November 1, 2010

NRAO Headquarters
520 Edgemont Road
Charlottesville, VA 22903-2475
United State of America

To whom it may concern:

Please find attached my 2011 Jansky Fellowship Program application titled “Mapping Galaxy Cluster Magnetic Fields: An Observational Study of ICM Physics.” I feel the Jansky post-doctoral program is an excellent fit for my research goals and that the host institution, the University of Maryland, as well as NRAO, will benefit from my addition. My expertise in radio and X-ray astrophysics, and mature collaborations with groups in both research areas, has prepared me for the rigors of the program proposed in this application.

Along with this letter are my curriculum vitae, a list of publications, a brief summary of my past and on-going research, a statement of my proposed research program, and an endorsement letter from the University of Maryland. Letters of recommendation from Dr. Megan Donahue, Dr. Mark Voit, and Dr. Brian McNamara should arrive under separate cover. In the event a conflict arises with the proposed host institution, I submit that the University of Wisconsin-Madison and University of Michigan should serve as the first and second back-up choices, respectively.

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

Kenneth W. Cavagnolo
Curriculum Vitae

Observatoire de la Côte d'Azur
Boulevard de l'Observatoire
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Citizenship: U.S.A.
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Education

Michigan State University — 2005 – 2008
Ph.D., Astronomy & Astrophysics

Michigan State University — 2002 – 2005
M.S., Astronomy & Astrophysics, *magna cum laude*

Georgia Institute of Technology — 1998 – 2002
B.S., Physics, *magna cum laude*

Research Experience

Opales Postdoctoral Fellow — 2010 – Present
Supervisor: Chiara Ferrari, *Obs. Côte d'Azur*

UW Postdoctoral Fellow — 2008 – 2010
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 physics of the intracluster and intra-group medium, and the role of feedback from active galactic nuclei & quasars on the formation and evolution of galaxies, galaxy groups, and galaxy clusters.

Specific areas of interest:
- Cosmic magnetic fields
- Non-thermal galaxy cluster emission
- Black hole accretion physics
- Relativistic jets
- Cosmological studies of structure formation

Honors

- Referee for ApJ, ApJL, AJ, CanTAC, & MNRAS — 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
- ΣΠΣ National Physics Honor Society Member — 2001 – Present
- American Astronomical Society Member — 2002 – Present

- American Physical Society Member — 2002 – Present
- LOFAR Consortium Member — 2010 – Present
- Perimeter Institute Black Hole Reading Group Member — 2009 – 2010
- Dean's List, Georgia Inst. of Tech. — 1998 – 2002

Scientific Skills

- Expert of radio and X-ray data analysis & interpretation
- Extensive experience analyzing infrared, optical, UV, and gamma-ray data
- Mastery of AIPS, CASA, CIAO, IRAF, OSA, and SAS analysis software
- Fluent in HTML, IDL, LaTeX, and PERL programming languages
- Familiar with C, Fortran, MySql, Python, SuperMongo, and Tcl
- Command of DOS, Linux, Macintosh, and Windows computing architectures
- Skillful in computer maintenance, construction, and troubleshooting

Observing Experience

Very Long Baseline Array (VLBA) — TBD
12 hours observing IRAS 09104+4109

Giant Metrewave Radio Telescope (GMRT) — Jan. 2010
60 hours observing 15 galaxy clusters

Chandra X-ray Observatory (CXO) — Jan. 2009
21 hour queued observation of IRAS 09104+4109

Very Large Array Radio Telescope (VLA) — Dec. 2008
39 hours observing 13 giant ellipticals

Accepted Proposals & Grants

VLBA Cycle 10, PI — 2010
Imaging the Misdirected QSO of IRAS 09104+4109

GMRT Cycle 17–19, Co-I — 2009 – 2010
Power and Particle Content of Extragalactic Radio Sources I–III
PI: Somak Raychaudhury, *Univ. Birmingham*

GMRT Cycle 17, Co-I — 2009
Morphology of Steepest Spectrum Radio Sources in Galaxy Cluster Cores
PI: Alastair Edge, *Durham Univ.*

NOAO Cycle 2008A, 2009A/B, & 2010A, Co-I — 2008 – 2010
Normalization and scatter of the $M - T$ relation for supermassive galaxy clusters
PI: Rachel Mandelbaum, *Princeton Univ.*

GMRT Cycle 16, Co-I — 2008
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 Star Formation and AGN Feedback in BCGs PI: Megan Donahue, *Mich. St. Univ.*	2008
	Spitzer Cycle 5, Co-I Infrared Properties of a Control Sample of Brightest Cluster Galaxies PI: Megan Donahue, *Mich. St. Univ.*	2008
	NSF Grant, Co-I Star Formation in the Universe's Largest Galaxies PI: Mark Voit, *Mich. St. Univ.*	2008
	CXO Cycle 9, Co-I Quantifying Cluster Temperature Substructure PI: Mark Voit, *Mich. St. Univ.*	2007
	VLA A-configuration Cycle, Co-I Radio Feedback in Clusters and Galaxies PI: Brian McNamara, *Univ. Waterloo*	2007
Students Advised	Clif Kirkpatrick, Ph.D. candidate, *Univ. Waterloo* The 2-Dimensional metal abundance distributions in galaxy clusters	2008 – 2010
	Mina Rohanizadegan, Ph.D. candidate, *Univ. Waterloo* Understanding SMBH accretion and spin	2008 – 2010
	Jason King, Undergraduate research, *Univ. Waterloo* Quantifying scatter in the $P_{\rm jet}$-$P_{\rm radio}$ relation	2010
	Brad Whuiska, Undergraduate research, *Univ. Waterloo* Finding the largest galactic cores in the *HST* archive	2009
	Rob Myers, Undergraduate research, *Univ. Waterloo* In search of galaxy cluster radio galaxies in the 400 deg^2 Survey	2009
Outreach	Non-thermal Phenomena in Colliding Galaxy Clusters Conference Local Organizing Committee	2010
	International Year of Astronomy Organized observing nights, talks, and workshops in Waterloo, ON	2009
Teaching Experience	Substitute Instructor Course: "Visions of the Universe"	Fall 2006
	Honors Physics Tutor Course: "Introductory Honors Physics I & II"	Summer 2003
	Graduate Teaching Assistant Course: "Visions of the Universe"	2002 - 2003
References	Megan Donahue, `donahue@pa.msu.edu` Tenured faculty, Michigan State University	517-884-5618

