January 19, 2010

Attn: Dr. Jimmy Irwin
University of Alabama

Dear Dr. Irwin:

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 environment.

I feel UA is an excellent fit for me, and the UA 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.

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 January 19, 2010; Hyperlinks colored blue

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Education

Michigan State University — 2005 - 2008
Doctor of Philosophy, Astronomy & Astrophysics

Michigan State University — 2002 - 2005
Master of Science, Astronomy & Astrophysics

Georgia Institute of Technology — 1998 - 2002
Bachelor of Science, Physics

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 formation and evolution of cosmic structure via physical properties of the most massive gravitationally-bound objects (galaxy groups and clusters) and their sub-systems, *e.g.* galaxies, supermassive black holes, active galactic nuclei & jets, and thermal instabilities (*i.e.* gaseous nebulae, star formation, gas accretion).

Additional areas of interest:
- Intracluster medium magnetic fields
- Diffuse radio halos
- Mechanical and radiative AGN feedback
- 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 Tech — 1998-2002

Scientific Skills

- Extensive experience with X-ray and low-frequency 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
- Worked with C, Flash, 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
56 hours observing 14 galaxy clusters at 325 MHz

Chandra X-ray Observatory (CXO) — Jan. 2009
21 hours 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*

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 — +00-1-505-835-7000
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, baseball, rock climbing, and Georgia Tech athletics.
- Hobbies: Backpacking, reading, building model airplanes, and raising bonsai trees.

Dr. Kenneth W. Cavagnolo
List of Publications

Last updated January 19, 2010; Hyperlinks colored blue

In Preparation

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

"Gas Uplift and AGN Heating from the Quasar in IRAS 09104+4109"
K. Cavagnolo, M. Donahue, B. McNamara, & G.M. Voit
In prep. for 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
In prep. for ApJL

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

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

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

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; Lorentz Center, 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; UAH-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; UAH-Huntsville

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

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

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

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 $K \lesssim 30$ 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 ($\sim 1\ \mu$G), modest heating from an AGN ($\sim 10^{43}$ 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 ($\lesssim 50$ kpc) and as large as cluster virial radii ($\sim$ 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 ($P_{\rm jet}$) and emergent radio emission ($L_{\rm radio}$) 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 $L_{\rm radio}$ at multiple frequencies using new and archival VLA observations. 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. 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 $L_{\rm radio}$) 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 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 [á la 24]. Another interesting use of a universal $P_{\rm jet}$-$L_{\rm radio}$ relation is using radio luminosities, lobe morphologies, and age estimates to predict ambient gas pressures: $p_{\rm amb} \propto (t_{\rm age} L_{\rm radio})/V_{\rm radio}$. 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 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 feedback 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 $P_{\rm jet}$-$L_{\rm radio}$ 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 $10-100\ L_{\rm Edd.}$), 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.

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

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[9] B. B. Nath and S. Roychowdhury. Heating of the intracluster medium by quasar outflows. *MNRAS*, 333:145–155, June 2002.

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