Summary of Research

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) 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 (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

Cluster mass functions and the 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).

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, and galaxy velocity dispersion. Empirically, the relationship of mass and these observable properties is well-established. However, if we could identify a “3rd parameter” – possibly reflecting the degree of relaxation in the cluster – we could improve the utility of clusters as cosmological probes.

One method of quantifying cluster substructure – a property of clusters which results in the underestimate of cluster temperatures and therefore cluster mass – employs the ratios of X-ray surface brightness moments to quantify the degree of relaxation. Although an excellent tool, power ratio suffers from being aspect dependent, much like other substructure measures such as axial ratio or centroid variation. The work of [1] found an auxiliary measure of substructure which does not depend on 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 is to find an aspect-independent measure for a cluster’s dynamic state. I have investigated the net temperature skew in my 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. Having confirmed the prediction of [1], 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 cites my work. In addition, this project has produced a first author paper which is near ApJ submission.

Cluster Feedback and ICM Entropy

The picture of the ICM entropy-feedback connection emerging from my work suggests that cD radio luminosity and Hα emission are anti-correlated with cluster central entropy. I have explored these relations with my thesis sample and am finding a trend of high central entropy favoring low $L_{H\alpha}$ and low L_{Radio}. I have also found the distribution central entropy and central cooling times are bimodal - a result which has implications for the timescales of feedback mechanisms operating in the core of clusters. The newest result from my work is a correlation between cD black hole mass and central entropy, which is more evidence feedback is regulated by AGN activity. These results fit well with the current framework for AGN heating and cooling flow retardation through the inflation of bubbles in the ICM and star formation in the cores of cooling flows. In addition, I am exploring the dependence of the X-ray loud AGN distribution on redshift and amount of cluster substructure.

This work has been very fruitful thus far: I am a co-author for two refereed journal papers ([2], [3]), generated new and unique work each year ([4], [5], [6], [7], [8], [9]), a first author paper which is in draft, and another first author paper in preparation containing my thesis results. I have also contributed to several successful *Chandra*, *XMM*, *Suzaku*, and *Subaru* proposals in addition to writing my own high scoring – although unsuccessful – *Chandra* proposal for time observing an amazing ULIRG. I am also planning Hα imaging observations for several previously unobserved clusters with MSU's SOAR telescope.

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 complimentary 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 (such as those discussed earlier or the Y_X parameter of [10]). 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 ([11]), 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.

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