G. Mark Voit, voit@pa.msu.edu 517-884-5619
Tenured faculty, Michigan State University

Brian McNamara, mcnamara@uwaterloo.ca 519-888-4567 ext. 38170
Tenured faculty, University of Waterloo

Chris Carilli, ccarilli@nrao.edu 575-835-7306
Chief Scientist, National Radio Astronomy Observatory

Jack Baldwin, baldwin@pa.msu.edu 517-884-5611
Associate Chair of Astronomy, Michigan State University

Mike Wise, wise@science.uva.nl 05-2159-5564
Chief Scientist, LOFAR Radio Observatory

Paul Nulsen, pnulsen@cfa.harvard.edu 617-495-7043
Research Scientist, Center for Astrophysics at Harvard University

Chiara Ferrari, ferrari@oca.eu 04-9200-3028
Adjunct Astronomer, Observatoire de la Côte d'Azur

Personal Interests

- Academic: Environmental sciences, "Cradle2Cradle" design, and urban planning.
- Athletics: Triathlons, running, baseball, and Georgia Tech athletics.
- Hobbies: Backpacking, reading, building model airplanes, and raising bonsai trees.

Kenneth W. Cavagnolo
Publications

Submitted

"Direct Evidence of Radiative and Mechanical Feedback from the Quasar in IRAS 09104+4109"
K. Cavagnolo, M. Donahue, B. McNamara, G. M. Voit, & M. Sun
Submitted to MNRAS

"A Powerful, Line-of-Sight AGN Outburst in RBS 797"
K. Cavagnolo, B. McNamara, M. Wise, P. Nulsen, M. Brüggen, M. Gitti, & D. Rafferty
Submitted to ApJ

In Preparation

"Identifying AGN Feedback Relics Via Steep Spectrum Radio Sources"
K. Cavagnolo, A. Edge, H. Röttgering, B. McNamara, M. Wise, M. Brüggen, R. van Weeren, G. Brunetti, & J. Croston
In prep. for A&A

"Entropy Scaling Relations of ACCEPT Galaxy Clusters"
K. Cavagnolo, G. M. Voit, M. Donahue, & S. Bruch
In prep. for ApJL

"How Difficult is SMBH Spin Axis Reorientation? Implications for AGN Feedback Models"
K. Cavagnolo & N. Afshordi
In prep. for ApJL

"The Radio Halo-Merger-Cooling Connection in Galaxy Clusters at $z \sim 0.5$"
E. Orrù, C. Ferrari, M. Arnaud, **K. Cavagnolo**, J. Croston, N. Jetha, G. Pratt, E. Pointecouteau, & S. Raychaudhury
In prep. for A&A

"Redistribution of Metals in Galaxy Clusters via AGN Feedback"
C. Kirkpatrick, B. McNamara, **K. Cavagnolo**, P. Nulsen, & M. Wise
In prep. for ApJ

"Normalization and Scatter of the M–T Relation for Supermassive Galaxy Clusters"
R. Mandelbaum, R. Nakajima, N. Bahcall, G. Bernstein, **K. Cavagnolo**, M. Donahue, J. Hughes, C. Keeton, A. Kravtsov, S. Miyazaki, N. Padmanabhan, & T. Schrabback
In prep. for ApJ

First Author Refereed

"A Relationship Between AGN Jet Power and Radio Luminosity"
K. Cavagnolo, B. McNamara, P. Nulsen, C. Carilli, C. Jones, & L. Bîrzan
ApJ Published, 2010

"Intracluster Medium Entropy Profiles for a Chandra Archival Sample Of Galaxy Clusters"
K. Cavagnolo, M. Donahue, G. M. Voit, & M. Sun
ApJ Published, 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 Published, 2008

"Bandpass Dependence of X-Ray Temperatures in Galaxy Clusters"
K. Cavagnolo, M. Donahue, G. M. Voit, & M. Sun
ApJ Published, 2008

Co-Author Refereed

"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 Published, 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 Published, 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 Published, 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 Published, 2007

"s-Process Abundances in Planetary Nebulae"
B. Sharpee, Y. Zhang, R. Williams, E. Pellegrini, **K. Cavagnolo**, J. Baldwin, M. Phillips, & X. Liu
ApJ Published, 2007

"Entropy Profiles in the Cores of Cooling Flow Clusters of Galaxies"
M. Donahue, D. Horner, **K. Cavagnolo**, & G. M. Voit
ApJ Published, 2006

Presented Work

INVITED TALK: *"Exploring the Radio-mode/Quasar-mode Feedback Dichotomy"*
Nov. 2010 – CNRS Colloquium; Observatoire de la Côte d'Azur

TALK: *"The AGN Jet Power and Radio Power Relationship"*
Jun. 2009 – The Monster's Fiery Breath Meeting; 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"*
Sept. 2008 – The Cool, Cooler, and Cold Meeting; 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 Intra-cluster 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

SUMMARY OF PAST AND ON-GOING RESEARCH

In a broad sense, my research program focuses on galaxy clusters, both as astrophysical laboratories and interesting structures in their own right. In the case of the latter, it is the properties of the intracluster medium (ICM) which have captivated me, while for the former, I am most interested in feedback from active galactic nuclei (AGN) and the processes which couple AGN activity and the ICM. Some highlights of my research in these areas are presented below.

I. ICM Temperature Inhomogeneity

If simple galaxy cluster observables such as temperature or luminosity are to serve as accurate mass proxies, how mergers alter these observables needs to be quantified. It is known that cluster substructure correlates well with dynamical state, and that the apparently most relaxed clusters have the smallest deviations from mean mass-observable relations [*e.g.* 1]. But, 2D analysis is at the mercy of perspective. If a cluster's ICM is nearly isothermal in the projected region of interest, the X-ray temperature inferred from a broadband (0.7-7.0 keV) spectrum should be identical to the X-ray temperature inferred from a hard-band (2.0-7.0 keV) spectrum. However, if there are unresolved, cool lumps of gas, the temperature of a single-component thermal model will be cooler in the broadband versus the hard-band. This difference is then possibly a diagnostic to indicate the presence of cooler gas, *e.g.* associated with merging sub-clusters, even when the X-ray spectrum itself may not have sufficient signal-to-noise to resolve multiple temperature components [2].

