

Dr. Kenneth W. Cavagnolo Statement of Research Interests

Introduction

The energy liberated by active galactic nuclei (AGN) plays a vital role in regulating the process of hierarchical structure formation [*e.g.* 1, 2, 3, 4, 5, 6]. Observations robustly indicate most, if not all, galaxies harbor a centralized SMBH which has co-evolved with the host galaxy giving rise to the well-known bulge luminosity-stellar velocity dispersion correlation [7, 8]. The current galaxy formation paradigm couples the processes of environmental cooling and heating via feedback loops [9, 10]. In broad terms, feedback has been segregated into two modes which occur at different cosmic epochs: an early-time radiatively-dominated quasar mode, and a late-time mechanically-dominated AGN mode. While this model is successful in reproducing the bulk properties of the Universe, the details (*i.e.* accretion processes, obscuration, power generation, energy dissipation) are poorly understood. It is these details which interest me most.

Relevant Completed and On-going Research

My research has focused primarily on understanding the mechanical feedback from AGN and the associated effects on galaxy clusters. I have devoted particular attention to intracluster medium (ICM) entropy distribution [11], the process of cluster virialization [12], the mechanisms by which SMBHs might accrete fuel from an environment [13], and how those mechanisms correlate with properties of clusters cores [14].

From these studies it has become apparent that certain conditions must be established within a cluster core (and presumably any environment which supplies fuel for a SMBH, *e.g.* cool coronae [15]), namely that the mean entropy (K) of the large-scale environment hosting a SMBH must be $K \lesssim 30 \text{ keV cm}^2$. Coincidentally, this is the entropy scale above which thermal electron conduction is capable of stabilizing a cluster core against the formation of thermal instabilities, hinting at a method for coupling AGN feedback energy to the ICM and establishing a self-regulating feedback loop. This result is made more interesting if the heat-flux-driven-buoyancy instability [HBI, 16] is an important process in clusters with central cooling times $\ll H_0^{-1}$. Full MHD simulations have shown that the HBI, in conjunction with reasonable magnetic field strengths ($\sim 1 \mu\text{G}$), modest heating from an AGN ($\sim 10^{43} \text{ erg s}^{-1}$) and subsonic turbulence, can feasibly stabilize a core against catastrophic cooling [17, 18]. In addition, recent radio polarization measurements for Virgo cluster galaxies suggest the large-scale magnetic field of Virgo's ICM is radial oriented [19]. This result is tantalizing since it suggests the magnetothermal instability [20] may be operating within Virgo, furthering the case that conduction is a vital component of understanding galaxy cluster evolution. In total, these studies touch on a larger subject which is of great interest to me: magnetic fields in clusters.

LOFAR came online fall 2009, and the order of magnitude improvement in angular resolution and sensitivity at low radio frequencies opens a new era in studying ICM magnetic fields via polarimetry [21]. Polarization measurements made with LOFAR will enable direct detection of ICM field strengths and structure on scales as small as cluster cores ($\lesssim 50 \text{ kpc}$) and as large as cluster virial radii ($\sim \text{few Mpc}$). A

systematic study of a cluster sample using LOFAR will expand our view of magnetic field demographics and how they relate to cluster properties like temperature gradients, core entropy, recent AGN activity, and the structure of cold gas filaments in cluster cores. In addition, we will be able to investigate the origin and evolution of the fields: were they seeded by early AGN activity? Are they amplified by mergers? Is there evidence of draping or entrainment? Understanding cluster magnetic fields will also place constraints on ICM properties, like viscosity, which govern the microphysics by which AGN feedback energy might be dissipated as heat, *e.g.* via turbulence and/or MHD waves.

My most recent research has focused on the SMBH engines which underlie AGN. One study recently completed [22] investigates a more precise calibration between AGN jet power (P_{jet}) and emergent radio emission (L_{radio}) for a sample of giant ellipticals (gEs) and BCGs. In this study we estimated P_{jet} using cavities excavated in the ICM as bolometers, and measured L_{radio} at multiple frequencies using new and archival VLA observations. We found, regardless of observing frequency, that $P_{\text{jet}} \propto 10^{16} L_{\text{radio}}^{0.7} \text{ erg s}^{-1}$, 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, and which is investigated in [23], is that FR-I radio galaxies (classified on morphology and not L_{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. One way to investigate this result more deeply is to undertake a systematic study of the environments hosting radio galaxies utilizing archival *Chandra* and VLA data.

With tighter observational constraints on the kinetic properties of AGN jets, of interest to me is re-visiting existing models for relativistic jets in an ambient medium. Utilizing observationally-based estimates of jet power, it is possible to better understand the growth of a radio source including effects like entrainment and evolution of jet composition [à la 24]. Another interesting use of a universal $P_{\text{jet}}-L_{\text{radio}}$ relation is using radio luminosities, lobe morphologies, and age estimates to predict ambient gas pressures: $p_{\text{amb}} \propto (\tau_{\text{age}} L_{\text{radio}})/V_{\text{radio}}$. This yields an estimate of ambient densities when basic assumptions are made about environment temperatures: $\rho_{\text{amb}} \propto p/T$. With an estimate of ambient densities, X-ray observing plans for very interesting radio sources which reside in faint group environments (*i.e.* FR-I sources) can be robustly prepared. An observationally-based estimate of P_{jet} also enables the investigation of relations between observable mass accretion surrogates (*i.e.* $\text{H}\alpha$ luminosity, molecular/dust mass, or nuclear X-ray luminosity) and AGN energetics for the purpose of establishing clearer connections with accretion mechanisms and efficiencies.

