November 18, 2007

Prof. W.N. Brandt
Penn State University
Dept. of Astronomy & Astrophysics
525 Davey Lab.
University Park, PA 16802

Dear Prof. Brandt:

Please accept the attached application for your postdoctoral position in active galaxy studies advertised in the October 2007 issue of the AAS Job Register. For my thesis, entitled *'Feedback, Evolution, and Dynamics in Galaxy Clusters'*, I am studying the coupling of feedback mechanisms – such as AGN, star formation, and conduction in cluster cores – to gas entropy, and the role of this feedback in altering global ICM properties and truncating the high mass end of the galaxy luminosity function. I have also been studying a method for quantifying the virialization state of clusters through the band dependence of X-ray temperatures. For my thesis I assembled a sample of 350 archival *Chandra* observations for 276 clusters totaling 11.6 Msec of data. The results of this laborious effort have been many and are detailed in my research summary.

My expertise in X-ray astronomy ideally suits me to further work on better understanding AGN, models for galaxy formation, and feedback in clusters. Adaptation of my skill sets to study clusters in the radio, optical, and infrared is the next step in my career and should come with a short learning curve thanks to my existing, mature programming ability. I am a great asset for anyone studying active galaxies and clusters both for my technical skills and to furthering their research objectives. I feel the post-doctoral position under your advisory at Penn State is an excellent fit for me, and your research goals will benefit from my addition.

Along with this letter are my CV, a summary of past and current research, and a brief description of possible research directions. Letters of recommendation from Megan Donahue, Mark Voit, and Jack Baldwin will 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,

Kenneth W. Cavagnolo
Michigan State University

Resumé of Kenneth W. Cavagnolo

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Education

Michigan State University 2005 - Present
Ph.D. Astrophysics, Expected August 2008
Thesis Title: "Feedback, Evolution, and Dynamics in Clusters of Galaxies"
Thesis Advisors: Dr. Megan Donahue & Dr. G. Mark Voit

Michigan State University 2002 - 2005
M.S. Astrophysics

Georgia Institute of Technology 1998 - 2002
B.S. Physics *Cum Laude*

Research Experience

Graduate Research Assistant 2003 - Present
Supervisor: Dr. Megan Donahue, *Mich. St. Univ.*
Studying clusters of galaxies via their X-ray properties to investigate feedback mechanisms, galaxy evolution, and the process of cluster virialization.

Graduate Research Assistant 2002 - 2003
Supervisor: Dr. Jack Baldwin, *Mich. St. Univ.*
Analyzing echelle spectra for use in studies of s-process abundances in planetary nebulae.

Undergraduate Research Assistant 2000 - 2002
Supervisor: Dr. James Sowell, *Georgia Tech*
Obtaining orbital solution for the eclipsing Algol binary ET Tau via UBV light curves and spectroscopic radial velocity curves.

Research Interests

- Feedback Mechanisms in Galaxy Clusters
- Galaxy Formation
- Supermassive Black Holes
- AGN Accretion Physics
- Large Scale Structure Formation and Cosmology

Teaching Experience

Substitute Instructor Fall 2006
Course: "Visions of the Universe"
Gave lectures covering stellar evolution, supernovae, white dwarves, neutron stars, and black holes.

Physics Tutor Summer 2003
Course: "Introductory Honors Physics I & II"
Tutored physics students taking introductory physics courses such as classical mechanics, optics, and electromagnetism.

Graduate Teaching Assistant 2002 - 2003
Course: "Visions of the Universe"
Directed and supervised laboratories for non-calculus based astronomy course.

