January 16, 2008

Dr. J. S. Mulchaey
Carnegie Observatories
813 Santa Barbara Street
Pasadena, CA 91101

Dear Dr. Mulchaey:

Please accept the attached application for your postdoctoral position in X-ray astronomy advertised in the December 2007 issue of the AAS Job Register. For my thesis (advised by Megan Donahue and Mark Voit), 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.

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 Carnegie is an excellent fit for me, and your research goals will benefit from my addition. 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.

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 should already have 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,

Kenneth W. Cavagnolo
Michigan State University

KENNETH W. CAVAGNOLO
CURRICULUM VITAE

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Education

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

Michigan State University 2002 - 2005
M.S. Astrophysics, *Magna Cum Laude*
Dissertation Title: "Entropy Profiles of Cooling Flow Clusters"
Advisor: Dr. Megan Donahue

Georgia Institute of Technology 1998 - 2002
B.S. Physics, *Magna Cum Laude*
Senior Thesis: "Analysis of the Eclipsing Binary ET Tau"
Advisor: Dr. James Sowell

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 Cluster Evolution
- Galaxy Formation
- Large Scale Structure Formation and Cosmology
- Supermassive Black Holes
- AGN Accretion Physics

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
- 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 customizing and debugging CIAO and CALDB.
- Familiarity with multiwavelength analysis packages: AIPS, IRAF, and PyRAF.
- Fluent in PERL, IDL, LaTeX and HTML.
- Working knowledge of C, FLASH, FORTRAN, MySQL, SuperMongo, and Tcl.
- Mastery of multiple computing architectures: DOS, Linux, Macintosh, and Windows.
- Expert of computer troubleshooting, maintenance, and system construction.

References

Dr. Megan Donahue
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Michigan State University

Dr. G. Mark Voit
(517)-355-9200 ext. 2419
voit@pa.msu.edu
Michigan State University

Dr. Jack Baldwin
(517)-355-9200 ext. 2411
baldwin@pa.msu.edu
Michigan State University

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.

KENNETH W. CAVAGNOLO

PUBLICATIONS

First Author Refereed Papers

"X-ray and Entropy Scaling Relations in Galaxy Clusters"
Cavagnolo, Kenneth W.; Voit, G. Mark; and Donahue, Megan
2008, in prep. for ApJ

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

"Star Formation in BCGs: Resurrecting Conduction"
Cavagnolo, Kenneth W.; Donahue, Megan; and Voit, G. Mark
2008, in prep. for ApJL

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

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

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

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

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

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

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

PROCEEDING: *"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

POSTER: *"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

Summary of Past Research and Future Interests

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. Mergers and feedback activity are interesting for two reasons: they potentially compromise the use of clusters for cosmological studies, and there is a tremendous amount of interesting astrophysics going on. My thesis research has focused on studying the details of feedback and mergers 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. Additionally I have examined the quantification of cluster virialization via aspect-independent metrics, with emphasis on understanding temperature inhomogeneity as a surrogate for cluster dynamic state.

Mining the CDA

My thesis makes use of a 350 observation sample (276 clusters; 11.6 Msec) taken from the *Chandra* archive. This massive undertaking necessitated the creation of a robust reduction and analysis pipeline which 1) interacts with mission specific software, 2) utilizes analysis software (i.e. `XSPEC`, `IDL`), 3) incorporates calibration and software updates, and 4) is highly automated. Because my pipeline is written in a very general manner, adding pre-packaged analysis tools from missions such as *XMM*, *Spitzer*, and *VLA* will be straightforward. Most importantly, my pipeline deemphasizes data reduction and accords me the freedom to move quickly into an analysis phase and generating publishable results.

Quantifying Cluster Virialization

Cluster mass functions and the evolution of the cluster mass function are useful for measuring cosmological parameters. Cluster evolution tests the effect of dark matter and dark energy on the evolution of dark matter halos, and therefore provides a complementary and distinct constraint on cosmological parameters to those tests which constrain them geometrically (e.g. supernovae and baryon acoustic oscillations).

Empirically, the relationship of mass and some observable properties is well-established. However, if we could identify a set of parameters – possibly reflecting the degree of relaxation in the cluster – we could improve the utility of clusters as cosmological probes. The work of Mathiesen and Evrard 2001 found an auxiliary measure of substructure which does not depend on perspective and could be combined with power ratio, axial ratio, and centroid variation to yield a more robust metric for quantifying a cluster's degree of relaxation.