In Cavagnolo et al. 2008 [3] we studied this temperature band dependence for 192 clusters taken from the *Chandra* Data Archive. We found, on average, that the hard-band temperature was significantly higher than the broadband temperature, and that their ratio was preferentially larger for known mergers (Fig. 1). The interpretation of this result is that, indeed, ICM temperature inhomogeneity is detectable via a simple bandpass comparison and, on average, it correlates with cluster dynamical state. Our results suggest such a temperature diagnostic may be useful when designing metrics to minimize the scatter about mean mass-scaling relations in an attempt to obtain smaller uncertainties in cluster mass estimates.

II. ICM Entropy and AGN Feedback

ICM temperature and density mostly reflect the shape and depth of a cluster's dark matter potential – it is the specific entropy ($K \approx kT_{\rm X} n_{\rm e}^{-2/3}$) which governs the density at a given pressure [4]. Ignoring convective instabilities induced by anisotropic conduction, the ICM is convectively stable when the lowest gas entropy occupies the bottom of the cluster potential and the highest entropy gas has buoyantly risen to larger radii. Further, ICM entropy is primarily changed through heat exchange. Thus, deviations of the ICM entropy structure from the azimuthally symmetric, radial power-law distribution which should result from pure cooling are useful in evaluating a cluster's thermodynamic history [5]. One key use of ICM entropy is for studying the effects of energetic feedback on the cluster environment and investigating the breakdown of cluster self-similarity [6].

In Cavagnolo et al. 2009 [7], the ICM entropy structure of 239 clusters taken from the *Chandra* Data Archive were studied. We found that most clusters have entropy profiles which are well-fit by a model which is a power-law at large radii and approaches a constant entropy value at small radii: $K(r) = K_0 + K_{100}(r/100 \text{ kpc})^{\alpha}$, where K_0 quantifies the typical excess of core entropy above the best fitting power-law found at larger radii and K_{100} is the entropy normalization at 100 kpc (Fig. 2). Our results are consistent with models which predict cooling of a cluster's X-ray halo is offset by energy injected via feedback from AGN [*e.g.* 6]. We also showed that the distribution of K_0 values in our archival sample is bimodal, with a distinct gap around $K_0 \approx 40$ keV cm^2.

If cooling of a galaxy cluster's halo triggers eventual heating via an AGN-centric feedback loop, then certain ICM properties (*e.g.* entropy) may correlate tightly with signatures of feedback and/or indicators of cooling. In Cavagnolo et al. 2008 [8] we explored the relationship between Hα emission from cluster cores, radio emission from cluster central galaxies, and cluster K_0 values. Utilizing the results of the archival study of intracluster entropy, we found that Hα and radio emission are almost strictly associated with K_0 values less than 30 keV cm^2 (Fig. 3), which is near the gap of the K_0 distribution. The prevalence of Hα emission below this threshold indicates that it marks a dichotomy between clusters that can harbor thermal instabilities (*e.g.* multiphase gas, star formation) in their cores and those that cannot. The fact that strong central radio emission also appears below this boundary suggests that feedback from an AGN turns on when the ICM starts to condense, strengthening the case for AGN feedback as the mechanism that limits star formation in the Universe's most luminous galaxies. In Voit et al. 2008 [9], we go on to suggest that core entropy bimodality and the sharp entropy threshold arises from the influence of thermal conduction. This result is one of the key motivating factors for the fellowship proposal that follows, and is discussed in more detail therein.

III. Details of AGN Feedback

A. Properties of Jets: A long-standing problem in observational and theoretical studies of AGN energetics is estimating total kinetic energy output. These estimates have historically been made using jet models built around first principles and observations of how it *appears* jets interact with their surroundings [*e.g.* 10]. However, X-ray observations of clusters have revealed that AGN outflows inflate cavities in the ICM, and these cavities yield a direct measure of the work, and hence total mechanical energy, exerted by the AGN on its environment [see 11, for details]. Hence, any correlation between derived cavity power and associated synchrotron radio power yields a useful device for constraining total AGN energy output when X-ray data or cavities are unavailable. Such relations between jet power ($P_{\rm jet}$) and radio power ($P_{\rm radio}$) for clusters were presented by Bîrzan et al. 2004, 2008 [12, 13]. In Cavagnolo et al. 2010 [14] we appended a sample of 13 giant ellipticals (gEs) to these studies to determine if a single $P_{\rm jet}$-$P_{\rm radio}$ relation extends from clusters down to isolated gEs.

Utilizing the analysis of $>$ 70 multifrequency, archival *VLA* observations and an array of low-frequency radio surveys, we found that the $P_{\rm jet}$-$P_{\rm radio}$ relation is continuous, and has similar scatter, from clusters down to gEs (Fig. 4). We also found that, independent of frequency, $P_{\rm jet}$ scales as $\sim P_{\rm radio}^{0.7}$ with a normalization of $\sim 10^{43}$ erg s^{-1}. Numerous jet models predict a power-law index of $\approx 12/17$, consistent with our results, and normalizations of $\sim 10^{43}$ erg s^{-1} when the ratio of non-radiating particles to relativistic electrons is $\gtrsim 20$ (*i.e.* moderately heavy jets). Our results imply that there does exist a universal scaling relation between jet power and radio power, which would be a useful tool for calculating AGN kinetic output over huge swathes of cosmic time using only all-sky, monochromatic radio surveys. The impact of this result extends into the areas of galaxy formation, black hole growth, and the mechanical heating of the universe.

