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The gravitational binding energy liberated by active galactic nuclei (AGN) plays a vital role in the process of hierarchical structure formation [*e.g.* 1, 2, 3, 4, 5, 6]. Observations robustly indicate most galaxies harbor a centralized supermassive black hole (SMBH) which likely co-evolved with the host galaxy giving rise to the well-known bulge luminosity-stellar velocity dispersion correlation [7, 8]. A key component in the galaxy formation paradigm which explains these observed correlations is that host environment thermodynamics are regulated via feedback from AGN [9, 10]. In broad terms, this model is successful in reproducing the bulk properties of the Universe, specifically the thermal properties of the intracluster medium (ICM) in galaxy clusters and the intragroup medium (IGM) in galaxy groups. However, the details of ICM/IGM evolution under the influence of AGN activity is still poorly understood, as is the ICM/IGM non-thermal component. There are many open questions regarding ICM/IGM magnetic fields, the origins of diffuse cluster-scale radio halos, and how AGN feedback is coupled to environment. It is these open questions which interest me as I develop a more diverse research program.

Relevant Completed Research

Part of my research program has focused primarily on understanding the mechanical feedback from AGN and the associated effects on galaxy clusters. I have devoted particular attention to ICM entropy distribution [11], the process of cluster virialization [12], the mechanisms by which SMBHs might acquire fuel from their environments [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 a large-scale environment hosting a SMBH must be $K \lesssim 30$ keV cm^2.

By a coincidence of scaling, $K \sim 30$ keV cm^2 is the entropy scale above which thermal electron conduction is capable of stabilizing gas against thermal instability. This link between large-scale environment and small-scale structure formation hints at a mechanism for channeling AGN feedback energy to cooling regions. If conduction operates in this fashion, then it may be a solution to the long-standing problem of tuning AGN heating to establish a self-regulating feedback loop. However, it is well-known that conduction on its own does not operate efficiently within the ICM, and that for most clusters, conduction has a minor role in defining ICM properties [16, 17, 18, 19].

But, if magnetohydrodynamic (MHD) processes like the heat-flux-driven-buoyancy instability [HBI, 20] are functioning in large-scale environments with cooling times $\ll H_0^{-1}$, then conduction may be important after all. In the presence of reasonable magnetic fields ($\sim 1\ \mu$G), modest AGN heating ($\sim 10^{43}$ erg s^{-1}) and subsonic turbulence, full MHD simulations have shown that the HBI aides conduction in stabilizing the cores of galaxy clusters against catastrophic cooling [21, 22]. What is most promising though it that these theoretical studies make specific observational predictions regarding the magnetic field configurations in clusters as a function of AGN activity and cluster dynamic state – predictions which can be tested using LOFAR and Simbol-X.

Furthermore, recent radio polarization measurements for galaxies in the Virgo cluster suggest Virgo's ICM magnetic fields are radially oriented [23]. This result is tantalizing since radially oriented magnetic fields can result from the effects of the MHD magnetothermal instability mechanism [MTI, 24]. The results for Virgo further suggest that through the assistance of particular ICM magnetic field configurations, conduction may play an important role in cluster evolution. If large-scale radial magnetic fields are common in clusters, then one can safely infer that MHD processes like MTI are indeed a vital component of understanding galaxy cluster evolution. While the results for Virgo provide only a single data point, it is sufficiently interesting that follow-up using a larger cluster sample should be undertaken. Such a study is possible using the capabilities of LOFAR and Simbol-X.

LOFAR's order of magnitude improvement in angular resolution and sensitivity at low radio frequencies opens a new era in studying ICM/IGM magnetic fields via polarimetry [25]. Polarization measurements made with LOFAR will enable direct detection of ICM/IGM field strengths and structure on scales as small as cluster cores ($\lesssim 50$ kpc, the scale where HBI operates) and as large as cluster virial radii ($\sim$ few Mpc, the scale where MTI functions). 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, merger activity which induce bulk motions, recent AGN activity, and the structure of cold gas filaments in cluster cores. In addition, we will be able to infer the possible origins and evolution of ICM/IGM fields: were they seeded by early AGN activity? Are they amplified and modified by mergers? Understanding cluster magnetic fields will also place constraints on ICM/IGM properties, like viscosity, which may govern the microphysics by which AGN feedback energy can be dissipated as heat, *e.g.* via turbulence and/or MHD waves.