I have studied this auxiliary measure: the bandpass dependence in determining X-ray temperatures and what this dependence tells us about the virialization state of a cluster. The ultimate goal of this project is to find an aspect-independent measure for a cluster's dynamic state. To this end, I have investigated the net temperature skew in my sample of the hard-band (2.0_{rest}-7.0 keV) and full-band (0.7-7.0 keV) temperature ratio for core-excised apertures. I have found this temperature ratio is statistically connected to mergers and the presence of cool cores. The next step is to make a comparison to the predicted distribution of temperature ratios and their relationship to putative cool lumps and/or non-thermal soft X-ray emission in cluster simulations. This will be carried out by a fellow graduate student as part of his thesis and funded by a successful *Chandra* theory proposal by Dr. Mark Voit which was motivated by my work. In addition, this project has produced a first author paper which has been submitted to the ApJ (in fact, I was informed it was sent to you for dissemination to a referee).

Cluster Feedback and ICM Entropy

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 cooling times (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 (Fig. 3) and AGN activity (Fig. 4) 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, λ_F, (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.

1) What is the origin of the bimodality in K_0?
Is it archival bias? Meaning, are clusters with $K_0 \sim 70$ keV cm^2 "boring" (and faint) and thus have not been proposed for observation? In which case I will select a representative sample of clusters from a flux-limited survey, such as *ROSAT* 400$\square^\circ$, which predictably fill this gap and observe them with *Chandra*. Or, is the gap physically driven? Is the gap representative of a very short period in a clusters life when AGN activity has boosted the core entropy to the point of being conductively stable ($K_0 > 20$ keV cm^2) and subsequent mergers have further elevated the ICM entropy to $K_0 > 100$ keV cm^2? A possible answer to this question may be found in analysis of simulations by asking the additional question: what is the timescale for depletion of $\sim 10^{12-13} M_\odot$ subclusters in a full dark matter halo? If this timescale is of the order a few Gyrs then this likely points to a collusion of AGN feedback and mergers to give rise to bimodality. But ultimately the questions I posed are related with two primary underlying questions: what does the distribution of K_0 for a complete sample of clusters look like? And what does the AGN energy injection distribution look like?

2) What role is star formation playing in the feedback cycle of clusters?
Thus far, indications from the literature are that most (possibly all?) BCGs in X-ray luminous clusters with $K_0 \leq 20$ keV cm^2 are dominated by star formation. But we can see from Figure 4 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. A cross-reference of my thesis sample (which is essentially the entire CDA) with the *Spitzer* data archive reveals 150+ clusters have already been observed by *Spitzer* (combinations of 75+ MIPS, 50+ IRAC, 30+ IRS) covering a broad entropy, luminosity (X-ray, Hα, radio), and mass range. The large pool to draw from makes selection of a representative subsample immediately possible. Does star formation precede/inhibit/enhance/stunt AGN feedback? Currently we do not know. All we know is these two processes are triggered in cluster BCGs which reside in low entropy environments. Surely they are coupled somehow, which is why I highlighted several poor clusters/rich groups in Figures 3 and 4 with blue boxes and red stars. These systems are in the proper regime for feedback, yet they exhibit only one or neither of star formation or AGN. Follow-up of these objects with *Spitzer* and *XMM*'s Optical Monitor to search for polycyclic aromatic hydrocarbon features, UV excess, or dusty AGN would be interesting.

3) How is energy generated on the parsec scale from a SMBH deposited uniformly in the ICM over a few cubic megaparsecs?
The role of AGN feedback in shaping global cluster properties is quite complex and to some extent poorly understood (e.g. Perseus). 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? We'd like to know if bubbles are pressure supported, and this could be studied via SZ effects. Radio sources are also being revealed as much more powerful than ever expected now that they have been observed at low radio frequencies (i.e. 330 MHz). Use of surveys such as LOFAR, LWA and EVLA will make study of clusters across a broad radio range a rich field for years to come. Also, what is the contribution of cosmic rays in bubbles? The presence of cosmic rays should be detectable with GLAST using observation of γ-rays from the decay of π^0 in bubble lobes. How do bubbles rise to distances ≥ 100 kpc without being shredded by instabilities? What is the role of $\vec{B}$ fields in stabilizing bubbles? And what is the origin of these fields? This area of cluster feedback studies is littered with more questions than current answers, which makes for an attractive research avenue for a post-doc to write many observing and grant proposals.

I have attempted to highlight without too much depth the areas I have already worked and the directions I would like to go. Most of my experience is with X-ray data, but multiwavelength analysis is the next necessary step in my career, and I hope it will be under your direction at Carnegie.

