January 17, 2008

Dr. D. Fadda
California Institute of Technology
770 So. Wilson Ave.
ME 100-22
Pasadena, CA 91125

Dear Dr. Fadda:

Please accept the attached application for your postdoctoral position in X-ray astronomy advertised in the January 2008 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 Caltech 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 cluster evolution, 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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Michigan State University
Department of Physics & Astronomy
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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**

- MSU 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
(517)-355-9200 ext. 2418
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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
Data accessible at: www.pa.msu.edu/astro/MC2/accept

*"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 Experience 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. My thesis research has focused on studying these details in clusters of galaxies via X-ray properties of the ICM. Utilizing a 350 observation (276 clusters; 11.6 Msec) sample taken from the CDA, I have paid particular attention to ICM entropy distribution, the process of cluster virialization, and the role of AGN feedback in shaping large scale cluster properties.

The picture of the ICM entropy-feedback connection emerging from my research suggests cluster cD radio luminosity and core H$\alpha$ emission are anti-correlated with cluster central entropy. Following analysis of 169 cluster radial entropy profiles (Fig. 1), I have found an apparent bimodality in the distribution of central entropy and central cooling times (Fig. 2) which is likely related to AGN feedback (and to a lesser extent, mergers). I have also found that clusters with central entropy $\lesssim 20$ keV cm$^2$ show signs of star formation (Fig. 3) and AGN activity (Fig. 4), 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 at which thermal conduction can stabilize a cluster core against ICM condensation. These results are highly suggestive that conduction in the cluster core is very important to solving the long-standing problem of how ICM gas properties are coupled to feedback mechanisms such that the system becomes self-regulating.

The final phase of my thesis is focused on further understanding why we observe bimodality, what role star formation is playing in the cluster feedback loop, refining a model for how conduction couples feedback to the ICM, and examining the peculiar class of objects which fall below the Field length criterion but *do not* have star formation and/or radio-loud AGN (blue boxes with red stars in two of the figures).

There are additional areas of my present research I'd like to expand on in the future. **(1)** Using the near-UV sensitivity of *XMM*'s Optical Monitor and the far-IR channels of *Spitzer*, I plan to propose a joint archival project to disentangle which $K_0 \lesssim 20$ cDs are star formation dominated and which are AGN dominated. **(2)** To check if bimodality is archival bias, I am submitting a *Chandra* Cycle 10 observing proposal for a sample of clusters which predictably fall into the $t_{\rm cool}$ and $K_0$ gaps. **(3)** Two classes of peculiar objects warrant intensive multiwavelength study: high-$K_0$ clusters with radio-loud AGN (e.g. AWM4) and low-$K_0$ clusters without any feedback sources (e.g. Abell 2107). The former likely have prominent X-ray corona, while the latter may be showing evidence that extremely low entropy cores inhibit the growth of gas density contrasts. **(4)** Thus far I have only focused on AGN which are radio-loud according to the 1.4 GHz eye of NVSS, but recent work has shown AGN radio halos are very powerful at low frequencies too. I'd like to know what the radio power is at these wavelengths for (ideally) my entire thesis sample and see if the $K_0$-radio correlation tightens.

In another part of my thesis research I studied an aspect-independent measure of temperature inhomogeneity as a means for quantifying cluster virialization state. I found the hard-band to full-band temperature ratio was robustly correlated to mergers and the absence of cool cores. This project touched on quantifying and reducing the scatter in mass-observable relations to bolster the utility of clusters as cosmology tools. I am eager to keep this area of my work alive as we get closer to having access to enormous catalogs of SZ detected clusters (*e.g.* from *Planck*) which require X-ray follow-up. To maximize the utility of these surveys, we must continue to investigate scatter, evolution, and covariance in the X-ray observables which serve as vital mass surrogates.

There are additional areas of study which I have not touched on in this summary but still interest me. Such as the micro-physics of ICM heating (e.g. turbulence and weak shocking), the thermalization of mechanical work done by bubbles, and the importance of non-thermal sources, like cosmic rays, in bubble heating. How prevalent are cold fronts? Can they be used to robustly quantify ICM magnetic fields and viscosity? Are they important in the feedback loop? How robust is the "X-ray Butcher-Oemler Effect" of Paul Martini if one studies a large sample of clusters? Can we deduce a low-scatter relation (or at least constrain one) between jet power and radio power? What is the explanation for the thermal inefficiency of jets? Many questions abound as a result of my thesis work, I hope to pursue the answers to them as a post-doc with you at Caltech.

