Dr. Kenneth W. Cavagnolo
Summary of Research Program

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 focused on studying these details via X-ray properties of the intracluster medium (ICM) in clusters of galaxies. I paid particular attention to ICM entropy distribution [1, 2], the process of cluster virialization [3], the role of AGN feedback in shaping large scale cluster properties [4], and how feedback signatures correlate with the properties of cluster cores [5]. The picture of the ICM entropy-feedback connection which emerged from these studies was that feedback is part of a finely-tuned mechanism with the requirement that the mean entropy (K) of the fueling environment hosting a SMBH must be $K \lesssim 30$ keV cm^2. In the three years since our first publication, the suite of papers from this work has garnered 100+ citations.

My dissertation work made use of 400+ *Chandra* archival X-ray observations (≈ 13 Msec of data). The massive undertaking necessitated the creation of a robust reduction and analysis pipeline which interacts with mission specific software (be it *Chandra*, *XMM-Newton*, *Suzaku*), utilizes analysis tool (*e.g.* XSPEC, IDL, IRAF), smoothly incorporates calibration/software updates, is highly automated, and continues to mature. My pipeline is written in a very general manner, and adaptation of the pipeline for use with pre-packaged analysis tools from other missions has been straightforward. Most importantly, the pipeline deemphasizes data reduction and accords the user with the freedom to move quickly into an analysis phase and generating publishable results.

More recently, my research has focused on extreme, individual examples of AGN feedback which are useful for confronting existing models of AGN feedback and galaxy formation. I have recently completed studies for two such systems: RBS 797 and IRAS 09104+4109. The rich dataset available for RBS 797 indicates that the AGN outburst is inclined along the line-of-sight, and that the outburst is one of the most powerful ever observed, *e.g.* the cluster-scale class of burst similar to MS 0735.6+7421 [6]. Our detailed study has been useful for further understanding how large outbursts affect hydrostatic equilibrium in clusters, whether such outbursts can be driven by classical gas accretion mechanisms, and if such outbursts can halt cooling in a cluster. The results for RBS 797 are being presented in an ApJ manuscript [7]. IRAS 09104+4109 is an enigmatic system with a long literature indicating the galaxy is simultaneously undergoing a variety of normally orthogonal phases of massive galaxy formation. The completed study highlights results from a new *Chandra* observation which shows the AGN in IRAS09 excavating cavities and uplifting cool gas from the core. This is unique for a radio-quiet, radiatively dominated QSO, and demonstrates that massive galaxies like BCGs and cDs may go through a brief phase of quasar-mode feedback which is immediately followed by a radio-mode. IRAS09 is currently the only system where both processes have been directly observed. These results are being presented in a MNRAS manuscript [8].

Another of my studies which was recently completed [9] investigates a more precise calibration between AGN jet power ($P_{\rm jet}$) and emergent radio emission ($L_{\rm radio}$) for a sample of giant ellipticals (gEs) and BCGs. In this study we estimated $P_{\rm jet}$ using cavities excavated in the ICM as bolometers, and measured $L_{\rm radio}$ at multiple frequencies using new and archival VLA observations. We found, regardless of observing frequency, that $P_{\rm jet} \propto 10^{16} L_{\rm radio}^{0.7}$erg s^{-1}, which is in general agreement with models for confined heavy jets. The utility of this relation lies in being able to estimate total jet power from monochromatic all-sky radio surveys for large samples of AGN at various stages of their outburst cycles. This should yield constraints on the kinetic heating of the Universe over swathes of cosmic time, and as a consequence, can be used to infer the total accretion history and growth of SMBHs over those same epochs. An interesting result which has emerged from our work is that FR-I radio galaxies (classified on morphology and not $L_{\rm radio}$) appear to be systematically more radiatively efficient than FR-II sources. This may mean there are intrinsic differences in radio sources (light and heavy jets), or possibly that all jets are born light and become heavy on large scales due to entrainment.

I am also involved in a number of other projects with both undergraduate and graduate students at the University of Waterloo, in addition to projects with peers. I am a member of the Supermassive Cluster Survey and am responsible for the X-ray analysis in the project. The study is headed-up by Rachel Mandelbaum (Princeton) and seeks to better understand the scatter between X-ray and weak lensing masses for a sample of 12 galaxy clusters. I am also working on the analysis and interpretation of the *Chandra* Large Project for MS 0735.6+7421. This project centers around 700 ksec of X-ray data which is being used to study the properties of the most energetic AGN outburst found to date. Brian McNamara has two Ph.D. students and two undergraduates, all of which I am helping to guide in their research on: finding large optical cores for BCGs in the Hubble archive, the spin of SMBHs, instantaneous accretion mechanisms for SMBHs, quantifying the 2D abundance distributions in galaxy clusters, and finding/studying radio sources from all-sky surveys coincident with clusters. I also maintain a close working relationship with my thesis research group at Michigan State University (David Ventimiglia and Seth Bruch), and am collaborating with two Ph.D. students on separate papers relating to the deviation of galaxy clusters from mean mass-scaling relations. There are also two on-going large radio observation based projects (PI's Somak Raychaudhury and Alastair Edge) which focus on low-frequency AGN emission in clusters and groups. I am responsible for data acquistion, reduction, and analysis in one project, and X-ray data analysis for another. It is expected that both of these projects will merge with Herschel and LOFAR Key Projects.

References

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