Statement of Research Interests

The gravitational energy liberated by active galactic nuclei (AGN), *i.e.* accreting supermassive black holes (SMBHs), plays a vital role in regulating the process of hierarchical structure formation [*e.g.* 1, 2, 3, 4, 5, 6]. Current cosmological models invoke a feedback loop where the processes of environmental cooling and heating are coupled via AGN [7, 8]. In broad terms, AGN feedback has been segregated into two modes which occur at different cosmic epochs: an early-time radiatively-dominated mode, and a late-time mechanically-dominated mode. While this model is successful in reproducing the bulk properties of the Universe, the details of AGN feedback are poorly understood. It is these details which interest me most.

My past research has focused 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 [9], the process of cluster virialization [10], the mechanisms by which SMBHs might acquire fuel from their environments [11], and how those mechanisms correlate with properties of clusters cores [12].

These studies have revealed that certain conditions must be established within a cluster core, namely that the mean entropy of the large-scale environment hosting a SMBH must be $\lesssim 30$ 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 mechanism 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, 13] 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, modest heating from an AGN, and subsonic turbulence can feasibly stabilize a core against catastrophic cooling [14, 15]. In addition, recent radio polarization measurements for Virgo cluster galaxies suggest the large-scale magnetic field of Virgo's ICM is radial oriented [16]. This result is tantalizing since it suggests the magnetothermal instability [17] may be operating within Virgo, furthering the case that conduction is a vital component of understanding galaxy cluster evolution under the influence of AGN. In total, these studies touch on the subject of magnetic fields in clusters, which is of great interest to me.

The Low Frequency Array (LOFAR) radio observatory began collecting data in fall 2009, and has opened a new era in studying ICM magnetic fields via polarimetry [18]. Polarization measurements made with LOFAR will enable direct detection of ICM field strengths and structure on scales as small as cluster cores and as large as cluster virial radii. A systematic study of a representative cluster sample (such as REXCESS [19]) 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.

A study I have recently completed [20] 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. 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. When applied to the radio luminosity function at various redshifts, the $P_{\rm jet}$-$L_{\rm radio}$ relation can be used to infer the kinetic heating of the Universe over cosmic time, and as a consequence, can be used to infer the total accretion history and growth of SMBHs over those same epochs. Further, inferences can be drawn regarding the amount of preheating AGN could have contributed as large-scale structure evolved, a long-standing question in cosmology [21].

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. 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 better 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 investigate the growth of a radio source including processes like entrainment, scale-dependent changes in jet composition, and shocks [á la 22]. The $P_{\rm jet}$-$L_{\rm radio}$ relation also enables the investigation of relations between observable mass accretion surrogates (*i.e.* nuclear Hα luminosity, molecular/dust mass, or nuclear X-ray luminosity) and AGN energetics for the purpose of establishing clearer connections with accretion mechanisms and efficiencies.

The study of mechanical AGN feedback has advanced quickly in the last decade primarily because the hot gas phase which this mode of feedback most efficiently interacts is resolved with the current generation of X-ray observatories. However, our understanding of radiative feedback, and the associated early era of rapid SMBH growth, has not progressed as quickly. This is mostly because cold/dusty gas is required for high efficiency radiative feedback, but the presence of cold/dusty gas is typically accompanied by significant optical obscuration which prevents direct observational study [23]. Luckily, the quality and availability of multi-frequency data needed to probe the epoch of SMBH growth 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.

(1) What is the evolutionary track from young, gas-rich, dusty galaxies to present-day old, parched gEs? It has been argued that high-z sub-mm galaxies (SMGs) are the progenitors for low-z Magorrian galaxies, suggesting SMGs are useful for studying the co-evolution of SMBHs and host galaxies. SMGs have also been shown to reside in very dense environments and have high AGN fractions ($\gtrsim 50\%$) [24], so they are excellent for identifying the rapidly cooling high-z gas-rich regions where star formation and AGN activity are occurring. Thus, SMGs identify a unique population to follow-up with far-IR and X-ray spectroscopy to study epochs of early AGN feedback and environmental cooling. It has also been posited that SMGs are high-z analogs of low-z ultraluminous infrared galaxies (ULIRGs). If this is the case, insight to ULIRG evolution can be gained from studying SMGs. ULIRGs are an interesting population on their own, one for which limited X-ray spectroscopic studies have been undertaken. We know these systems to, on average, be dominated by star formation, however, some systems also have significant contribution from very dusty AGN, and these systems can be used to further understand the nature of evolving gas-rich environments.

(2) What is the relationship between redshift, environment, and AGN feedback energy? The answer thus far is unclear, most because of limited observational constraints. 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 SMBHs depends on small and large scale environment. Deep *Chandra* observations for a sample of FR-I's (a poorly studied population in the X-ray) would be useful for such a study. Using the $P_{\rm jet}$-$L_{\rm radio}$ relation, radio luminosities, lobe morphologies, and age estimates can be used to predict ambient gas densities for the purpose of robustly preparing the X-ray observations.

(3) How does the transition of the nuclear region of a forming galaxy 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, 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 an atmosphere? Gas deposited by merging companions? A related curiosity which has emerged in recent years is the role of multiple AGN 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 $\gg t_{\rm cool}$ of an obscuring atmosphere. If the SMBHs which are merging have, or acquire, their own accretion disks, then it is reasonable to question how the atmospheres surrounding a host galaxy with multiple AGN is affected.

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