Summary of Experience 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 primary research makes use of a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. Of these 276 clusters, 16 lie in the redshift range $0.6 < z < 1.2$. Ongoing and future X-ray surveys will be heavily focused on the cluster population at $z > 1.0$. By gaining experience with low count, low surface brightness clusters now, I am amply prepared to work with much larger datasets of these objects in the future. In addition, 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, adapting the pipeline for use with pre-packaged analysis tools from missions such as *XMM-Newton*, *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. The evolution of large scale structure formation is a test of how dark matter and dark energy effect the cluster-scale evolution of dark matter halos, and therefore provides a complementary and distinct constraint on cosmological parameters to those tests which constrain them geometrically, such as supernovae and baryon acoustic oscillations.

However, clusters are a useful cosmological tool only if we can infer cluster masses from observable properties such as X-ray luminosity, X-ray temperature, lensing shear, optical luminosity, or galaxy velocity dispersion. Empirically, the correlation of mass to these observable properties is well-established. However, if we could identify a “2nd 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 empirical method of quantifying the degree of relaxation involves using ICM substructure and employs the power in ratios of X-ray surface brightness moments. Although an excellent tool, power ratios suffer from being aspect-dependent. The work of Mathiesen & Evrard 2001 suggested a complementary measure of substructure which does not depend on projected 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 was to find an aspect-independent measure for a cluster’s dynamic state. To this end, I have investigated the net temperature skew in my archive 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 and has further stimulated the discussion for the continuing need of accurate cross-calibration between *XMM-Newton* and *Chandra*.

Cluster Feedback and ICM Entropy

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 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 $\lesssim 20$ 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 at which thermal conduction can stabilize a cluster core against ICM condensation. These results are highly suggestive that conduction in the cluster core 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 expand on in the future. **(1)** To check if bimodality is archival bias, I am submitting a *Chandra* Cycle 10 observing proposal for a sample of clusters which predictably fall into the $t_{\rm cool}$ and K_0 gaps. **(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)** 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 radio halos are very powerful at low frequencies too. 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. **(4)** Using the near-UV sensitivity of *XMM*'s Optical Monitor and the far-IR channels of *Spitzer*, I plan to propose a joint archival project to disentangle which $K_0 \lesssim 20$ cDs are star formation dominated and which are AGN dominated.

Future Work with *Planck*

As I mentioned earlier, there are several extensions of my thesis work which I can pursue independently. But in the context of the post-doc position at Saclay and specifically working toward exploitation of the *Planck* cluster catalogue, I see a multitude of projects. Unless it is possible to commandeer *XMM-Newton* and *Chandra* for an entire year, X-ray follow-up of every SZ detected cluster is not possible. It is therefore of the utmost importance to calibrate SZ flux to mass scale so that a robust scaling relation can be used to directly infer masses from SZ observations. But while this sounds simple, there are complications which must be sorted out prior to the analysis of a large SZ cluster catalogue like *Planck*'s.

Existing studies so far suggest there is no redshift evolution in X-ray mass-scaling relations. But these studies suffer from a major flaw: they are hardly complete or unbiased. It would be wise to carefully select a representative sample of clusters, calculate their masses using a "robust, low-scatter" proxy (*e.g.* the Y_X parameter of Kravtsov et al. 2006), and check for redshift dependence in mass-scaling relations. There is the added complication that non-gravitational effects in clusters (*i.e.* AGN feedback, radiative cooling, and especially mergers) become more important at higher redshifts and at the lower end of the mass spectrum where the SZ effect will be a valuable probe. Understanding how these processes conspire to scatter a cluster away from tight scaling relations will also be integral to utilizing SZ flux for mass determination.

Beyond the technical issues and preparatory work, the *Planck* cluster catalogue will be a powerful observational tool. One can readily select interesting sub-samples (such as the 100 SZ brightest clusters) to be used in other studies, for example a study of their entropy distributions using *Chandra*data. From my own work and the work of people like Ian McCarthy and Michael Balogh, we know some clusters must have experienced some amount of "pre-heating" to reach the entropy levels seen in the ICM at present ($K > 150$ keV cm^2).

Because the normalization of the Y-M relation if sensitive to pre-heating, the SZ effect can be used to place constraints on the level of pre-heating which occurred at high-redshift, and thus can tell us about the feedback mechanisms which were active in clusters at early epochs – mechanisms which most likely played a role in shaping properties of the earliest galaxies. There are many other uses for the catalogue: combining SZ and Z-ray data to constrain H_0, analyzing the SZ power spectrum of clusters to constrain the dark energy equation of state, measuring f_{gas} for a sample of clusters and truly testing it's utility as a cosmology tool, the presence of high energy electrons (even at the low spatial resolution of *Planck*) would be confirmation that non-thermal processes are important in cluster formation (*e.g.* from AGN bubbles), and there is even the possibility that cooling flows could be identified by culling outliers from scaling relations.