Honors

- College of Natural Science Dissertation Fellow 2007 - Present
- American Astronomical Society Member 2002 - Present
- American Physical Society Member 2002 - Present
- NASA Center for Astronomy Education Participant 2007
- Sigma Pi Sigma National Honor Society 2001 - Present
- Dean's List, Georgia Tech 1998-2002

Scientific Skills

- Profound skills in reducing and analyzing data taken with *Chandra* X-ray Telescope.
- Extensive experience with `CIAO` and `CALDB`.
- Familiarity with multiwavelength analysis packages: `AIPS`, `IRAF`, and `PyRAF`.
- Fluent in Perl, IDL, LaTeX, and HTML.
- Working knowledge of Bash, C, CSH, Flash, Fortran, MySQL, and Supermongo.
- Mastery of multiple computing architectures: UNIX/Linux, Windows, and Macintosh.
- Expert of computer troubleshooting, maintenance, and system construction.

First Author Refereed Papers

"Feedback Mechanisms in Galaxy Clusters and Alteration of ICM Entropy"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2008, in prep.

"Athenaeum of Galaxy Cluster Entropy Profiles"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007, in prep.

"X-ray Band Dependence of X-ray Temperatures in Galaxy Clusters"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007, near ApJ submission.

Other Refereed Papers

"Star Formation, Radio Sources, Cooling X-Ray Gas and Galaxy Interactions in the Brightest Cluster Galaxy in 2A0335+096"
Donahue, Megan; Sun, Ming; O'Dea, Christopher P.; Voit, G. Mark; **Cavagnolo, Kenneth W.**
2007AJ....134...14D

"Entropy Profiles in the Cores of Cooling Flow Clusters of Galaxies"
Donahue, Megan; Horner, Donald J.; **Cavagnolo, Kenneth W.**; Voit, G. Mark
2006ApJ...643..730D

"s-Process Abundances in Planetary Nebulae"
Sharpee, Brian; Zhang, Yong; Williams, Robert; Pellegrini, Eric; **Cavagnolo, Kenneth**;

Baldwin, Jack A.; Phillips, Mark; Liu, Xiao-Wei
2007ApJ...659.1265S

Presented Work & Talks

"Library of Galaxy Cluster Entropy Profiles: A Study in Feedback"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2008 Winter Meeting of the American Astronomical Society, Poster

"The Entropy-Feedback Connection and Quantifying Cluster Virialization"
Cavagnolo, Kenneth W.; Donahue, Megan; Voit, G. Mark; and Sun, Ming
2007 Eight Years of Science with Chandra Symposium, Poster

"Chandra Studies of Dark Matter and Galaxy Formation: Signatures from the Intracluster Medium"
Donahue, Megan; Sun, M.; **Cavagnolo, K.**; Voit, G.
2006 Winter Meeting of the American Astronomical Society, Poster

"Abundances of s-process elements in planetary nebulae: Br, Kr & Xe"
Zhang, Y.; Williams, R.; Pellegrini, E.; **Cavagnolo, K.**; Baldwin, J. A.; Sharpee, B.; Phillips, M.; Liu, X.-W.
2006 IAU Symposium, Proceeding

"Studies of Entropy Distributions in X-ray Luminous Clusters of Galaxies"
Cavagnolo, K. W.; Donahue, M. E.; Voit, G. M.; Sun, M.; Evrard, A. E.
2005 Winter Meeting of the American Astronomical Society, Poster

"Entropy Distributions in the Cores of Nearby X-ray Luminous Clusters of Galaxies"
Cavagnolo, K. W.; Donahue, M. E.; Voit, G. M.; Horner, D. J.; Evrard, A. E.
2004 Winter Meeting of the American Astronomical Society, Poster

"Radio-Free Cluster Cooling Flows"
Donahue, M. E.; Voit, G. M.; **Cavagnolo, K.**
2004 Winter Meeting of the American Astronomical Society, Poster

References

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Dr. Jack Baldwin
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Personal Interests

- Academic: environmental sciences, "Cradle2Cradle" design, and urban planning.
- Athletics: triathlons, baseball, and everything Georgia Tech.
- Hobbies: reading, building model airplanes, and raising bonsai trees.

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 has focused on studying these details via X-ray properties of the ICM in clusters of galaxies. I have paid particular attention to ICM entropy distribution and the role of AGN feedback in shaping large scale cluster properties.

