January 1, 2010

Attention: Marijn Franx
Leiden Observatory

To whom it may concern:

Please accept the attached application for the Leiden Astronomy Fellowship. My current (and proposed) research program focuses on better understanding feedback from active galactic nuclei, with a specific emphasis on the connection between the accretion modes of supermassive black holes, their environments, and the resulting transport of radiative and mechanical energy back to that environment. I am also interested in expanding 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 rich clusters.

My expertise in radio and X-ray astronomy – in addition to extensive experience with infrared, optical, and UV data analysis – ideally suits me to be a fellow at Leiden Observatory utilizing the existing and next generation of facilities/instruments, some of which Leiden Observatory has a vested interest (*i.e.* Herschel and LOFAR). Along with this letter are my CV, a list of publications, a brief summary of past/current research, and a research proposal. Letters of recommendation should have already arrived 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 1, 2010; Hyperlinks colored blue

University of Waterloo
Department of Physics & Astronomy
200 University Avenue West
Waterloo, Ontario, Canada N2L 3G1

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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, 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

- $\Sigma\Pi\Sigma$ 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 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
168 hours observing 13 galaxy groups and 20 galaxy clusters

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, *Inst. for Adv. Study*

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 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
In prep. for 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

"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

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

INVITED TALK: *"Toward a Universal Relation of AGN Kinetic-Radio Luminosity"*
Jan. 2010 – National Centre for Radio Astrophysics; Tata Institute

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 Program

The general process of galaxy cluster formation through hierarchical merging is well understood, but many details, such as the impact of feedback sources on the cluster environment and radiative cooling in the cluster core, are not. My thesis research focused on studying these details via X-ray properties of the intracluster medium (ICM) in clusters of galaxies. I paid particular attention to ICM entropy distribution [1, 2], the process of cluster virialization [3], the role of AGN feedback in shaping large scale cluster properties [4], and how feedback signatures correlate with the properties of cluster cores [5]. The picture of the ICM entropy-feedback connection which emerged from these studies was that feedback is part of a finely-tuned mechanism with the requirement that the mean entropy (K) of the fueling environment hosting a SMBH must be $K \lesssim 30$ keV cm^2. In the three years since our first publication, the suite of papers from this work has garnered 100+ citations.

My dissertation work made use of 400+ *Chandra* archival X-ray observations ($\approx$ 13 Msec of data). The massive undertaking necessitated the creation of a robust reduction and analysis pipeline which interacts with mission specific software (be it *Chandra*, *XMM-Newton*, *Suzaku*), utilizes analysis tool (*e.g.* XSPEC, IDL, IRAF), smoothly incorporates calibration/software updates, is highly automated, and continues to mature. My pipeline is written in a very general manner, and adaptation of the pipeline for use with pre-packaged analysis tools from other missions has been straightforward. Most importantly, the pipeline deemphasizes data reduction and accords the user with the freedom to move quickly into an analysis phase and generating publishable results.

More recently, my research has focused on extreme, individual examples of AGN feedback which are useful for confronting existing models of AGN feedback and galaxy formation. I have recently completed studies for two such systems: RBS 797 and IRAS 09104+4109. The rich dataset available for RBS 797 indicates that the AGN outburst is inclined along the line-of-sight, and that the outburst is one of the most powerful ever observed, *e.g.* the cluster-scale class of burst similar to MS 0735.6+7421 [6]. Our detailed study has been useful for further understanding how large outbursts affect hydrostatic equilibrium in clusters, whether such outbursts can be driven by classical gas accretion mechanisms, and if such outbursts can halt cooling in a cluster. The results for RBS 797 are being presented in an ApJ manuscript [7]. IRAS 09104+4109 is an enigmatic system with a long literature indicating the galaxy is simultaneously undergoing a variety of normally orthogonal phases of massive galaxy formation. The completed study highlights results from a new *Chandra* observation which shows the AGN in IRAS09 excavating cavities and uplifting cool gas from the core. This is unique for a radio-quiet, radiatively dominated QSO, and demonstrates that massive galaxies like BCGs and cDs may go through a brief phase of quasar-mode feedback which is immediately followed by a radio-mode. IRAS09 is currently the only system where both processes have been directly observed. These results are being presented in a MNRAS manuscript [8].

