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.

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 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? However, this result serves to highlight unresolved issues requiring further intensive study.

1) What is the origin of the bimodality in K_0 and t_{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_{cool} gaps and will be submitting a Cycle 10 proposal to observe these clusters with *Chandra*. There is also the possibility that the gap is a physical manifestation of underlying timescales. For example, is the gap 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 question 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 can ask the question: are there any AGN dominated nebular cDs? 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 cD galaxy and attempt to reveal if the cD 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. This large data pool to draw from makes selection of a representative subsample immediately possible to answer the question, 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 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 (Perseus being a perfect example) and to some extent poorly understood. Models for the process of thermalizing energy in AGN blown bubbles have been proposed, but details of these models still need to be explored. Equally important are models which account for the range of environments we know AGN to be interacting with: spirals, 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 are they truly 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.

NGC 4151 and NGC 1365

Your upcoming 260 ks ACIS-S/HRC observations of NGC 4151 are exactly the kind of long exposure *Chandra* observations of AGN feedback which are necessary to detail the mechanisms by which an AGN interacts with the ISM. In a broader sense, the AGN feedback in NGC 4151 is a scaled down version of what occurs in the core of a massive cluster and understanding the sub-kpc interaction of an AGN with the ISM should yield insight, and at least constraints, on what is happening in other similar systems. With these long observations one should be able to detail the physical state of the ISM (temperature, density, pressure, entropy) with both generalized radial profiles and detailed 2D-maps. In addition, the ionization and thermal state of the ISM will tell us about the photoionization and collisional ionization processes near the nucleus and may also provide information about shocking as a result of the AGN outflows. From my own work I see two interesting possibilities for these observations: 1) what is the AGN doing to the star formation in the galaxy? If NGC 4151 is anything like the systems I have studied, the AGN might be depositing energy into the ISM via shocks and from there conduction is doing the "grunt" work of heating the ISM and preventing low entropy gas from cooling any further and making stars. 2) This is a radio-quiet AGN, where is the jet energy going? The answer to this question will be interesting because NGC 4151 provides an interesting test case of thermal and non-thermal jet emission.

I am admittedly unfamiliar with NGC 1365, but am aware that it has been the focus of much study because of the extreme variability of the AGN. A scan of the literature shows me that NGC 1365 may have something in common with another favorite object of mine, IRAS 09104+4109 – a source which I proposed to re-observe for 50 ks with *Chandra*, and while unsuccessful the proposal scored very high and received recommendation for re-submittal in the next cycle. Both these objects are AGN which have undergone dramatic state changes over very short timescales, and are interesting in their own right as to how SMBHs are feed and operate.

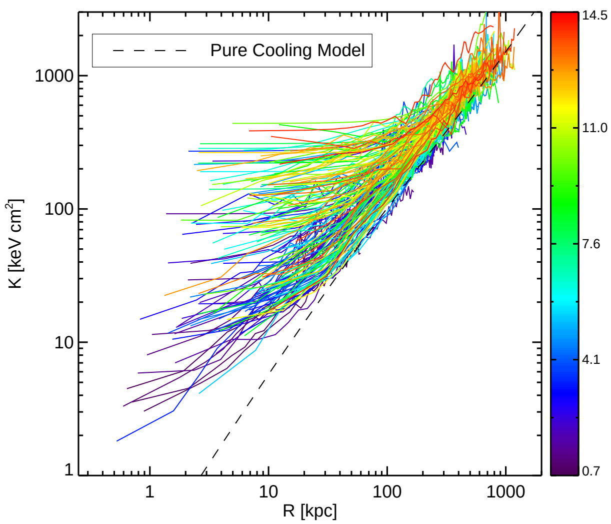

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

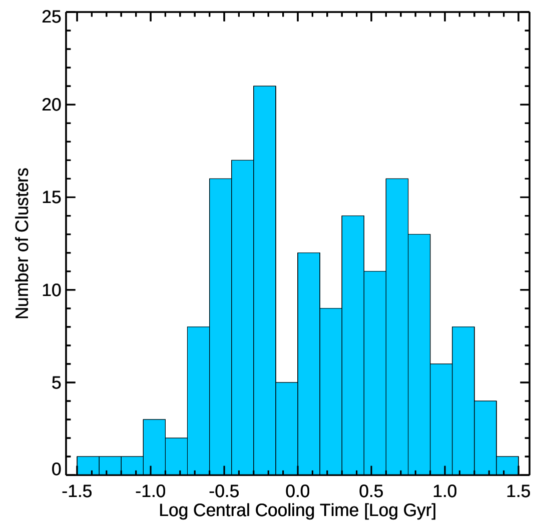

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct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

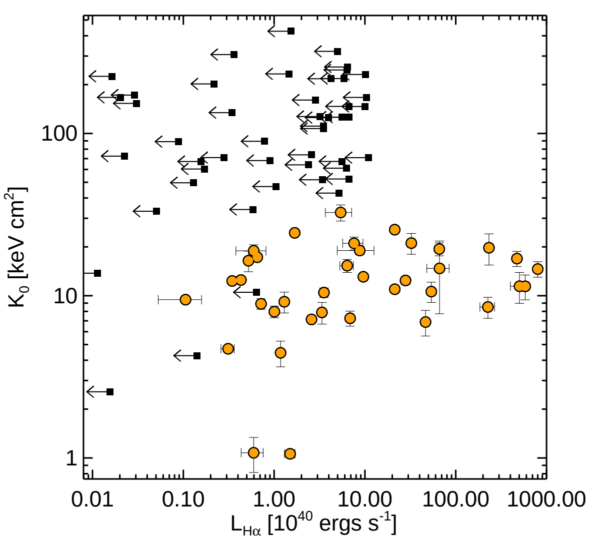

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances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

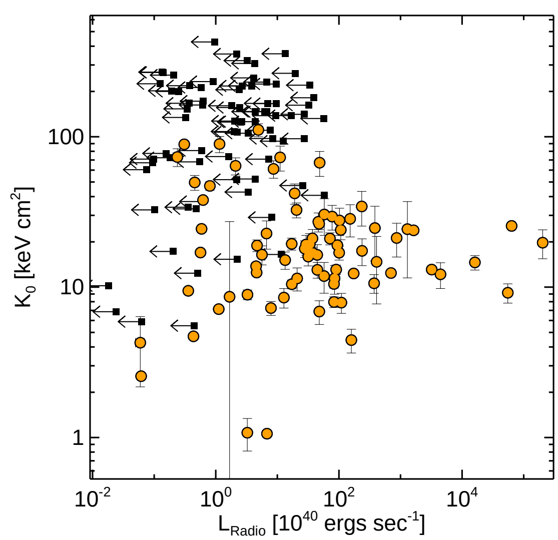

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections and black boxes with arrows are non-detection upper-limits. There appears to be a dichotomy which might be related to AGN fueling mechanisms: AGN which are feed via low entropy gas, and the smattering of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