October 1, 2007

Prof. Patricia Burchat
Stanford University
382 via Pueblo Mall
Varian 158
Stanford, CA 94305-4060

Dear Prof. Burchat:

Please accept the attached application for your postdoctoral position in galaxy cluster studies advertised in the September 2007 edition of the AAS Job Register. For my thesis, entitled *'Feedback, Evolution, and Dynamics in Galaxy Clusters'*, I am studying the connection of feedback mechanisms – such as AGN, star formation, and radiative cooling in cluster cores – to gas entropy, and the role of this feedback in altering global properties of the ICM and impacting galaxy formation. 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. The results of this laborious task have been many and are detailed in the research summary.

My expertise in X-ray astronomy, with *Chandra* specifically, ideally suits me to further study the evolution of galaxy clusters and mass-observable relations as tools for conducting tests of cosmological models and better understanding galaxy formation/evolution. 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 clusters both for my technical skills and to furthering their research objectives. I feel the post-doctoral position at Stanford is an excellent fit for me, and the groups research goals will benefit from my addition.

Along with this letter are my curriculum vitae, a list of publications, 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

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

- Large Scale Structure Formation and Cosmology
- Characterization of Dark Energy
- Galaxy Cluster Evolution
- Feedback Mechanisms in Galaxy Clusters
- Galaxy Formation

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, 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.

"Library 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, Thesis Talk and 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, the process of virialization, and the role of AGN feedback in shaping large scale cluster properties.

Mining the CDA

My primary research makes use of a 350 observation sample (276 clusters) taken from the *Chandra* archive. Of these 276 clusters, 16 lie in the redshift range $0.6 < z < 1.2$. Ongoing and future X-ray surveys will be heavily focused on the cluster population at $z > 1.0$. By gaining experience with low count, low surface brightness clusters now I am amply prepared to work with much larger datasets of these objects in the future. In addition, 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 provide a complementary and distinct constraint on cosmological parameters to those tests which constrain them geometrically (e.g. supernovae and baryon acoustic oscillations).

However, clusters are a useful cosmological tool only if we can infer cluster masses from observable properties such as X-ray luminosity, X-ray temperature, lensing shear, optical luminosity, and galaxy velocity dispersion. Empirically, the relationship of mass and these observable properties is well-established. However, if we could identify a "3rd parameter" – possibly reflecting the degree of relaxation in the cluster – we could improve the utility of clusters as cosmological probes.

One method of quantifying cluster substructure – a property of clusters which results in the underestimate of cluster temperatures and therefore cluster mass – employs the ratios of X-ray surface brightness moments to quantify the degree of relaxation. Although an excellent tool, power ratio suffers from being aspect dependent, much like other substructure measures such as axial ratio or centroid variation. The work of [1] 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. 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. Having confirmed the prediction of [1], 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 cites my work. In addition, this project has produced a first author paper which is near ApJ submission.

Cluster Feedback and ICM Entropy

The picture of the ICM entropy-feedback connection emerging from my work suggests that cD radio luminosity and Hα emission are anti-correlated with cluster central entropy. I have explored these relations with my thesis sample and am finding a trend of high central entropy favoring low $L_{H\alpha}$ and low L_{Radio}. These results fit well with the current framework for AGN heating and cooling flow retardation through the inflation of bubbles in the ICM and star formation in the cores of cooling flows. I am following up these results by examining the distribution of central cooling times as a window onto the timescale of AGN feedback. In addition, I am exploring the dependence of the X-ray loud AGN distribution on redshift and amount of cluster substructure.

This work has been very fruitful thus far: I am a co-author for two refereed journal papers ([2], [3]), generated new and unique work each year ([4], [5], [6], [7], [8], [9]), a first author paper which is in draft, and another first author paper in preparation containing my thesis results. I have also contributed to several successful *Chandra*, *XMM*, *Suzaku*, and *Subaru* proposals in addition to writing my own high scoring – although unsuccessful – *Chandra* proposal for time observing an amazing ULIRG. I am also planning Hα imaging observations for several previously unobserved clusters with MSU's SOAR telescope.

Future Work

All of the questions and studies which follow are possible through the continuation of my present work. There is no need for additional observing time to make these studies possible. The ever growing data available in data archives for *Chandra*, *XMM*, *Spitzer*, *VLA*, and *HST*, to name a few, makes conducting multiwavelength analysis of clusters at all redshifts possible right now.

Looking ahead, the natural extension of my thesis is to further study questions regarding cluster environments and their impact on galaxy formation and participating in the construction of large samples of distant clusters. More specifically, I'd like to use these samples to measure the evolution of the cluster mass function as a direct means of breaking the degeneracy between Ω_M and σ_8. Combined with complimentary surveys such as SDSS, X-ray surveys will help further constrain the fundamental parameters defining the current cosmological model.

But, the detailed analysis of the cluster population at redshifts greater than $z \sim 1$ will be very difficult, and establishing the self similar model as a reliable tool for calibrating the cluster mass function will lead to better studies of hierarchical structure formation and dark energy. But even calibration is not enough, we must also understand the scatter in these relations. And to this end, one needs two components: verified high-z clusters and methods for quantifying deviation from mean mass-scaling relations (such as those discussed earlier or the Y_X parameter of [10]). But the simple application of existing metrics which have been calibrated to low-z samples or high resolution simulations will begin to breakdown as spatial and spectroscopic information is reduced at high redshifts. I look forward to being a part of generating new, novel solutions to these problems.