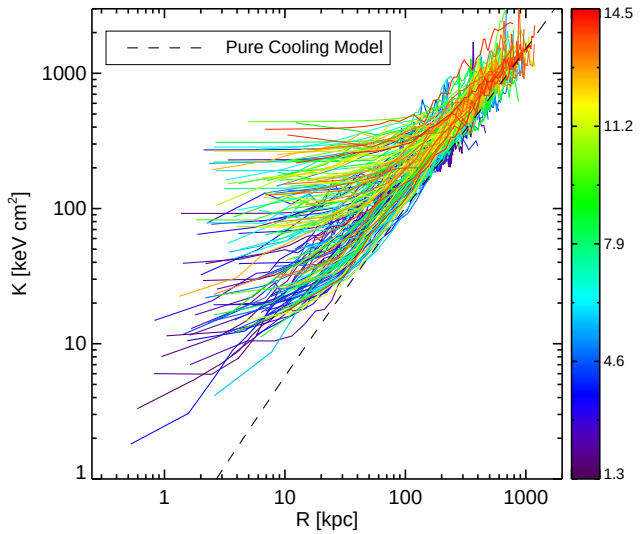


Figure 1: Radial entropy profiles of 169 clusters of galaxies in my thesis sample. The observed range of $K_0 \lesssim 70$ keV cm$^2$ is consistent with models of episodic AGN heating. Color coding indicates global cluster temperature (in keV) derived from core excised apertures of size $R_{2500}$.

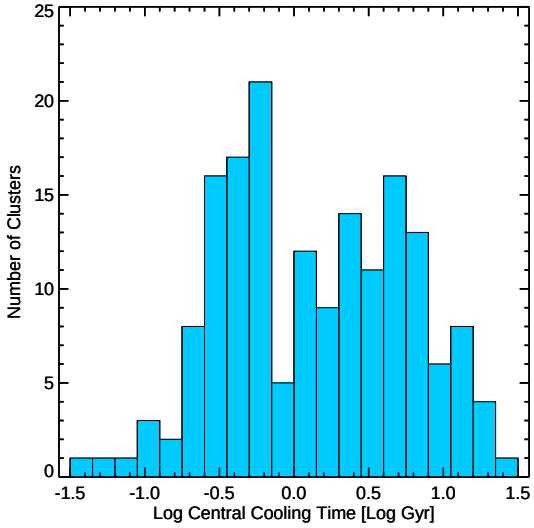


Figure 2: Distribution of central cooling times for 169 clusters in my thesis sample. The peak in the range of cooling times (several hundred Myrs) is consistent with inferred AGN duty cycles of both weak ($\sim 10^{40-50}$ ergs) and strong ($\sim 10^{60}$ ergs) outbursts. However, note the distinct gap at $0.6-1$ Gyr. An explanation for this bimodality does not currently exist.

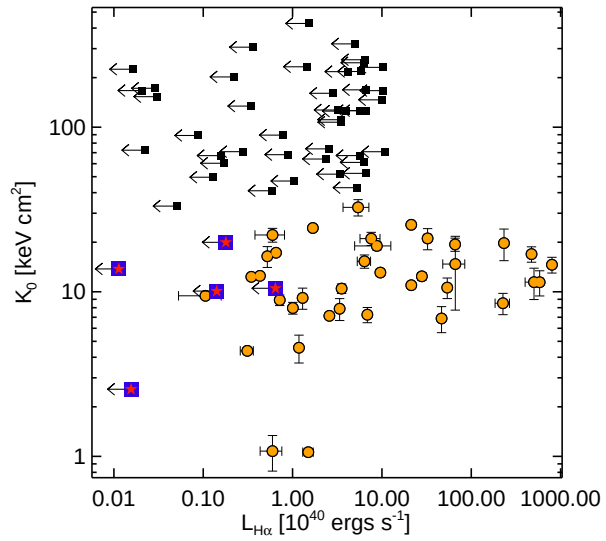


Figure 3: Central entropy plotted against H$\alpha$ luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Notice the characteristic entropy threshold for star formation of $K_0 \lesssim 20$ keV cm$^2$. This is also the entropy scale at which conduction no longer balances radiative cooling and condensation of low entropy gas onto a cD can proceed.

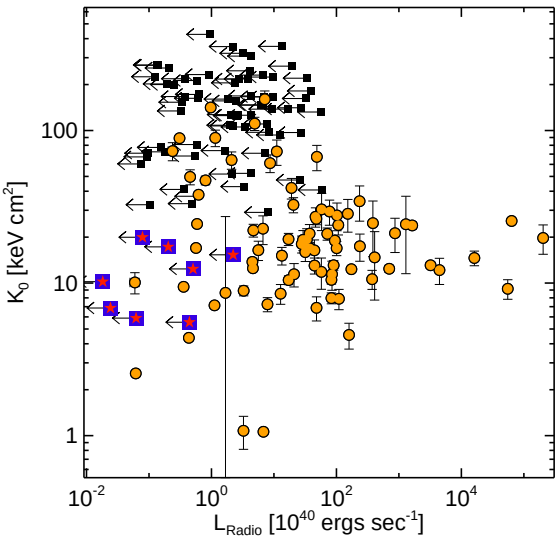


Figure 4: Central entropy plotted against NVSS radio luminosity. Orange dots are detections and black boxes with left-facing arrows are non-detection upper-limits. Radio-loud AGN clearly prefer low entropy environs but the dispersion at low luminosity is large. It would be interesting to radio date these sources as this figure may have an age dimension.