Statement of Research Interests

Several decades of observations have helped define the current galaxy formation paradigm in which supermassive black holes (SMBHs) and active galactic nuclei (AGN) play a vital role in regulating structure formation [*e.g.* 1, 2, 3, 4, 5, 6, 7, 8, 9]. Following the lead of observations, the current generation of large-scale structure formation models now include some variation of a positive feedback loop in which secondary processes like radiative cooling and star formation are offset via heating by AGN activity [*e.g.* 10, 11, 12, 13]. While these models are successful in reproducing the bulk properties of the Universe, the details of AGN feedback are still poorly understood. One reason being that additional observation-based constraints are needed on, for example, (1) how AGN energy is transported beyond jets and dissipated as heat, (2) the role/importance of magnetic fields within the hot, diffuse gas of galaxy clusters and groups, (3) the connection between radio galaxy properties and their host environments, and (4) the phase of obscuration that possibly all AGN experience during SMBH assembly. Further exploration of these topics comprises the research proposed here.

(1 & 2) I propose, as a Leiden Fellow, to participate in, or undertake, an observational study of the evolution of galaxy clusters/groups under the influence of magnetic fields. Preferably, such a study will be part of the LOFAR Cosmic Magnetism Key Project. My research program has revealed that certain environmental conditions must be met to promote feedback, namely that the mean entropy of the environment hosting a SMBH must be $\lesssim 30$ keV cm^2 [14, 15, 16, see also Fig. 1]. By a coincidence of scaling, this is also the entropy level above which thermal electron conduction is capable of stabilizing an environment against the formation of thermal instabilities [17]. The connection of large-scale environmental properties with the process of conduction hints at a mechanism for heating an environment via AGN feedback energy and possibly toward the establishment of a self-regulating feedback loop. Simulators investigating magnetohydrodynamic (MHD) processes in groups and clusters have seized upon these findings due to the connection between MHD processes, conduction, and entropy structure.

It has been suggested that the MHD heat-flux-driven-buoyancy instability (HBI) is an important process in clusters with core cooling times $\ll H_0^{-1}$ [18]. 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 [19, 20]. In addition, recent radio polarization measurements for the Virgo cluster of galaxies suggest the large-scale magnetic field of Virgo's intracluster medium (ICM) is radially oriented [21], which may result from the influence of the MHD magnetothermal instability mechanism [MTI, 22]. Because both HBI and MTI can connect regions of differing temperatures via magnetic fields, both mechanisms are capable of channeling heat throughout the ICM via conduction. If HBI and MTI have a significant influence in clusters and groups, then it furthers the case that conduction is a vital component of understanding galaxy cluster evolution. However, the observational evidence remains circumstantial, and these MHD processes (and conduction) require additional indirect investigation via magnetic field strengths and structures.

The Low Frequency Array (LOFAR) radio observatory recently began collecting data, marking the beginning of a new era in the study of ICM and intragroup medium (IGM) magnetic fields via polarimetry [23]. Polarization measurements made with LOFAR will enable direct study of ICM & IGM field strengths and structure on scales as small as group cores and as large as cluster virial radii. A systematic study of a representative cluster/group sample (such as REXCESS [24] or HIFLUGCS [25]) using LOFAR will broaden our view of magnetic field demographics and how they relate to cluster/group properties such as temperature gradients, core entropy, AGN activity, and the presence of cold gas filaments. In addition, it is possible to investigate the origin and evolution of the fields: could the fields have been seeded by early AGN activity? Are fields amplified by mergers or recent AGN outbursts? Is there further evidence of galactic draping? Understanding cluster magnetic fields will also place constraints on ICM/IGM properties, such as viscosity, which govern the microphysics by which AGN feedback energy might be dissipated as heat, *e.g.* via turbulence and/or MHD waves.

(3) As a Leiden Fellow, I propose to pursue research into forming a more comprehensive understanding of the connection between the properties of radio galaxies, redshift, and host environments, with a focus on galaxy evolution and structure formation. A study we have recently completed [26] 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 have 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 (see Fig. 1). 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 cosmological studies [*i.e.* 27].

What is the relationship between redshift, environment, and AGN feedback energy? The answer thus far is unclear, partly as a result of limited observational constraints. 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, host galaxy X-ray halo compactness) can help address how AGN energetics couple to environment. Such a study can also be used to suggest how accretion onto SMBHs depends on small and large scale environment. To this end, a study of the faint radio galaxy population using archival *Chandra* and VLA data would be useful, as would deep *Chandra* observations for a sample of FR-I's – a poorly studied population in the X-ray.

An interesting result which has emerged from our work shows that FR-I radio galaxies (classified on morphology and not $L_{\rm radio}$) appear to be systematically more radiatively efficient than FR-II sources. Ostensibly this may serve as an indicator of intrinsic differences in radio sources (light and heavy jets), or that possibly all jets are born light and become heavy on large scales due to entrainment. One method of investigating this result more deeply is to undertake a systematic study of the environments hosting radio galaxies utilizing archival *Chandra*, *XMM-Newton*, and VLA data.