Relevant On-going Research

My on-going research has focused on the SMBH engines which underlie AGN. A study which was recently completed [26] investigates a more precise calibration between AGN jet power ($P_{\rm jet}$) and emergent radio emission ($P_{\rm radio}$) 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 $P_{\rm radio}$ at multiple frequencies using new and archival VLA observations. We found, regardless of observing frequency, that $P_{\rm jet} \propto 10^{16} P_{\rm radio}^{0.7}$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 radio galaxies. Such a study should yield interesting constraints on the kinetic heating of the Universe over vast swathes of cosmic time. As a consequence, inferences can be drawn about AGN duty cycles, the total accretion history of SMBHs, and the growth of SMBHs as a function of redshift. A low-frequency all-sky survey from LOFAR should provide an ideal catalog for conducting such a study.

An interesting result which has emerged from the $P_{\rm jet}$-$P_{\rm radio}$ work is that FR-I radio galaxies (classified on morphology and not $P_{\rm radio}$) appear to be systematically more radiatively efficient than FR-II sources. This may mean there are intrinsic differences in radio galaxies (*i.e.* light vs. heavy relativisic jet compositions), or possibly that all AGN 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. Supplementary low-frequency data from LOFAR would be invaluable for such a study as the low-frequency data provides important constraints on the full extent of the energy in the radio lobes.

The $P_{\rm jet}$-$P_{\rm radio}$ work has also provided a means to establish tighter observational constraints on the kinetic properties of AGN jets. With this new leverage, 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 [á la 27]. Another interesting use of a universal $P_{\rm jet}$-$P_{\rm radio}$ relation is using radio luminosities, lobe morphologies, and age estimates to predict ambient gas pressures: $p_{\rm amb} \propto (t_{\rm age} P_{\rm radio})/V_{\rm radio}$. This yields an estimate of ambient densities when basic assumptions are made about environment temperatures: $\rho_{\rm amb} \propto p/T$. 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 $P_{\rm jet}$ also enables the investigation of relations between observable mass accretion surrogates (*i.e.* 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.

Future Research

The study of AGN feedback and ICM/IGM thermal properties has advanced quickly in the last decade primarily because the the current generation of X-ray and radio observatories have provided access to the datasets needed for detailed studies. However, our understanding of non-thermal cluster emission and the origin of the emitting particles has not progressed as quickly. Serendipitously, the quality and availability of multi-frequency data (low-frequency radio, sub-mm, IR, optical, UV, and hard X-ray) needed to probe non-thermal emission is poised to improve with new facilities and instruments coming on-line (*i.e.* LOFAR, Herschel, SCUBA-2, SOFIA, ALMA, NuStar, Simbol-X, LWA). As such, there are a number of research topics I am interested in pursuing at NRL using LOFAR and Simbol-X.

What is the origin of cluster-scale radio halos? Detection of large-scale, diffuse radio halos in clusters emphasized the need to further understand the non-thermal component of the ICM/IGM [*e.g.* 28, 29]. Though the case connecting radio halos to mergers is increasingly convincing [30], the prevalence of radio halos in clusters is not as high as expected given that all clusters are in some stage of merger.

Moreover, galaxy groups provide an additional constraint on the properties of radio halos and their possible origins, yet no study of these lower-mass analogs of clusters has been undertaken. Adding to the mystery of radio halos is that the details regarding the processes which generate the synchrotron emission are unknown. A number of models have been proposed to explain the emission (*e.g. in situ* acceleration), but discerning between them observationally has not been possible prior to LOFAR coming online. The systematic study of a large sample of X-ray selected clusters with LOFAR (*e.g.* replicating the work of [31, 32]) will aide in addressing how radio halos form and evolve.

How does AGN activity depend on environment? Specifically what is the relationship between redshift, environment, 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. 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 $P_{\rm jet}$-$P_{\rm radio}$ relation to define robust observation requests.

How does the obscuration state of a SMBH correlate with radiative and mechanical 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.* Simbol-X), far-IR (*i.e.* SOFIA), sub-mm (*i.e.* SCUBA-2), and low-frequency radio (*i.e.* LOFAR) 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 $10-100\ L_{\rm Edd.}$), 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.* $L_{\mathrm{Edd.}} \propto \mu$). 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 $\gg t_{\mathrm{cool}}$ 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.

Summary

The general picture of structure formation is much clearer now than a decade ago, and the role of SMBHs and mergers in defining the thermal and non-thermal emission from clusters and groups is undeniably important. But, missing is a better understanding of cosmic magnetic fields, AGN feedback properties, the feedback-environment connection, diffuse cluster radio emission, modes of SMBH accretion, and how AGN interact with/heat host atmospheres. To this end, more observational constraints are needed, particularly using multiwavelength datasets from upcoming missions. I am well-positioned to make meaningful contributions in such pursuits, and would like to do so as a member of the LOFAR consortium at NRL.

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