Another of my studies which was recently completed [9] 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 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.

I am also involved in a number of other projects with both undergraduate and graduate students at the University of Waterloo, in addition to projects with peers. I am a member of the Supermassive Cluster Survey and am responsible for the X-ray analysis in the project. The study is headed-up by Rachel Mandelbaum (Princeton) and seeks to better understand the scatter between X-ray and weak lensing masses for a sample of 12 galaxy clusters. I am also working on the analysis and interpretation of the *Chandra* Large Project for MS 0735.6+7421. This project centers around 700 ksec of X-ray data which is being used to study the properties of the most energetic AGN outburst found to date. Brian McNamara has two Ph.D. students and two undergraduates, all of which I am helping to guide in their research on: finding large optical cores for BCGs in the Hubble archive, the spin of SMBHs, instantaneous accretion mechanisms for SMBHs, quantifying the 2D abundance distributions in galaxy clusters, and finding/studying radio sources from all-sky surveys coincident with clusters. I also maintain a close working relationship with my thesis research group at Michigan State University (David Ventimiglia and Seth Bruch), and am collaborating with two Ph.D. students on separate papers relating to the deviation of galaxy clusters from mean mass-scaling relations. There are also two on-going large radio observation based projects (PI's Somak Raychaudhury and Alastair Edge) which focus on low-frequency AGN emission in clusters and groups. I am responsible for data acquistion, reduction, and analysis in one project, and X-ray data analysis for another. It is expected that both of these projects will merge with Herschel and LOFAR Key Projects.

References

[1] M. Donahue, D. J. Horner, K. W. Cavagnolo, and G. M. Voit. Entropy Profiles in the Cores of Cooling Flow Clusters of Galaxies. *ApJ*, 643:730–750, June 2006.

[2] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Intracluster Medium Entropy Profiles for a Chandra Archival Sample of Galaxy Clusters. *ApJS*, 182:12–32, May 2009.

[3] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Bandpass Dependence of X-Ray Temperatures in Galaxy Clusters. *ApJ*, 682:821–834, August 2008.

[4] G. M. Voit, K. W. Cavagnolo, M. Donahue, D. A. Rafferty, B. R. McNamara, and P. E. J. Nulsen. Conduction and the Star Formation Threshold in Brightest Cluster Galaxies. *ApJ*, 681:L5–L8, July 2008.

[5] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. An Entropy Threshold for Strong Hα and Radio Emission in the Cores of Galaxy Clusters. *ApJ*, 683:L107–L110, August 2008.

[6] B. R. McNamara, P. E. J. Nulsen, M. W. Wise, D. A. Rafferty, C. Carilli, C. L. Sarazin, and E. L. Blanton. The heating of gas in a galaxy cluster by X-ray cavities and large-scale shock fronts. *Nature*, 433:45–47, January 2005.

[7] K. W. Cavagnolo and B. R. McNamara. The AGN Outburst in RBS 797: One of the Most Powerful Ever Observed. *In preparation for ApJ*, 2010.

[8] K. W. Cavagnolo, M. Donahue, B. R. McNamara, G. M. Voit, and M. Sun. Cavities and Changing-Look QSO in the ULIRG IRAS 09104+4109. *In preparation for ApJL*, 2010.

[9] K. W. Cavagnolo, B. R. McNamara, C. L. Carilli, C. Jones, W. R. Forman, P. E. J. Nulsen, L. Bîrzan, and S. Murray. A Relationship Between AGN Jet Power and Radio Luminosity. *In preparation for ApJ*, 2009.

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.

