enormous catalogs of SZ detected clusters which require X-ray follow-up. To maximize the utility of these surveys, we must continue to investigate scatter, evolution, and covariance in X-ray observables which serve as vital mass surrogates.

Looking ahead, the natural extension of my thesis is to further study questions regarding the details of cluster feedback and galaxy formation. Is conduction the long-sought answer for 1) how energy is uniformly distributed in the ICM; 2) how stars form in the most massive galaxies; 3) why feedback is so tightly correlated with the state of the ICM. There are additional avenues which I have not touched on in this summary but still interest me, such as the micro-physics of ICM heating (e.g. turbulence and weak shocking), the thermalization of mechanical work done by bubbles, and the importance of non-thermal sources like cosmic rays. How prevalent are cold fronts? Can they be used to robustly quantify ICM magnetic fields and viscosity? Are they important in the feedback loop? Building on the work of Paul Martini and Greg Sivakoff, how robust is their "X-ray Butcher-Oemler Effect" if one expands their work to a very large sample of clusters? This is a project which I essentially have in hand because identifying full-field point sources is an integral first step in my reduction. Can we deduce a low-scatter relation (or at least constrain one) between jet power and radio power? What is the explanation for the thermal inefficiency of jets? Many questions abound as a result of my thesis work, I hope to pursue the answers to them a post-doc with you at UVA.

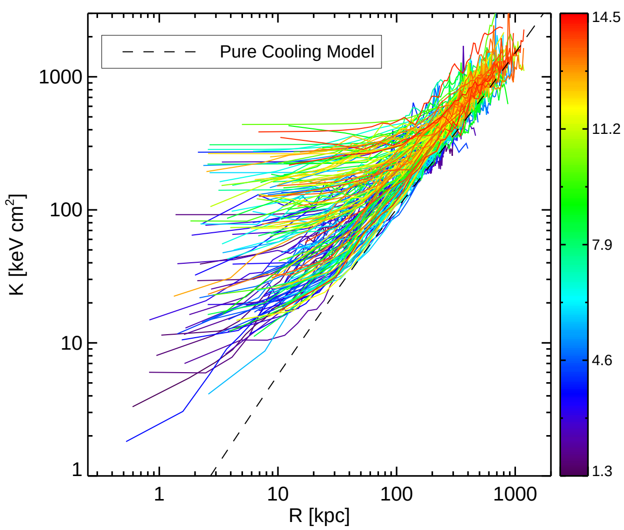

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 70$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

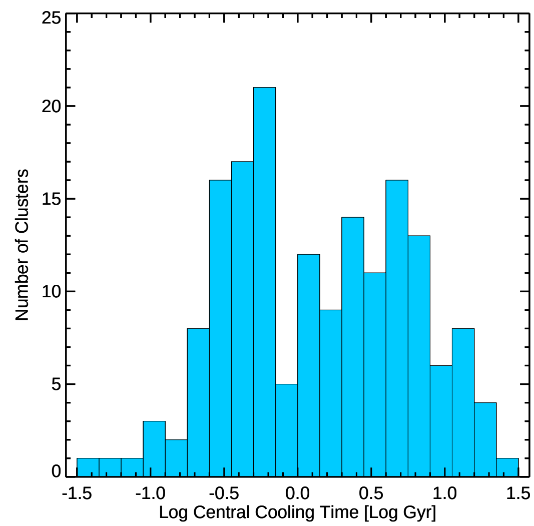

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct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

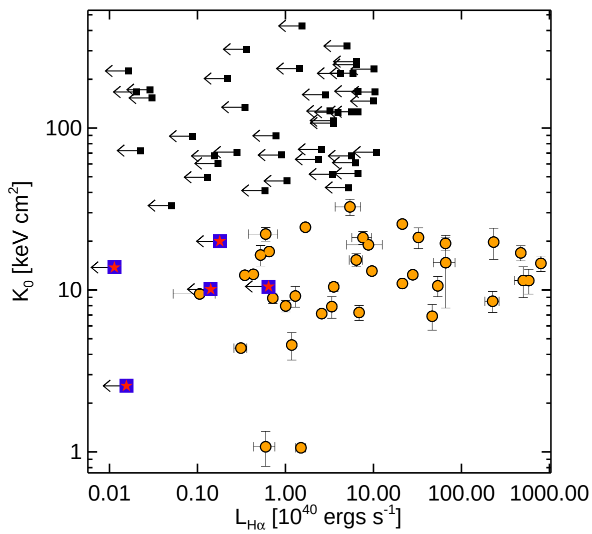

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction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

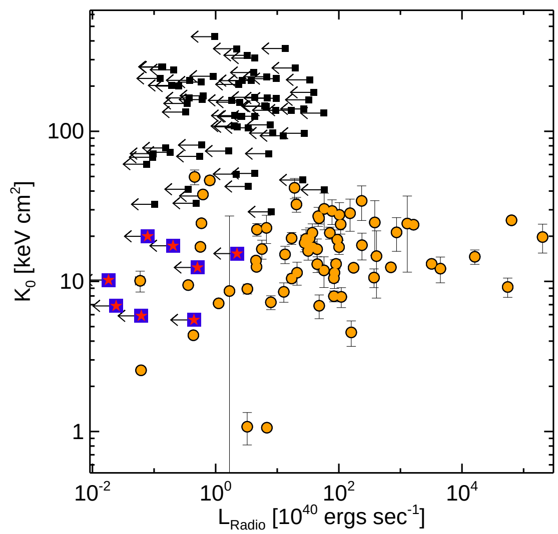

Figure 4: Central entropy plotted against NVSS radio luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Radio-loud AGN clearly prefer low entropy environs but the dispersion at low luminosity is large. It would be interesting to radio date these sources as this figure may have an age dimension.