The identification of high-z clusters proceeds in a straight forward manner: X-ray selecting a cluster candidate from serendipitous surveys (such as those being conducted by members of the Stanford cosmology group), infrared follow-up with *Spitzer* or *Keck*'s DEIMOS for example, and then spectroscopic identification of cluster members with archival *HST* data or dedicated *VLT* time. The mass observables luminosity and temperature are obtained directly from X-ray observation and mass can then be inferred from a deprojected gas density profile. Where high-z clusters lie in the luminosity-mass and temperature-mass planes is an excellent complimentary tool for studying scaling-relation evolution.

In the case of high-z clusters, the entropy distribution can also be derived from using modified beta-models to fit the ICM density and temperature profiles. After analyzing the entropy distribution, it will be interesting to see where high-z clusters fit into the framework of feedback models. There are additional corollaries to such work: studying the cluster environment of these high redshift objects in relation to the galaxy population of the cluster (i.e. strength of the red sequence), or looking for signs of feedback in the cluster (i.e. optical or radio AGN). The gas mass fraction is also of special interest along with the cooling time of the cluster ICM.

In the low-z regime, additional questions exist regarding details of feedback and galaxy formation. What are the micro-physics of ICM heating, including the thermalization of mechanical work done by bubbles and the effect of non-thermal sources like cosmic rays. How prevalent are cold fronts and do they play a role in galaxy and star formation? Also of interest are how accretion onto the cD SMBH is regulated by large-scale ICM properties and what the AGN energy injection function looks like and how it correlates with cluster environment.

There are also exciting theoretical cluster feedback model developments on the horizon which will need observational investigation, and for which I am well positioned to study. Developments such as: how exactly are AGN fueled? Does accretion of the hot ICM/ISM proceed via Bondi-eque flows? What is the efficiency of the accretion? Why do we see metallicity gradients in the ICM/ISM when some amount of mixing should take place? How is feedback energy distributed symmetrically throughout the ICM?

The synergy of large X-ray and optical surveys, such as those which will come from LSST and Con-X, creates vast opportunities for the study of clusters. My expertise in X-ray astronomy, with the goal of expanding my research to all wavelengths, ideally suits me to continue studying cluster virialization, feedback, and galaxy formation models to prepare interesting and novel uses for these large samples. As Stanford is the epicenter for the future of my field, I'm eager to be a contributor in your research group.

References

[1] B. F. Mathiesen and A. E. Evrard. Four Measures of the Intracluster Medium Temperature and Their Relation to a Cluster's Dynamical State. *ApJ*, 546:100–116, January 2001.

[2] M. Donahue, M. Sun, C. P. O'Dea, G. M. Voit, and K. W. Cavagnolo. Star Formation, Radio Sources, Cooling X-Ray Gas, and Galaxy Interactions in the Brightest Cluster Galaxy in 2A0335+096. *AJ*, 134:14–25, July 2007.

[3] 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.

[4] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. Library of Galaxy Cluster Entropy Profiles: A Study in Feedback. In *Bulletin of the American Astronomical Society*, Bulletin of the American Astronomical Society, January 2008.

[5] K. W. Cavagnolo, M. Donahue, G. M. Voit, and M. Sun. The Entropy-Feedback Connection and Quantifying Cluster Virialization. Eight Years of Science with Chandra Symposium, October 2007.

[6] M. Donahue, M. Sun, K. Cavagnolo, and G. Voit. Chandra Studies of Dark Matter and Galaxy Formation: Signatures from the Intracluster Medium. In *Bulletin of the American Astronomical Society*, volume 38 of *Bulletin of the American Astronomical Society*, pages 998–+, December 2006.

[7] K. W. Cavagnolo, M. E. Donahue, G. M. Voit, M. Sun, and A. E. Evrard. Studies of Entropy Distributions in X-ray Luminous Clusters of Galaxies. In *Bulletin of the American Astronomical Society*, volume 37 of *Bulletin of the American Astronomical Society*, pages 1393–+, December 2005.

[8] K. W. Cavagnolo, M. E. Donahue, G. M. Voit, D. J. Horner, and A. E. Evrard. Entropy Distributions in the Cores of Nearby X-ray Luminous Clusters of Galaxies. In *Bulletin of the American Astronomical Society*, volume 36 of *Bulletin of the American Astronomical Society*, pages 1595–+, December 2004.

[9] M. E. Donahue, G. M. Voit, and K. Cavagnolo. Radio-Free Cluster Cooling Flows. In *Bulletin of the American Astronomical Society*, volume 36 of *Bulletin of the American Astronomical Society*, pages 1445–+, December 2004.

[10] A. V. Kravtsov, A. Vikhlinin, and D. Nagai. A New Robust Low-Scatter X-Ray Mass Indicator for Clusters of Galaxies. *ApJ*, 650:128–136, October 2006.