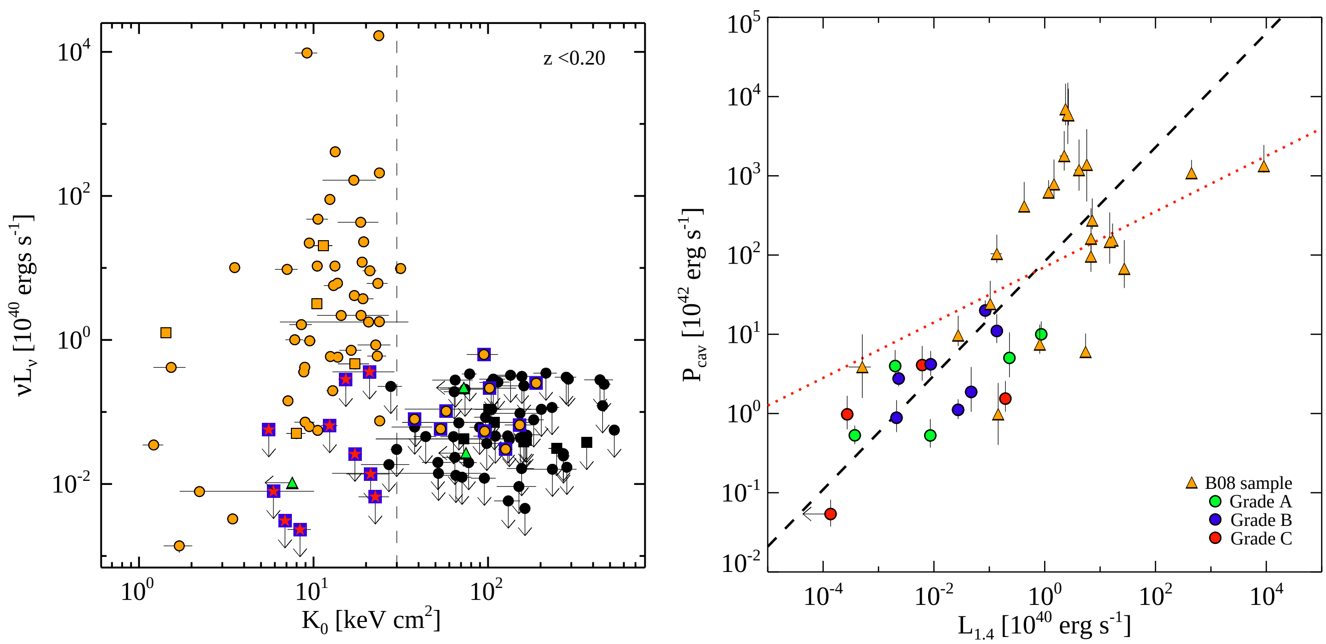

Figure 1: *Left:* BCG radio power vs. core entropy (K_0) for clusters with redshift $z < 0.2$. Orange symbols represent radio detections and black symbols are non-detection upper-limits. Circles are for NVSS observations and squares are for SUMSS observations. The blue squares with inset red stars or 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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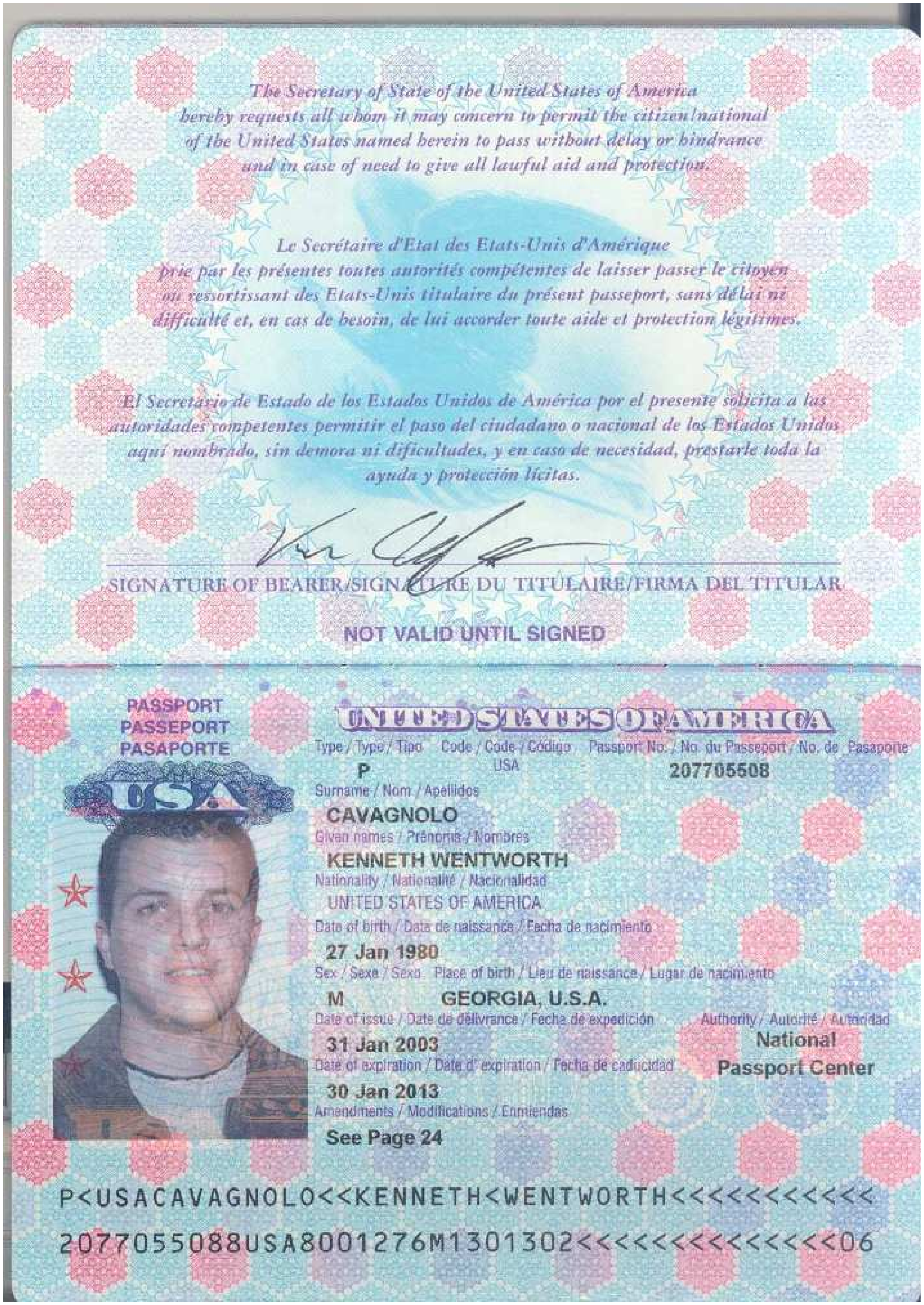

The Secretary of State of the United States of America hereby requests all whom it may concern to permit the citizen/national of the United States named herein to pass without delay or hindrance and in case of need to give all lawful aid and protection.

Le Secrétaire d'Etat des Etats-Unis d'Amérique prie par les présentes toutes autorités compétentes de laisser passer le citoyen ou ressortissant des Etats-Unis titulaire du présent passeport, sans délai ni difficulté et, en cas de besoin, de lui accorder toute aide et protection légitimes.