B. Radio-mode and Quasar-mode Feedback: Galaxy formation models typically segregate AGN feedback into a distinct early-time, radiatively-dominated quasar mode [*e.g.* 15] and a late-time, mechanically-dominated radio mode [*e.g.* 16]. In quasar-mode, it is believed that intense quasar radiation ($> 10^{46}$ erg s^{-1}) couples to gas within the host galaxy and drives strong winds which deprive the SMBH of additional fuel, regulating growth of black hole mass. At later times, when quasar activity has faded and radio mode feedback takes over, SMBH launched jets regulate the growth of galaxy mass through prolonged and intermittent mechanical heating of a galaxy's gaseous halo (*i.e.* the process discussed in Section A). Though AGN feedback models are broken into two generic modes, they still form a unified schema [*e.g.* 17] which predicts a continuous distribution of AGN luminosities. However, the association of the modes, and whether they interact, is still poorly understood. In Cavagnolo et al. 2010 [18] we present a study of the famous & enigmatic massive galaxy IRAS 09104+4109 (IRAS09) which simultaneous exhibits all the characteristics of a system in radio- and quasar-mode of feedback, perhaps implying it is a "transition" object cycling between the modes.

A joint X-ray/radio analysis of IRAS09 reveals cavities in the galaxy's X-ray halo associated with an AGN outflow having $\sim 10^{44}$ erg s^{-1} of mechanical energy and an obscured nuclear quasar with a luminosity of $\sim 10^{47}$ erg s^{-1}. We directly measure, for the first time, that the radiative to mechanical feedback energy ratio for a "transition" object is $\sim$1000:1. Further, the cavities contain enough energy to offset $\approx 25 - 35\%$ of the host cluster's ICM radiative cooling losses. However, how this energy is thermalized remains unknown – which is one aspect of the fellowship proposal which follows. Nonetheless, our results suggest 3–4 similar strength AGN outbursts are sufficient to suppress ICM core cooling and freeze-out rapid BCG star formation. We also unambiguously demonstrate that the beaming directions of the jets and nuclear radiation are indeed misaligned, as previous studies have suggested. Our interpretations of these findings are that IRAS09 may be providing a local example of how the AGN feedback cycle of massive galaxies at higher redshifts evolves, and may also be offering clues as to how the evolution of black hole spin is closely correlated with the feedback cycle.

C. Black Hole Spin: Current models of the late-time feedback loop posit that cooling processes in a galaxy's halo result in mass accretion onto a central supermassive black hole (SMBH), thereby driving AGN activity. While there is direct evidence that halo cooling and feedback are linked [*e.g.* 8], the observational constraints on how AGN are fueled and powered remain loose. For example, what fraction of the energy released in an AGN outburst is attributable to the gravitational binding energy of the accreting matter [19] and the SMBH's rotational energy [20] is still unclear. Mass accretion alone can, in principle, fuel most AGN [*e.g.* 21]. However, there are gas-poor systems which host very powerful AGN (energies $> 10^{61}$ erg) where mass accretion alone appears unlikely as a power source. The importance of these systems in understanding AGN feedback is that either the AGN fueling has been astoundingly efficient, or the power has come from an alternate source, such as the release of angular momentum stored in a rapidly spinning SMBH [*e.g.* 22]. If more such systems can be found, then it may be necessary to incorporate a SMBH spin feedback pathway into galaxy formation models.

In Cavagnolo et al. 2010 [23], we present analysis of the AGN outburst in the galaxy cluster RBS 797 and, because of the extreme energetic demands of the outburst, suggest it may have been powered by black hole spin. We estimate the total energy output and jet power to be of the order 10^{61} erg and 10^{46} erg s^{-1}, respectively. These enormous energies demand that mass accretion alone is an implausible explanation for how the outburst was powered, and we thus suggest that the outburst resulted from the extraction of rotational energy stored in a rapidly-spinning SMBH. We conclude that RBS 797 may be further observational evidence that some AGN are powered by the release of SMBH spin energy.

The model of Garofalo et al. 2010 [24] suggests that the evolution of a black hole's spin state is closely tied to the process of AGN feedback. In their model, during the process of retrograde accretion induced spin-down, a black hole should pass through a state where its spin is ≈ 0. At this point, an asymmetric accretion flow exceeding a mass-dependent critical accretion rate can drastically and quickly reorient a spin axis. This process is the focus of Cavagnolo et al. 2010 [25] as it can possibly give rise to the type of beamed jet-radiation misalignment observed in IRAS09, and can also result in the extraction of extreme jet powers like in RBS 797. In this work, we discuss the complications of re-orienting the spin axis of a SMBH via mergers, which has become a bit fashionable as an explanation for how AGN feedback energy is distributed beyond the small cross-section of AGN jets. In the following fellowship proposal, how AGN feedback energy may be distributed is instead discussed in terms of microphysical ICM processes like conduction, turbulence, and magnetohydrodynamic instabilities.

IV. References

[1] D.A. Ventimiglia et al. *ApJ*, 685:118–127, Sept. 2008.
[2] B.F. Mathiesen and A.E. Evrard *ApJ*, 546:100–116, Jan. 2001.
[3] K.W. Cavagnolo et al. *ApJ*, 682:821–834, Aug. 2008.
[4] G.M. Voit et al. *ApJ*, 576:601–624, Sept. 2002.
[5] G.M. Voit et al. *MNRAS*, 364:909–916, Dec. 2005.
[6] G.M. Voit and M. Donahue *ApJ*, 634:955–963, Dec. 2005.
[7] K.W. Cavagnolo et al. *ApJS*, 182:12–32, May 2009.
[8] K.W. Cavagnolo et al. *ApJ*, 683:L107–L110, Aug. 2008.
[9] G.M. Voit et al. *ApJ*, 681:L5–L8, Jul. 2008.
[10] C.J. Willott et al. *MNRAS*, 309:1017–1033, Nov. 1999.
[11] B.R. McNamara and P.E.J. Nulsen *ARA&A*, 45:117–175, Sept. 2007.
[12] L.Bîrzan et al. *ApJ*, 607:800–809, Jun. 2004.
[13] L.Bîrzan et al. *ApJ*, 686:859–880, Oct. 2008.
[14] K.W. Cavagnolo *ApJ*, 720:1066–1072, Sep. 2010.
[15] V. Springel et al. *Nature*, 435:629–636, Jun. 2005.
[16] D.J. Croton et al. *MNRAS*, 365:11–28, Jan. 2006.
[17] D. Sijacki et al. *MNRAS*, 380:877–900, Sept. 2007.
[18] K.W. Cavagnolo et al. *Submitted to MNRAS*, 2010.
[19] M.C. Begelman et al. *Reviews of Modern Physics*, 56:255–351, Apr. 1984.
[20] D.L. Meier *New Astronomy Review*, 46:247–255, May 2002.
[21] D.A. Rafferty et al. *ApJ*, 652:216–231, Nov. 2006.
[22] B.R. McNamara et al. *ApJ*, 698:594–605, Jun. 2009.
[23] K.W. Cavagnolo et al. *Submitted to ApJ*, 2010.
[24] D. Garofalo et al. *MNRAS*, pages 820–+, May 2010.
[25] K.W. Cavagnolo and N. Afshordi *In prep. for ApJL.*