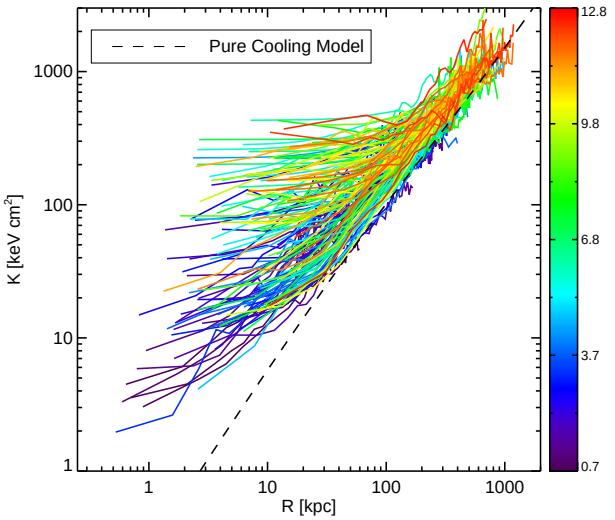

Figure 1: Radial entropy profiles of 143 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 40$ keV cm^2 is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size R_{2500}.

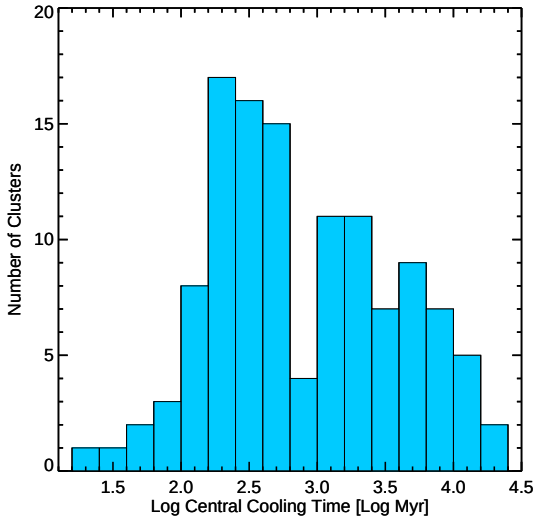

Figure 2: Distribution of central cooling times for an unbiased sub-sample of the clusters analyzed for my thesis. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct gap at $0.6 - 1$ Gyr. An explanation for this bimodality does not currently exist.

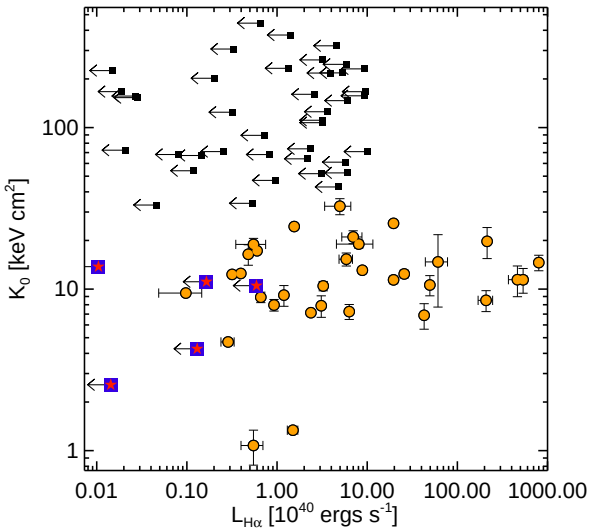

Figure 3: Central entropy plotted against Hα luminosity. Orange dots are detections, black boxes with arrows are non-detection upper-limits, and blue boxes with red stars are poor clusters/rich groups which do not match the trend. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm^2. This is also the entropy scale at which conduction no longer balances radiative cooling and condensation of low entropy gas onto a BCG can proceed.

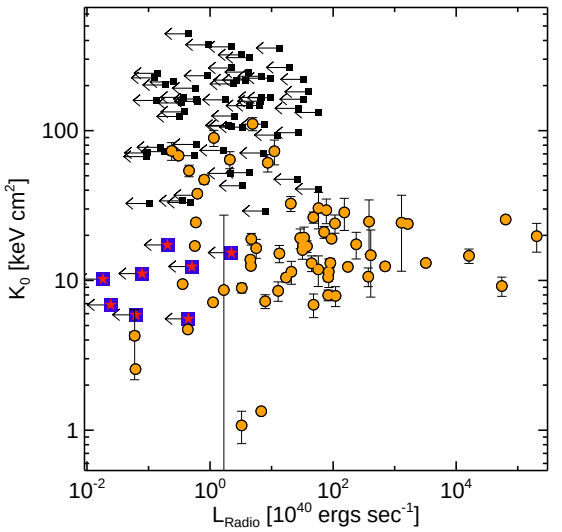

Figure 4: Central entropy plotted against NVSS or PKS radio luminosity. Orange dots are detections, black boxes with arrows are non-detection upper-limits, and blue boxes with red stars are poor clusters/rich groups which do not match the trend. There appears to be a dichotomy which might be related to AGN fueling mechanisms: AGN which are feed via low entropy gas, and the smattering of points at $K_0 > 50$ keV cm^2 which are likely fueled by mergers.