Future Research

The study of mechanically-dominated AGN feedback has advanced quickly in the last decade primarily because the process is readily observed at low-redshifts, and the hot gas phase which this mode of feedback most efficiently interacts is accessible with the current generation of X-ray observatories. However, the frequency of AGN feedback as a function of environment and our understanding of radiative feed-

back has not progressed as quickly. The former results from the limitations of existing X-ray samples, while the latter is a consequence of obscuration which prevents direct observational study [25]. Luckily, the quality and availability of multi-frequency data (radio, sub-mm, IR, optical, UV, and X-ray) needed to probe AGN duty cycles and obscuration is poised to improve with new facilities and instruments coming on-line (*i.e.* LOFAR, Herschel, SCUBA-2, SOFIA, ALMA, NuStar, Simbol-X). As such, there are a number of questions regarding the formation and evolution of SMBHs that I would like to pursue.

How does AGN activity depend on environment? Specifically what is the relationship between redshift, environment, duty cycle, and feedback energy? The answer thus far is unclear, most likely because the influence of environment on AGN jets (through entrainment and confinement) has been neglected or treated too simply in models. The lack of comprehensive X-ray samples, particularly at low-masses, also has prevented the study of duty cycles. This is where observations step in to place interesting constraints on the problem. To this end, a study of the faint radio galaxy population using archival *Chandra* and VLA data would be interesting. Undertaking a systematic study of radio galaxy properties (*i.e.* jet composition, morphologies, outflow velocities, magnetic field configurations) as a function of environment (*i.e.* ambient pressure, halo compactness) can help address how AGN energetics couple to environment, which ultimately suggests how accretion onto the SMBH couples to environment on small and large scales. Deep *Chandra* observations for a sample of FR-I's (a poorly studied population in the X-ray) would also be useful for such a study, using the $P_{\text{jet}}-L_{\text{radio}}$ relation to define robust observation requests.

How does the transition from an obscured to unobscured state correlate with AGN feedback and SMBH growth? As suggested by the low AGN fraction in the *Chandra* Deep Fields, a significant population of obscured AGN must exist at higher redshifts. One method of selecting unbiased samples of these objects is to assemble catalogs of candidate AGN using hard X-ray (*i.e.* NuStar), far-IR (*i.e.* SOFIA), and sub-mm (*i.e.* SCUBA-2) observations. Because current models suggest the luminous quasar population begins in an obscured state, and rapid acquisition of SMBH mass may occur in this phase because of high accretion rates (possibly exceeding $10 - 100 L_{\text{Edd}}$), understanding the transition from obscured to unobscured states is vital. How does accretion proceed and where does the accreting material come from: gas cooling out of the atmosphere? Gas stripped from merging companions? Is accretion spherical and dictated by local gas density (*e.g.* Bondi)? A key component which has been neglected in AGN studies is the contribution of dust (which should be a significant component in the atmospheres of obscured AGN) in increasing the allowed Eddington luminosity for an accreting SMBH (*i.e.* $L_{\text{Edd}} \propto \mu$). A curiosity which has emerged in recent years which may be interesting, particularly during the obscured stage when the merger rate is presumably high, is the role of multiple SMBHs within the core of a host galaxy. At a minimum, SMBH mergers occur on a timescale determined by dynamical friction, which for a typical dense bulge is $\gtrsim 1$ Gyr, which is $\gg t_{\text{cool}}$ of an obscuring atmosphere. If the SMBHs which are merging have their own accretion disks, then it is reasonable to question how the atmospheres surrounding a host galaxy with multiple AGN is affected, particularly since the transition from obscured to unobscured should proceed more quickly.

References

- [1] A. C. Fabian, J. S. Sanders, S. Ettori, G. B. Taylor, S. W. Allen, C. S. Crawford, K. Iwasawa, R. M. Johnstone, and P. M. Ogle. *Chandra* imaging of the complex X-ray core of the Perseus cluster. *MNRAS*, 318:L65–L68, November 2000.
- [2] D. J. Croton, V. Springel, S. D. M. White, G. De Lucia, C. S. Frenk, L. Gao, A. Jenkins, G. Kauffmann, J. F. Navarro, and N. Yoshida. The many lives

of active galactic nuclei: cooling flows, black holes and the luminosities and colours of galaxies. *MNRAS*, 365:11–28, January 2006.