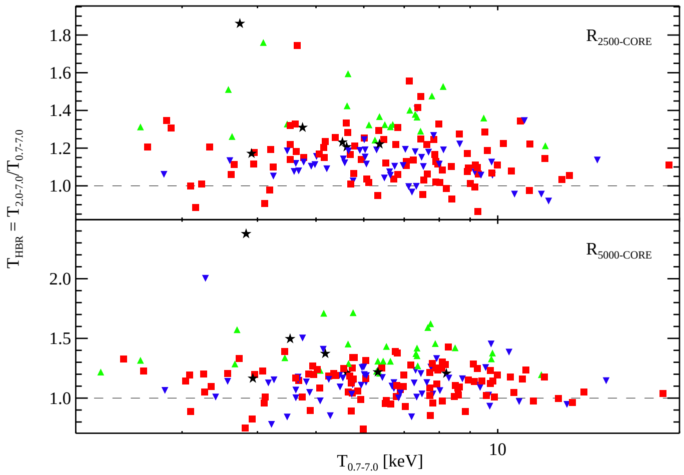

Figure 1: T_{HBR} vs. $T_{0.7-7.0}$. The dashed line is the line of equivalence. Symbols and color coding are based on two criteria: 1) presence of a cool core (CC) and 2) value of T_{HBR}. Black stars are clusters with a CC and T_{HBR} significantly greater than 1.1. Green upright-triangles are NCC clusters with T_{HBR} significantly greater than 1.1. Blue down-facing triangles are CC clusters and red squares are NCC clusters. It is found that most, if not all, of the clusters with $T_{HBR} \gtrsim 1.1$ are merger systems.

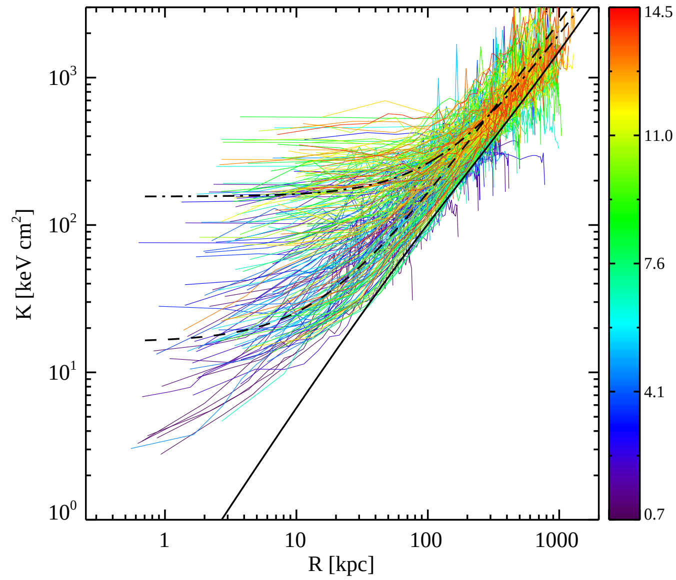

Figure 2: Composite plot of entropy profiles for archival sample. Profiles are color-coded based on average cluster temperature; units of the color bar are keV. The solid line is the pure-cooling model of Voit et al. 2002 [4], the dashed line is the mean profile for clusters with $K_0 \leq 50$ keV cm^2, and the dashed-dotted line is the mean profile for clusters with $K_0 > 50$ keV cm^2.

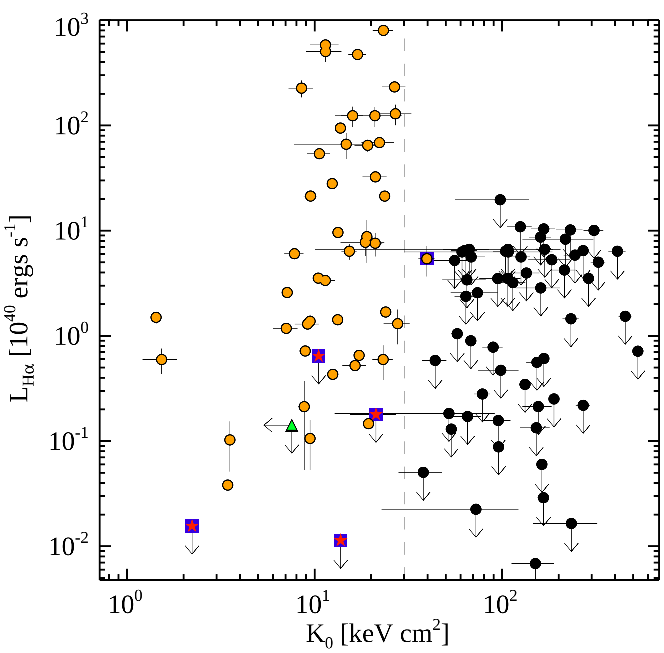

Figure 3: Central entropy vs. Hα luminosity. Orange circles represent Hα detections, black circles are non-detection upper limits, and blue squares with inset red stars or orange circles are peculiar clusters which do not adhere to the observed trend. The vertical dashed line marks $K_0 = 30$ keV cm^2. Note the presence of a sharp Hα detection dichotomy beginning at $K_0 \lesssim 30$ keV cm^2.