My thesis makes use of a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. The picture of the ICM entropy-feedback connection (Fig. 1) emerging from my work suggests cluster radio luminosity and Hα emission are anti-correlated with cluster central entropy ($K = T_X n_e^{2/3}$). There also appears to be a bimodality in the distribution of central entropies (Fig. 2) which is likely related to AGN feedback (and to a lesser extent, mergers). I have found that clusters with central entropy ≤ 20 keV cm^2 exhibit star formation and AGN activity in the BCG while clusters above this threshold unilaterally do not have star formation and exhibit diminished AGN radio feedback. This entropy level is auspicious as it coincides with the Field length (assuming reasonable suppression) at which thermal conduction can stabilize a cluster core. It is possible we have opened a window to solving a long-standing problem in massive galaxy formation (and truncation): how are ICM gas properties coupled to feedback mechanisms such that the system becomes self-regulating? However, this result serves to highlight unresolved issues requiring further intensive study.

Most pressing of these issues is to better understand the fueling and feedback from AGN. We know low entropy ($K_0 \leq 20$) systems contain multi-phase gas (stars, cold molecular gas, warm/hot dust, et cetera), but as evidenced by copious radio emission, some of this gas is likely condensing onto the SMBH and resulting in episodic AGN feedback which retards further cooling in the cluster core. My work in the X-ray can only tell us about the hot atmospheres with which AGN are interacting, but to attain a more complete picture of this multi-phase gas, and its connection to fueling the AGN, it behooves us to look in other bands, specifically the infrared.

In Figure 3 I have plotted central entropy derived in my thesis work versus NVSS radio luminosity and overlaid symbols indicating availability of data in the *Spitzer* archive. Thus far, indications from the literature are that most, if not all, of the BCGs in X-ray luminous clusters with $K_0 \leq 20$ keV cm^2 are dominated by star formation. But we can see from the figure that most of these systems contain radio AGN. So one can ask the question: are there any AGN dominated nebular BCGs? An interesting project to pursue with the *Spitzer* archive would be to examine the shape of spectral energy distributions (SEDs) for all clusters with a BCG and attempt to reveal if the BCG is star formation or AGN dominated.

For those BCGs which do exhibit AGN dominance it will be interesting to exclude extended galaxy emission and analyze spectra from only the (unresolved) nuclear region in an effort to characterize AGN spectral features. The ultimate goal being an accounting of the very lowest entropy gas which is likely feeding the SMBH, and at the very least enshrouding the AGN. Clusters without star formation and no AGN will also be an important constraint in such a project.

There are a multitude of other directions I would also like to pursue which are essentially extensions of my thesis. The role of AGN feedback in shaping global cluster properties is still poorly understood. Models for the process of thermalizing energy in AGN blown bubbles have been proposed, but details of these models still need to be explored. For example, do bubbles contain a very low density non-relativistic thermal plasma or are they truly voids in the ICM (potentially an SZ experiment)? Maybe bubbles contain cosmic rays, a possibility which will make for an interesting GLAST project. How do bubbles rise to distances ≥ 100 kpc without being shredded by instabilities? The answer to this question will likely entail better understanding ICM $\vec{B}$ fields, with their origin being either from preheating, AGN deposition, or a combination of both.

I have also contributed to several successful *Chandra*, *XMM*, *Suzaku*, *NSF*, and *Subaru* proposals in addition to writing my own high scoring – although unsuccessful – *Chandra* proposal for time observing the amazing ULIRG IRAS 09104+4109. I am also planning Hα imaging observations for several previously unobserved BCGs using SOI on MSU's SOAR telescope, and will be active in submitting *Chandra* and *XMM* proposals (both spectroscopy and grating) for unobserved and interesting clusters, groups, and galaxies which have turned up in my thesis work.