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. Given the opportunity to branch out from my X-ray roots, I will be an excellent collaborator for maximizing the scientific returns of *Planck*'s galaxy cluster studies.

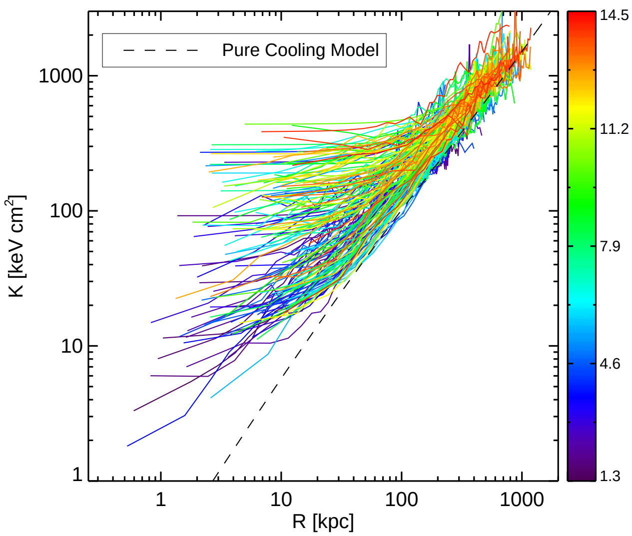

Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 70$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

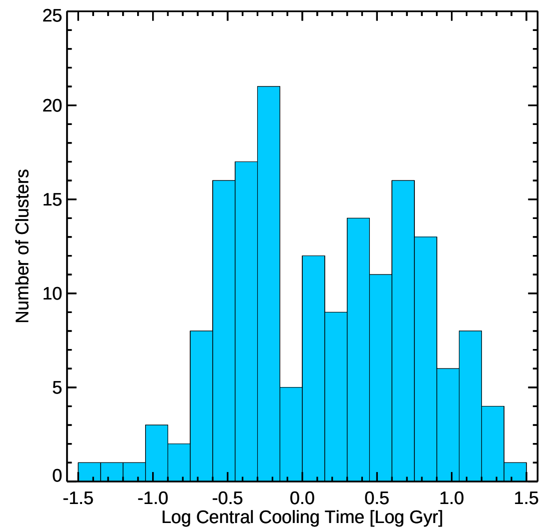

Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct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

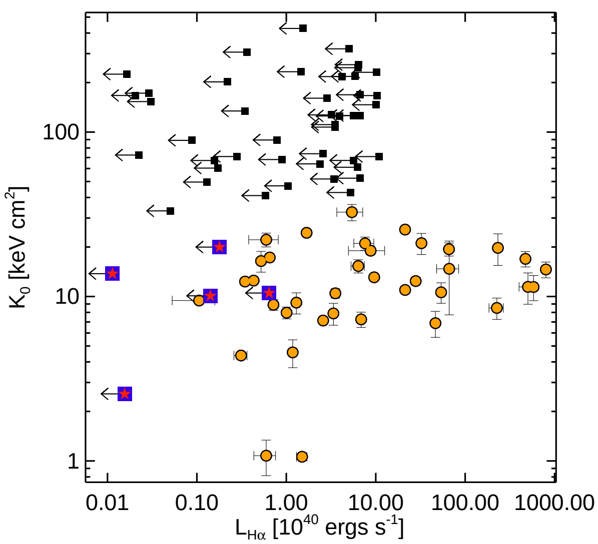

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction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

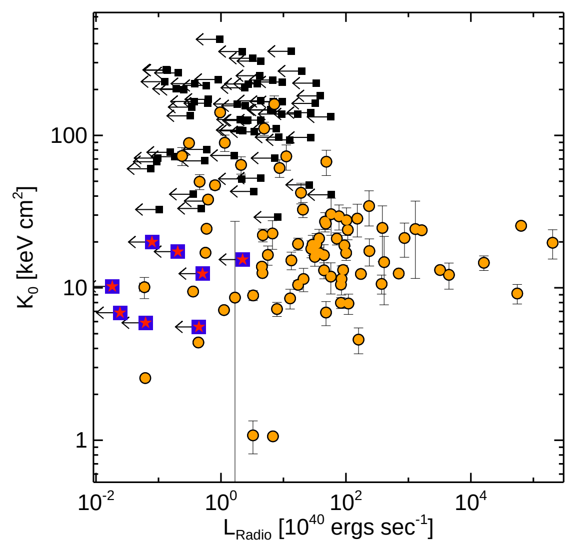

Figure 4: Central entropy plotted against NVSS radio luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Radio-loud AGN clearly prefer low entropy environs but the dispersion at low luminosity is large. It would be interesting to radio date these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