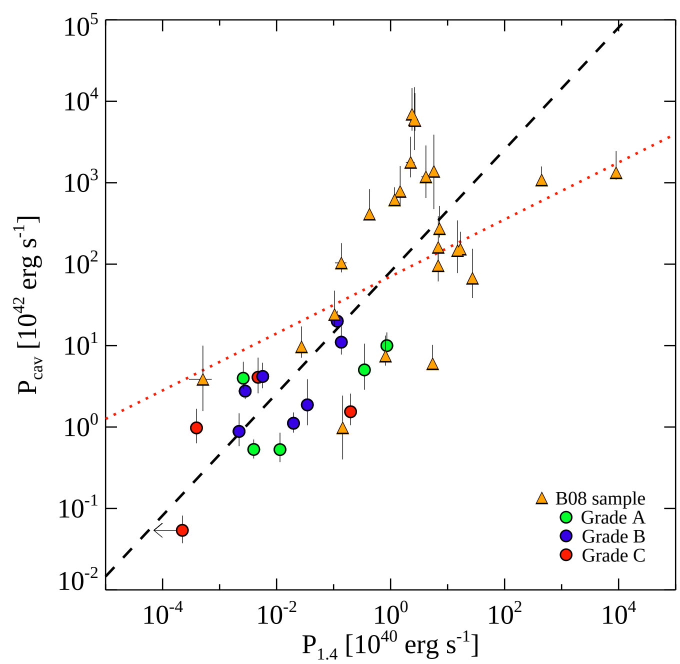

Figure 4: Cavity power vs. 1.4 GHz radio power. Orange triangles represent cluster and group sample of Bîrzan et al. 2008 [13], filled circles are our gE sample, colors represent the quality of cavities: green = 'A,' blue = 'B,' and red = 'C.' Dotted red lines represent Bîrzan et al. best-fit relations. Dashed black lines represent our BCES best-fit power-law relations.

MAPPING GALAXY CLUSTER MAGNETIC FIELDS: AN OBSERVATIONAL STUDY OF ICM PHYSICS

I. Motivation

Clusters of galaxies are the largest structures in the Universe to have reached dynamic equilibrium, and most cluster baryonic mass resides in the intracluster medium (ICM), a hot, dilute, weakly magnetized plasma filling a cluster's volume [1]. As the defining characteristic of the most massive objects in the Universe, the thermal properties of the ICM are well-known, but a similarly detailed description of ICM non-thermal properties – specifically diffuse cluster magnetic fields (CMFs) – and how they relate to the thermodynamic nature of the ICM remains elusive. Filling this gap in knowledge is vital because clusters help us constrain cosmological parameters [2], develop hierarchical structure formation models [3], and study the synergy of many physical processes to answer the question, "How does the Universe work?" [4].

At present, one of the biggest challenges in cluster studies is explaining the relative thermal equilibrium of the ICM. Many clusters have core ICM cooling times much less than a Hubble time, and it was hypothesized that these systems should host prodigious "cooling flows" [5]. But, only minimal mass deposition rates and cooling by-products have ever been detected, requiring that the ICM be heated [6]. Observational and theoretical studies have strongly implicated feedback from active galactic nuclei (AGN) in supplying the *energy* needed to regulate ICM cooling and late-time galaxy growth [7]. However, precisely how AGN feedback energy is thermalized and which processes comprise a complete AGN feedback loop remain to be fully understood [8].

Theoretical studies are now focused on coupling AGN feedback and ICM heating using combinations of anisotropic thermal conduction, cosmic ray diffusion, and subsonic turbulence [*e.g.* 9–17] after observations suggested the ICM is turbulent and conducting on small scales [*e.g.* 18–20]. These microphysical processes are intrinsically linked to macroscopic CMF topologies through gas viscosity and magnetohydrodynamic (MHD) instabilities [21, 22]. Thus, to observationally test and refine this theoretical framework, it is ideal to have uniform measurements of CMF strengths, orientations, and spatial distributions for large cluster samples spanning a broad range of evolutionary & dynamical states. Unfortunately, CMFs must be indirectly observed via induced synchrotron emission and imposed changes to polarization properties of background sources. Obtaining these detailed measurements was a complex task for the previous radio observatory generation because of the extreme sensitivity limits needed to detect faint emission and densely sample background sources [23], thus limiting our knowledge of CMF demographics to a few clusters [24]. Additionally, the lack of observations has inhibited the study of CMF origins and how much ICM pressure support they provide [25].

The *EVLA* radio observatory will change this situation by providing the unprecedented sensitivity, resolution, and frequency coverage required to study CMFs in a survey fashion [26]. **As a Jansky fellow, I propose to use radio polarimetry in conjunction with X-ray & optical imaging to map CMFs (magnitudes, orientations, 3D structure) and evaluate their relationship with ICM thermal properties (*e.g.* temperature, entropy, pressure) to constrain which physical mechanisms are responsible for the qualitative differences between observed and theoretical CMFs.** This work will 1) determine which microphysical processes significantly contribute to heating of the ICM by directly comparing the predictions of theoretical models with CMF observations, and 2) place constraints on the origin of CMFs and the cosmological implications of non-thermal pressure support on cluster mass estimates. The proposed project includes plans for an *EVLA* radio survey and NOAO optical Hα survey of two well-studied cluster samples, and incorporates an on-going pipeline analysis of an archive-limited sample of clusters having X-ray data.

II. Observations and Analysis

The *EVLA* Polarimetry Cluster Survey (EPiCS) will target the flux-limited HIFLUGCS [27] and representative REXCESS [28] cluster samples for which uniform *Chandra* and *XMM-Newton* X-ray data is available. EPiCS will utilize *EVLA*'s increased polarimetry bandwidth (8 GHz per polarization) and frequency accessibility (74 MHz; 330 MHz; full coverage 1–50 GHz) to obtain deep ($\sigma_{\rm rms} < 10\ \mu$Jy beam^{-1}) full Stokes observations of each cluster. The improved *EVLA* efficiency and dynamic range mean extended sources as faint as $\sim$2-3 μJy will be detected with integration times < 5 hrs, well into the regime where μG CMFs excite emission. One of *EVLA*'s two low-frequency (< 0.5 GHz) systems is now functioning, and EPiCS will be cross-calibrated with data from *LOFAR* to expand the utility of the dataset. The observations are designed to enable measurements of: 1) CMF strengths from Faraday rotation measures (RM) of previously undetected embedded & background cluster radio sources [see Fig. 1 and 29 for method], 2) CMF orientations from coherent polarized emission from orbiting cluster member galaxies [see Fig. 2 and 30 for method], and 3) CMF spatial distributions from low-surface brightness emission of radio halos [see 31 for method]. Combined with the archival X-ray data for each source, the following outstanding issues will be investigated.