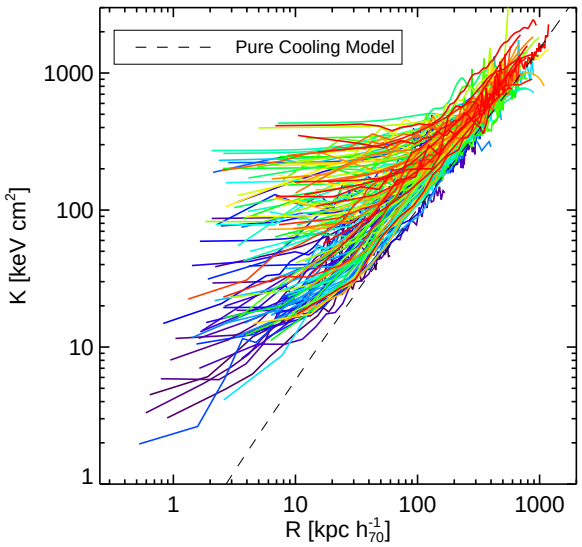

Figure 1: Entropy profiles for 143 clusters of galaxies in my thesis sample. The range of central entropies is consistent with models of episodic AGN heating which regulate the presence of low entropy gas in cluster cores. The so-called "cooling flow" problem does not appear to be a problem any longer.

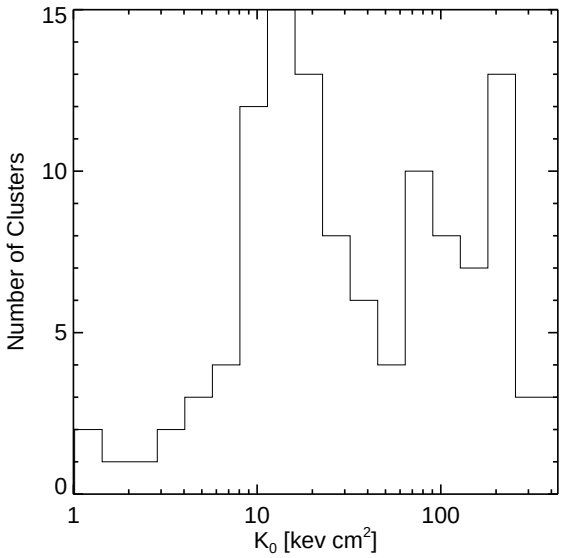

Figure 2: Distribution of central entropy for an unbiased sub-sample of the clusters analyzed for my thesis. Note the fall-off of clusters with $K_0 \sim 30 - 50$ keV cm^2. An explanation for this bimodality utilizing AGN feedback (the most likely candidate) does not currently exist.

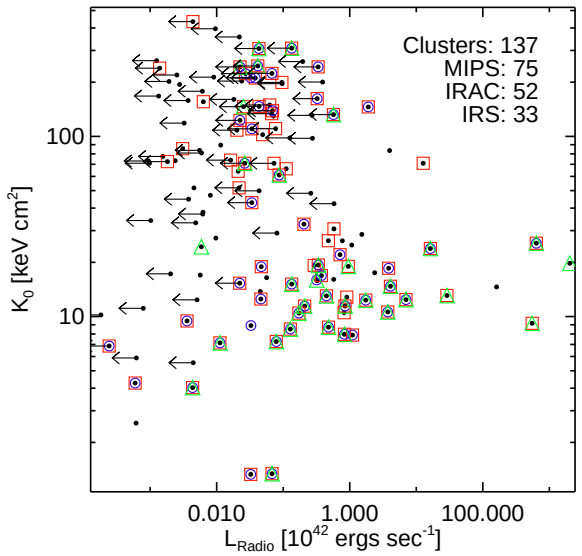

Figure 3: Central entropy derived in my thesis work plotted against radio luminosity calculated using NVSS. Cluster centers with MIPS observations are plotted with red squares; IRAC observations have blue circles; IRS observations have green triangles. The Spitzer archive provides excellent coverage for a possible study of low entropy, radio-loud and radio-quiet systems.