As an extension of the observational work, and with a model-independent method of estimating 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 further investigate the growth of a radio source including prescriptions for entrainment, scale-dependent changes in jet composition, and shocks [á la 28]. 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.

(4) I propose a comprehensive multiwavelength study of obscured AGN, their host galaxies, and the progenitors of the host galaxies to better understand SMBH formation and subsequent AGN feedback. 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 proceeded as quickly. This is partly 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 [29]. 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), and a number of questions regarding the formation and evolution of SMBHs can be pursued.

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 ($\gtrsim 50\%$) [30], 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.

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.

If offered a position as a Leiden Fellow, I look forward to forming collaborations with Leiden Observatory faculty, research associates, and students on all levels to further the Observatory's, and my own, science goals. The research proposal suggested here covers a number of areas where Leiden Observatory has already invested resources, not the least of which are the Herschel and LOFAR missions. My interests in high-energy astrophysics, galaxies, large-scale structure, and modeling directly relate to the work of Prof. Franx, Prof. Jaffe, Prof. Katgert, Prof. Miley, Prof. Röttgering, Prof. Schaye, and Prof. Snellen. Due to my established history of working within highly collaborative environments with teams composed of people from various personal and professional backgrounds, it will be a natural extension of my existing research program to begin working with other researchers at Leiden Observatory. I am also excited at the prospect of working within the LOFAR Consortium and with researchers at other LOFAR affiliated institutions.

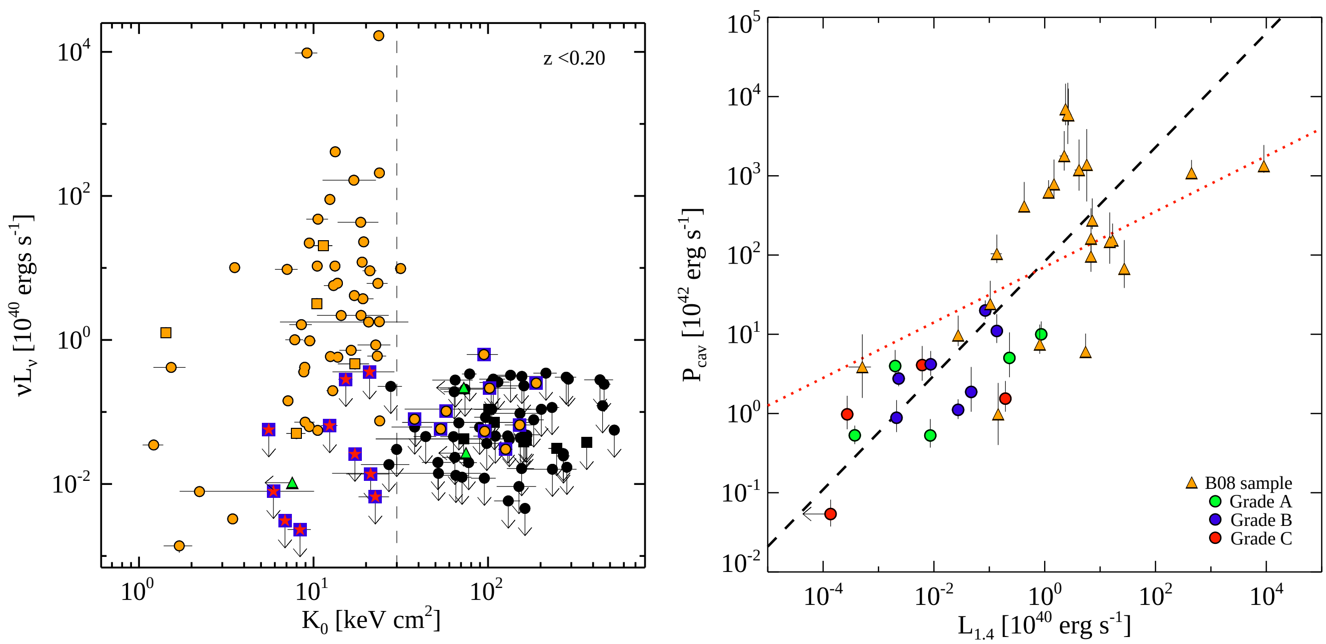

Figure 1: *Left:* BCG radio power vs. core entropy (K_0) for clusters with redshift $z < 0.2$. Orange symbols represent radio detections and black symbols are non-detection upper-limits. Circles are for NVSS observations and squares are for SUMSS observations. The blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend of being radio-loud below ≈ 30 keV cm^2. Green triangles denote clusters plotted using the 2σ upper-limit of the best-fit K_0. The vertical dashed line marks $K_0 = 30$keV cm^2. *Right:* Cavity power vs. bolometric radio power estimated from 1.4 GHz monochromatic flux. Orange triangles represent the galaxy clusters and groups sample from [9]. Filled circles represent our sample of gEs with colors representing the cavity system grade of green = 'definite,' blue = 'moderate,' and red = 'marginal.' The dotted red line represents the best-fit power-law relations presented in [9] using only the orange triangles. The dashed black lines represent our BCES best-fit power-law relations.

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