A. Testing Models of ICM Heating: The EPiCS campaign will produce data of sufficient quality to measure RM dispersions, estimate CMF radial amplitude profiles, directly reconstruct CMF power spectra, and model 3D CMF structure using RM synthesis [see methods in 32–34]. Each of these CMF diagnostics will be directly compared with results from MHD models in the literature (see Fig. 3 for example) to determine which predictions are replicated (*e.g.* preferentially radial CMFs, CMF profile shapes, CMF magnitude–ICM $n_{\rm e}$ & $kT_{\rm X}$ correlations), which predictions indicate the input physics may be incomplete, and to help constrain which microphysical processes might participate in ICM heating. Since AGN feedback is the likely progenitor of heating, an investigation of possible correlations between CMF properties and feedback signatures (*e.g.* cluster core entropy, jet powers for systems with cavities, 2D thermal distributions, and extent of central AGN activity) will be undertaken. Further, turbulence is considered vital for promoting ICM heating, but is difficult to directly measure. However, secondary diagnostics (*e.g.* AGN outflows, mergers, cold fronts, shocks) may indicate the presence of turbulence even when the data is insufficient to do so. These indicators will be considered during the analysis to check if trends exist with CMF properties.

B. CMFs in Cluster Cores: It is hypothesized that the Hα filaments seen in almost all cool core clusters provide a local measure of CMF strength and orientation since they may form along field lines and be excited by some combination of turbulent mixing and conduction [35, 36]. To probe CMF configurations and conductive heating on kpc scales, below the reach of the radio observations, a uniform optical survey for extended Hα filaments in the EPiCS cluster samples will be undertaken using new NOAO instruments (*i.e.* Magellan Maryland Tunable Filter, WIYN HiRes IR Camera, SOAR Spartan IR Camera) [see 37, for method]. The observations will allow, for the first time, a complete characterization of filament morphologies and energetics to be compared with uniform ICM and CMF properties for the same objects. These observations will confront model predictions by answering the question, "Are filament energetics and morphologies consistent with them being magnetic structures conductively heated by the ICM?" Combined with the radio-derived CMF properties, inferences will also be drawn about if, and possibly how, large- and small-scale CMF properties are related (*e.g.* the coherence length). The model comparisons from Section A will also answer the questions: do filaments thrive in low-turbulence, high-magnetic field strength environs? Does this imply MHD instabilities are suppressed or inactive in some cluster cores?

C. Constraining CMF Origins and Non-thermal Pressure Support: Simply put, where do CMFs come from (*e.g.* amplified cosmic seed field? the Biermann battery process? AGN/galactic outflow seeding of protoclusters?), and are they dynamically important [38]? The EPiCS project will help address these questions. As the quantities most closely related to dynamo-driven CMF formation, I will investigate how redshift, halo concentration, and cluster mass relate to the derived CMF power spectra and radial profiles [39]. At a minimum, these comparisons will place limits on the strength and distribution of allowable seed field models, and may possibly suggest whether early- or late-time amplification processes dominate [40]. Deriving halo concentrations and cluster masses follow directly from the X-ray analysis already in-hand. However, cluster masses are traditionally derived by assuming the ICM is in hydrostatic equilibrium. If CMFs provide significant ICM pressure support, then cluster masses may be systematically overestimated, having interesting repercussions on cluster cosmological studies. Thus, cluster masses and the cluster mass function will be recalculated [*e.g.* 41] including terms for CMF pressure support determined from the EPiCS measurements. How cosmological parameter uncertainties depend on CMFs can then be determined. This exercise will be particularly interesting for the REXCESS sample which has high-quality hydrostatic mass estimates [42].

D. Archival Project and Legacy: Work has started on archival *Chandra* and *VLA* data to build the infrastructure needed to maximize the ultimate scientific impact of this project and produce initial results for an archive-limited sample of clusters. There are ≈ 450 clusters which have archival *Chandra* (≈ 900 observations) and *VLA* (≈ 1000 observations) data. Of these, 325 clusters have had the X-ray data reduced using an extensible and mature pipeline, while 50 of those clusters have had the multifrequency radio data reduced. The X-ray results are being kept in a public database[1] while the radio analysis continues. The on-going analysis entails production of 2D ICM temperature, density, pressure, & entropy maps, more radial profiles (*e.g.* effective conductivity, implied suppression factors), and refinement of the radio reduction pipeline. Removal of radio frequency interference (RFI) is among the longest steps in radio analysis, and to alleviate this tension, a python version of the 'RfiX' rejection algorithm [43] has been written and is being tested. To widen this proposal's scientific impact and relevance to future radio observatories (*e.g. LOFAR*, *LWA*, *SKA*), all code, software, and results will be made freely available to the research community.

III. Host Institution and Timeline

The University of Maryland (UMD) is an ideal host for this ambitious project as it boasts a team of experts well-suited to assist with this work. The UMD Astronomy Department, the Center for Research and Exploration in Space Science and Technology, and the Center for Theory and Computation are hosts to (to name but a few) Keith Arnaud, Tamara Bogdanović (current Einstein fellow), Michael Loewenstein, Craig Markwardt, Cole Miller, Richard Mushotzky, Eve Ostriker, Chris Reynolds (the sponsor), Massimo Ricotti, and Sylvain Veilleux. All those listed are experts in one, or several, of the areas of AGN feedback, ICM physics, computational modeling, magnetic field polarimetry, plasma physics, and X-ray/radio observing & analysis. In addition, UMD has close ties with the Naval Research Lab where Tracy Clarke and Namir Kassim are appointed – both experts in the radio techniques and science topics discussed here. **Year one:** Data acquisition begins, the archival project and tool development continue; I initiate a theoretical/simulation collaboration with the UMD plasma physics group to study new questions like: How do convective instabilities couple with ICM cooling and the actual accretion which drives AGN activity? What is the relation between these processes, ICM temperature & density, and thermal instability formation? **Year two:** Data acquisition continues, first round of archival-based results is published, and observation-model comparisons begin. **Year three:** Data acquisition and analysis of REXCESS conclude, second round of results published, and the investigation of CMF origins and non-thermal pressure support is underway.