- [3] R. G. Bower, A. J. Benson, R. Malbon, J. C. Helly, C. S. Frenk, C. M. Baugh, S. Cole, and C. G. Lacey. Breaking the hierarchy of galaxy formation. *MNRAS*, 370:645–655, August 2006.
- [4] A. Saro, S. Borgani, L. Tornatore, K. Dolag, G. Murante, A. Biviano, F. Calura, and S. Charlot. Properties of the galaxy population in hydrodynamical simulations of clusters. *MNRAS*, 373:397–410, November 2006.
- [5] D. Sijacki, V. Springel, T. di Matteo, and L. Hernquist. A unified model for AGN feedback in cosmological simulations of structure formation. *MNRAS*, 380:877–900, September 2007.
- [6] L. Birzan, B. R. McNamara, P. E. J. Nulsen, C. L. Carilli, and M. W. Wise. Radiative Efficiency and Content of Extragalactic Radio Sources: Toward a Universal Scaling Relation between Jet Power and Radio Power. *ApJ*, 686:859–880, October 2008.
- [7] J. Kormendy and D. Richstone. Inward Bound—The Search For Supermassive Black Holes In Galactic Nuclei. *ARA&A*, 33:581–, 1995.
- [8] J. Magorrian, S. Tremaine, D. Richstone, R. Bender, G. Bower, A. Dressler, S. M. Faber, K. Gebhardt, R. Green, C. Grillmair, J. Kormendy, and T. Lauer. The Demography of Massive Dark Objects in Galaxy Centers. *AJ*, 115:2285–2305, June 1998.
- [9] B. B. Nath and S. Roychowdhury. Heating of the intracluster medium by quasar outflows. *MNRAS*, 333:145–155, June 2002.
- [10] B. R. McNamara and P. E. J. Nulsen. Heating Hot Atmospheres with Active Galactic Nuclei. *ARA&A*, 45:117–175, September 2007.
- [11] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Intracluster Medium Entropy Profiles for a Chandra Archival Sample of Galaxy Clusters. *ApJS*, 182:12–32, May 2009.
- [12] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Bandpass Dependence of X-Ray Temperatures in Galaxy Clusters. *ApJ*, 682:821–834, August 2008.
- [13] G. M. Voit, K. W. Cavagnolo, M. Donahue, D. A. Rafferty, B. R. McNamara, and P. E. J. Nulsen. Conduction and the Star Formation Threshold in Brightest Cluster Galaxies. *ApJ*, 681:L5–L8, July 2008.
- [14] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. An Entropy Threshold for Strong H α and Radio Emission in the Cores of Galaxy Clusters. *ApJ*, 683:L107–L110, August 2008.
- [15] M. Sun, C. Jones, W. Forman, A. Vikhlinin, M. Donahue, and M. Voit. X-Ray Thermal Coronae of Galaxies in Hot Clusters: Ubiquity of Embedded Mini-Cooling Cores. *ApJ*, 657:197–231, March 2007.
- [16] I. J. Parrish and E. Quataert. Nonlinear Simulations of the Heat-Flux-driven Buoyancy Instability and Its Implications for Galaxy Clusters. *ApJ*, 677:L9–L12, April 2008.
- [17] I. J. Parrish, E. Quataert, and P. Sharma. Anisotropic Thermal Conduction and the Cooling Flow Problem in Galaxy Clusters. *ApJ*, 703:96–108, September 2009.
- [18] M. Ruszkowski and S. P. Oh. Shaken and stirred: conduction and turbulence in clusters of galaxies. *ArXiv e-prints: 0911.5198*, November 2009.
- [19] C. Pfrommer and L. J. Dursi. Detecting the orientation of magnetic fields in galaxy clusters. *ArXiv e-prints: 0911.2476*, November 2009.
- [20] S. A. Balbus. Stability, Instability, and “Backward” Transport in Stratified Fluids. *ApJ*, 534:420–427, May 2000.
- [21] T. G. Arshakian and R. Beck. Exploring Weak Magnetic Fields with LOFAR and SKA. In D. J. Saikia, D. A. Green, Y. Gupta, & T. Venturi, editor, *Astronomical Society of the Pacific Conference Series*, volume 407 of *Astronomical Society of the Pacific Conference Series*, pages 33–, September 2009.
- [22] K. W. Cavagnolo, B. R. McNamara, C. L. Carilli, C. Jones, W. R. Forman, P. E. J. Nulsen, L. Birzan, and S. Murray. A Relationship Between AGN Jet Power and Radio Luminosity. *In preparation for ApJ*, 2009.
- [23] J. H. Croston, M. J. Hardcastle, M. Birkinshaw, D. M. Worrall, and R. A. Laing. An XMM-Newton study of the environments, particle content and impact of low-power radio galaxies. *MNRAS*, 386:1709–1728, May 2008.
- [24] C. J. Willott, S. Rawlings, K. M. Blundell, and M. Lacy. The emission line-radio correlation for radio sources using the 7C Redshift Survey. *MNRAS*, 309:1017–1033, November 1999.
- [25] D. M. Alexander. Identifying the Obscured Black-Hole Growth Phase of Distant Massive Galaxies. *ArXiv e-prints: 0911.3911*, November 2009.