El Secretario de Estado de los Estados Unidos de América por el presente solicita a las autoridades competentes permitir el paso del ciudadano o nacional de los Estados Unidos aquí nombrado, sin demora ni dificultades, y en caso de necesidad, prestarle toda la ayuda y protección lícitas.

SIGNATURE OF BEARER/SIGNATURE DU TITULAIRE/FIRMA DEL TITULAR

NOT VALID UNTIL SIGNED

PASSPORT
PASSEPORT
PASAPORTE

USA

UNITED STATES OF AMERICA

Type / Type / Tipo: P
Code / Code / Código: USA
Passport No. / No. du Passeport / No. de Pasaporte: 207705508

Surname / Nom / Apellidos: CAVAGNOLO

Given names / Prénoms / Nombres: KENNETH WENTWORTH

Nationality / Nationalité / Nacionalidad: UNITED STATES OF AMERICA

Date of birth / Date de naissance / Fecha de nacimiento: 27 Jan 1980

Sex / Sexe / Sexo: M

Place of birth / Lieu de naissance / Lugar de nacimiento: GEORGIA, U.S.A.

Date of issue / Date de délivrance / Fecha de expedición: 31 Jan 2003

Authority / Autorité / Autoridad: National Passport Center

Date of expiration / Date d' expiration / Fecha de caducidad: 30 Jan 2013

Amendments / Modifications / Enmiendas: See Page 24

P<USACAVAGNOLO<<KENNETH<WENTWORTH<<<<<<<<<<<

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Figure 1: Valid United States Passport for Kenneth W. Cavagnolo