February 1, 2010

Dr. Craig L. Sarazin, Professor
Department of Astronomy, University of Virginia
530 McCormick Road
P.O. Box 400325
Charlottesville, VA 22904-4325
USA

Dear Prof. Sarazin:

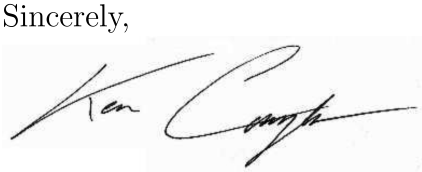
Please accept the attached application for your advertised postdoctoral position. A major part of my past and on-going research has focused on better understanding feedback from active galactic nuclei (AGN). As such, I am interested in the formation and evolution of supermassive black holes, the accretion modes which fuel AGN activity, and how AGN interact with, and alter, their host environments.

I feel UVA is an excellent fit for me, and the UVA research environment will benefit from my addition. My expertise in radio and X-ray astronomy – in addition to experience with infrared, optical, and UV analysis – ideally suits me for your advertised position. I am also eager to expand my research into theoretical modeling, specifically to consolidate our understanding of radio galaxies and their environments into a unified model which describes isolated FR-Is through FR-IIs in dense clusters. The UVA high-energy astrophysics group is an excellent place to pursue this goal.

Along with this letter are my CV, a list of publications, and a brief summary of my research interests. Letters of recommendation from Megan Donahue, Brian McNamara, and Mark Voit should arrive under separate cover. Please do not hesitate to contact me if there is any further information I can provide as you review my application.

Thank you for your consideration.

Sincerely,



Dr. Kenneth W. Cavagnolo
University of Waterloo

Dr. Kenneth W. Cavagnolo
Curriculum Vitae

Last updated February 1, 2010; Hyperlinks colored blue

University of Waterloo
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Education

Michigan State University — 2005 - 2008
Ph.D., Astronomy & Astrophysics

Michigan State University — 2002 - 2005
M.S., Astronomy & Astrophysics, *magna cum laude*

Georgia Institute of Technology — 1998 - 2002
B.S., Physics, *magna cum laude*

Research Experience

Postdoctoral Fellow — 2008 - Present
Supervisor: Brian McNamara, *Univ. of Waterloo*

Graduate Research Assistant — 2003 - 2008
Supervisor: Megan Donahue, *Mich. St. Univ.*

Graduate Research Assistant — 2002 - 2003
Supervisor: Jack Baldwin, *Mich. St. Univ.*

Undergraduate Research Assistant — 2000 - 2002
Supervisor: James Sowell, *Geor. Inst. of Tech.*

Research Program & Interests

My research program is focused on better understanding the connection between AGN and their host environments, with a specific interest in the role of AGN feedback on the formation and evolution of galaxies, galaxy groups, and galaxy clusters.

Areas of interest:
- Mechanical and radiative AGN feedback
- Cosmic magnetic fields
- Conditions for quasar-mode vs. radio-mode dominance
- Black hole accretion mechanisms
- Thermalization of AGN feedback energy
- Formation of ICM thermal instabilities
- Galaxy cluster radio halos
- Cosmological studies via structure formation

Honors

- Referee for ApJ, ApJL, AJ, and CanTAC — 2008 - Present
- Sherwood K. Haynes Award for Outstanding Graduate Student — 2008

- MSU College of Natural Science Dissertation Fellow 2007 - 2008
- ΣΞ National Scientific Research Society Member 2009 - Present
- ΣΠΣ National Physics Honor Society Member 2001 - Present
- American Astronomical Society Member 2002 - Present
- American Physical Society Member 2002 - Present
- Perimeter Institute Black Hole Reading Group Member 2009 - Present
- Dean's List, Georgia Inst. of Tech. 1998-2002

Scientific Skills

- Extensive experience with X-ray and radio data analysis
- Familiarity with infrared, optical, and UV data analysis
- Understanding of AIPS, CASA, CIAO, IRAF, OSA, and SAS analysis software
- Fluent in HTML, IDL, LaTeX, and PERL programming languages
- Working knowledge of C, Fortran, MySql, Python, SuperMongo, and Tcl
- Mastery of DOS, Linux, Macintosh, and Windows computing architectures
- Expert of computer maintenance, system construction, and troubleshooting

Observing Experience

Giant Metrewave Radio Telescope (GMRT) Jan. 2010
60 hours observing 15 galaxy clusters

Chandra X-ray Observatory (CXO) Jan. 2009
21 hour queued observation of IRAS 09104+4109

Very Large Array Radio Telescope (VLA) Dec. 2008
39 hours observing 13 giant ellipticals

Accepted Proposals & Grants

GMRT Cycle 17, Co-I 2009
The Power and Particle Content of Extragalactic Radio Sources
PI: Somak Raychaudhury, *Univ. Birmingham*

GMRT Cycle 17, Co-I 2009
The Morphology of Steepest Spectrum Radio Sources in Galaxy Cluster Cores
PI: Alastair Edge, *Durham Univ.*

NOAO Cycle 2008A & 2009A/B, Co-I 2008-2009
Normalization and scatter of the $M-T$ relation for supermassive galaxy clusters
PI: Rachel Mandelbaum, *Princeton Univ.*

GMRT Cycle 16, Co-I 2008
The Content of Giant Cavities in the IGM of Galaxy Clusters
PI: Somak Raychaudhury, *Univ. Birmingham*

CXO Cycle 10, PI 2008
IRAS 09104+4109: An Extreme Brightest Cluster Galaxy

CXO Cycle 10, Co-I 2008
Conduction and Multiphase Structure in the ICM
PI: Mark Voit, *Mich. St. Univ.*

Spitzer Cycle 5, Co-I — 2008
Star Formation and AGN Feedback in BCGs
PI: Megan Donahue, *Mich. St. Univ.*

Spitzer Cycle 5, Co-I — 2008
Infrared Properties of a Control Sample of Brightest Cluster Galaxies
PI: Megan Donahue, *Mich. St. Univ.*

NSF Grant, Co-I — 2008
Star Formation in the Universe's Largest Galaxies
PI: Mark Voit, *Mich. St. Univ.*

CXO Cycle 9, Co-I — 2007
Quantifying Cluster Temperature Substructure
PI: Mark Voit, *Mich. St. Univ.*

VLA A-configuration Cycle, Co-I — 2007
Radio Feedback in Clusters and Galaxies
PI: Brian McNamara, *Univ. Waterloo*

Students Advised

Clif Kirkpatrick, Ph.D. candidate, *Univ. Waterloo* — 2008-present
The 2-Dimensional metal abundance distributions in galaxy clusters

Mina Rohanizadegan, M.Sc. candidate, *Univ. Waterloo* — 2008-present
Constraining the spin of SMBHs using measured AGN jet powers

Brad Whuiska, Undergraduate research, *Univ. Waterloo* — 2009-present
Finding the largest galactic cores in the HST archive

Rob Myers, Undergraduate research, *Univ. Waterloo* — 2009-present
In search of radio galaxies via X-ray and radio catalog cross-correlation

Teaching Experience

Substitute Instructor — Fall 2006
Course: "Visions of the Universe"

Honors Physics Tutor — Summer 2003
Course: "Introductory Honors Physics I & II"

Graduate Teaching Assistant — 2002 - 2003
Course: "Visions of the Universe"

References

Megan Donahue, donahue@pa.msu.edu — +00-1-517-884-5618
Tenured professor, Michigan State University

Brian McNamara, mcnamara@uwaterloo.ca — +00-1-519-888-4567 ext. 38170
Tenured professor, University of Waterloo

G. Mark Voit, voit@pa.msu.edu — +00-1-517-884-5619
Tenured professor, Michigan State University

Chris Carilli, ccarilli@nrao.edu +00-1-575-835-7306
National Radio Astronomy Observatory Chief Scientist

Jack Baldwin, baldwin@pa.msu.edu +00-1-517-884-5611
Associate Chair for Astronomy, Michigan State University

Paul Nulsen, pnulsen@cfa.harvard.edu +00-1-617-495-7043
Research Scientist, Center for Astrophysics at Harvard University

Mike Wise, wise@science.uva.nl +31-0-521-595-564
LOFAR Radio Observatory Chief Scientist

Personal Interests

- Academic: Environmental sciences, “Cradle2Cradle” design, and urban planning.
- Athletics: Triathlons, running, baseball, and Georgia Tech athletics.
- Hobbies: Backpacking, reading, building model airplanes, and raising bonsai trees.

Dr. Kenneth W. Cavagnolo
List of Publications

Last updated February 1, 2010; Hyperlinks colored blue

In Preparation

"A Relationship Between AGN Jet Power and Radio Luminosity"
K. Cavagnolo, B. McNamara, P. Nulsen, C. Carilli, C. Jones, W. Forman, & L. Bîrzan
Submitted to ApJ

"Mechanical Feedback from the Obscured Quasar in IRAS 09104+4109"
K. Cavagnolo, M. Donahue, B. McNamara, G. M. Voit, & M. Sun
Submitted to MNRAS

"A Multiwavelength Analysis of the Galaxy Cluster RBS 797: Evidence for a Cluster-scale Line-of-Sight AGN Outburst"
K. Cavagnolo, B. McNamara, P. Nulsen, M. Wise, M. Gitti, & M. Brüggen
In prep. for ApJ

"Entropy Scaling Relations of ACCEPT Galaxy Clusters"
K. Cavagnolo, G. M. Voit, M. Donahue, & S. Bruch
In prep. for ApJL

"The Complications of SMBH Spin Axis Reorientation and Implications for AGN Feedback Models"
K. Cavagnolo, B. McNamara, & N. Afshordi
In prep. for ApJL

"Normalization and Scatter of the Mass-Temperature relation for Supermassive Galaxy Clusters"
R. Mandelbaum, R. Nakajima, G. Bernstein, **K. Cavagnolo**, M. Donahue, C. Keeton, J. Hughes, N. Bahcall, T. Schrabback, N. Padmanabhan, S. Miyazaki, & A. Kravtsov
In prep. for ApJ

"Constraining the Spin of Supermassive Black Holes Using Measured AGN Jet Powers"
M. Rohanizadegan, B. McNamara, F. Kazemzadeh, P. Nulsen, & **K. Cavagnolo**
In prep. for ApJ

"Identifying AGN Feedback Relics Via Steep Spectrum Radio Sources"
A. Edge, **K. Cavagnolo**, H. Röttgering, B. McNamara, M. Wise, M. Brüggen, R. van Weeren, G. Brunetti, & J. Croston
In prep. for MNRAS

First Author Refereed Papers

"Intracluster Medium Entropy Profiles for a Chandra Archival Sample Of Galaxy Clusters"
K. Cavagnolo, M. Donahue, G. M. Voit, & M. Sun
ApJ Accepted, 2009

"An Entropy Threshold for Strong Hα and Radio Emission in the Cores of Galaxy Clusters"
K. Cavagnolo, M. Donahue, G. M. Voit, & M. Sun
ApJ Accepted, 2008

"Bandpass Dependence of X-Ray Temperatures in Galaxy Clusters"
K. Cavagnolo, M. Donahue, G. M. Voit, & M. Sun
ApJ Accepted, 2008

Co-Author Refereed Papers

"Direct Evidence for an Outflow of Metal-Enriched Gas Along the Radio Jets of Hydra A"
C. Kirkpatrick, M. Gitti, **K. Cavagnolo**, B. McNamara, L. David, P. Nulsen, & M. Wise
ApJL Accepted, 2009

"A Chandra X-ray Analysis of Abell 1664: Cooling, Feedback and Star Formation in the Central Cluster Galaxy"
C. Kirkpatrick, B. McNamara, D. Rafferty, P. Nulsen, L. Birzan, F. Kazemzadeh, M. Wise, M. Gitti, & **K. Cavagnolo**
ApJ Accepted, 2009

"Conduction and the Star Formation Threshold in Brightest Cluster Galaxies"
G. M. Voit, **K. Cavagnolo**, M. Donahue, D. Rafferty, B. McNamara, & P. Nulsen
ApJ Accepted, 2008

"Star Formation, Radio Sources, Cooling X-Ray Gas and Galaxy Interactions in the Brightest Cluster Galaxy in 2A0335+096"
M. Donahue, M. Sun, C. O'Dea, G. M. Voit, & **K. Cavagnolo**
AJ Accepted, 2007

"s-Process Abundances in Planetary Nebulae"
B. Sharpee, Y. Zhang, R. Williams, E. Pellegrini, **K. Cavagnolo**, J. Baldwin, M. Phillips, & X. Liu
ApJ Accepted, 2007

"Entropy Profiles in the Cores of Cooling Flow Clusters of Galaxies"
M. Donahue, D. Horner, **K. Cavagnolo**, & G. M. Voit
ApJ Accepted, 2006

Presented Work & Talks

POSTER: *"IRAS 09104+4109: At the Cross-roads of Massive Galaxy Formation?"*
Jun. 2010 – From Massive Galaxy Formation to Dark Energy; University of Tokyo-Kashiwa

POSTER: *"Probing SMBH Accretion History Via Radio Luminosities"*
Apr. 2010 – What drives the growth of black holes?; Durham University

TALK: *"The AGN Jet Power and Radio Power Relationship for Isolated Giant Elliptical Galaxies"*
Jun. 2009 – The Monster's Fiery Breath: Feedback in galaxies, groups, and clusters; University of Wisconsin-Madison

INVITED TALK: *"Using Galaxy Clusters as Galaxy Formation Labs"*
Oct. 2008 – Undergraduate Seminar Series; University of Waterloo

INVITED TALK: *"Understanding Cluster Cores: The Role of Core Entropy"*
Sep. 2008 – The Cool, Cooler and Cold - Cluster Cooling Flows in a New Light; Leiden University

INVITED TALK: *"Investigating Feedback and Relaxation in Clusters of Galaxies"*
Jul. 2008 – Center for Study of Cosmic Evolution; Michigan State University

INVITED TALK: *"From Cluster Cosmology to Galaxy Formation in Under One Hour"*
Mar. 2008 – Astrophysics Seminar; University of Waterloo

INVITED TALK: *"The Effect of Cluster Feedback on High-Precision Cosmology"*
Feb. 2008 – NASA Space Science and Technology Center; University of Alabama-Huntsville

INVITED TALK: *"Understanding Feedback in Galaxy Clusters"*
Jan. 2008 – Center for Study of Cosmic Evolution; Michigan State University

INVITED TALK: *"Band Dependence of X-ray Temperatures"*
Oct. 2007 – Astrophysics Seminar; University of Michigan

POSTER: *"The Entropy-Feedback Connection and Quantifying Cluster Virialization"*
Oct. 2007 – Eight Years of Science with Chandra; University of Alabama-Huntsville

POSTER: *"Chandra Studies of Dark Matter and Galaxy Formation: Signatures from the Intracluster Medium"*
Dec. 2006 – American Astronomical Society Meeting

PROCEEDING: *"Abundances of s-process elements in planetary nebulae: Br, Kr & Xe"*
Jul. 2006 – International Astronomical Union Symposium

POSTER: *"Studies of Entropy Distributions in X-ray Luminous Clusters of Galaxies"*
Dec. 2005 – American Astronomical Society Meeting

POSTER: *"Entropy Distributions in the Cores of Nearby X-ray Luminous Clusters of Galaxies"*
Dec. 2004 – American Astronomical Society Meeting

POSTER: *"Radio-Free Cluster Cooling Flows"*
Dec. 2004 – American Astronomical Society Meeting

Dr. Kenneth W. Cavagnolo
Summary of Research and Interests

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 Fermi, GMRT, LOFAR, and future hard X-ray missions like Simbol-X and NuStar.

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 VLA, GMRT, LOFAR, and Simbol-X or NuStar.

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 $P_{\rm jet} \propto 10^{16} P_{\rm radio}^{0.7} {\rm erg~s^{-1}}$, 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. Existing low-frequency all-sky surveys such as VLSS, and upcoming surveys from LOFAR and LWA, provide ideal catalogs 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 GMRT and 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 UVA.

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, duty cycle, 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. 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 $P_{\rm jet}$-$P_{\rm radio}$ relation to define robust observation requests.

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 spirals and ellipticals, suggesting SMGs are useful for studying the co-evolution of SMBHs and host galaxies. It has been shown SMGs are found in very dense environments and have high AGN fractions ($\gtrsim 50\%$) [33], so they are excellent for identifying the rapidly cooling high-z gas-rich regions where star formation and AGN activity can be fueled. Hence, SMGs identify a population primed for follow-up with far-IR and X-ray spectroscopy to study feedback and cooling in unique environments. In total, SMGs may be the missing piece to understanding how SMBH evolution and AGN activity regulate the transition from gas-rich progenitors to "red and dead" ellipticals. It has also been posited that SMGs are high-z analogs of low-z ULIRGs (objects typically associated with the sites of merging gas-rich spirals). 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 may have significant contribution from AGN, and these systems can be used to further understand the nature of evolving gas-rich systems.

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.* $L_{\rm Edd.} \propto \mu$). 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 $\gg t_{\rm cool}$ 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 your research group.

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.

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