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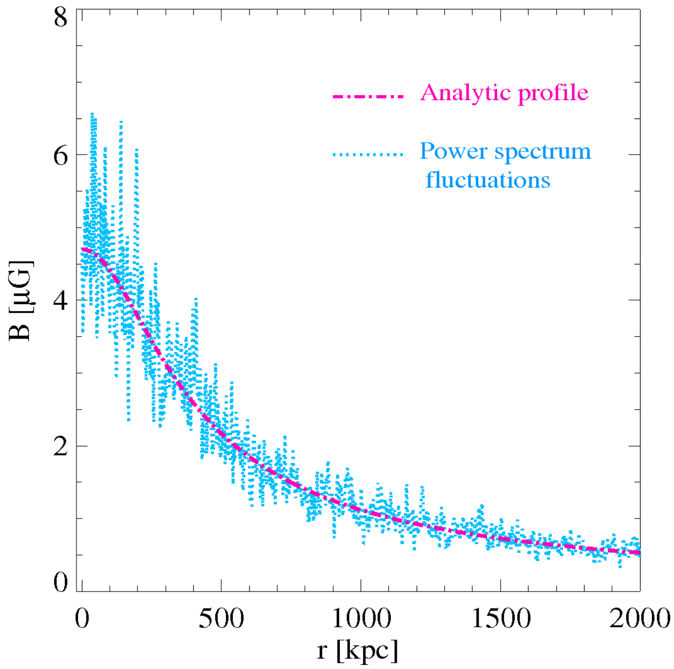

Figure 1: Radial profile and power spectrum of the Coma CMF derived from 3D simulations which reproduce observed RMs of embedded and background radio sources (taken from Bonafede et al. 2010 [29]). If one assumes the CMF and ICM thermal radial distributions trace each, then comparison of observed RM dispersions and 3D simulations lead to constraints like this on the CMF profile without the need to make measurements at every radius. One goal of this proposal is to expand upon the Bonafede et al. result using a larger cluster sample and EVLA observations.

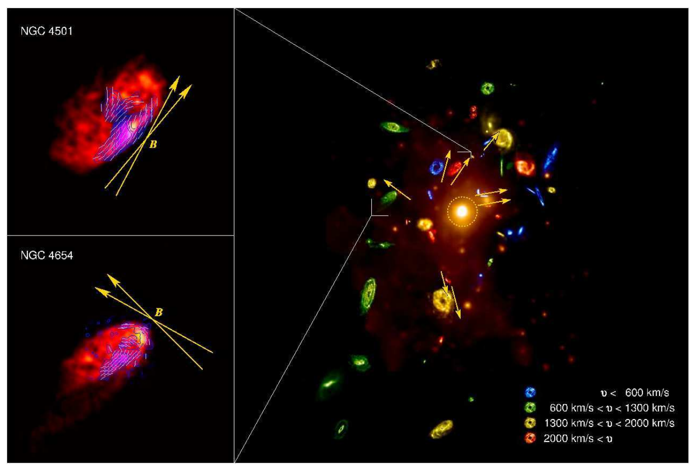

Figure 2: Virgo CMF orientations (yellow arrows) taken from Pfrommer & Dursi 2010 [30] where they argue draping of CMF lines at the ICM-infalling galaxy interface explains the CPE (left panel at 5 GHz). The CPE results from galactic cosmic rays gyrating around regularly compressed field lines. The authors argue the Virgo CMF is preferentially radial, consistent with the effects of a large-scale MHD convective instability [*i.e.* the MTI; 21]. Similar measurements are a key feature of the EPiCS project and will help us constrain CMF orientations as never before.

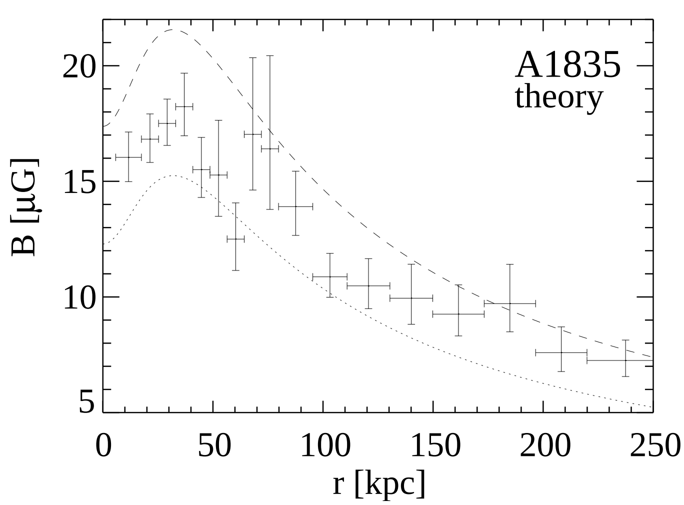

Figure 3: Predicted CMF strength of Abell 1835 from model of Kunz et al. 2010 [16] which heats the ICM *only* via viscous dissipation of turbulent ICM motions. The Kunz et al. model takes in X-ray derived ICM density and temperature measurements alone and returns estimates of field strengths. These profiles have already been derived for over 300 clusters using the *Chandra* archival project, and will be compared with the results of the EPiCS program (*e.g.* radial profiles and power spectra, like Fig. 1) to test how important turbulent heating is for an array of cluster types. This is one example of how the proposed CMF measurements will be directly compared with model predictions to aide theorists in refining models for ICM heating.

UNIVERSITY OF MARYLAND

Department of Astronomy

October 31, 2010

Jansky Fellow Selection Committee
National Radio Astronomy Observatory

Dear Colleagues:

I write in regard to the proposal by **Dr. Ken Cavagnolo** for a Jansky Fellowship to be hosted in the Department of Astronomy at the University of Maryland. Professor Chris Reynolds has agreed to serve as his scientific mentor at the University of Maryland. He and I have read and approved his proposal. Should he be offered the fellowship, we would be delighted to provide the facilities and support needed to enable the research activities described in his proposal.

As noted in Dr. Cavagnolo's proposal, there is considerable expertise at Maryland in related areas. He would work closely with Prof. Chris Reynolds, who has overlapping interests. We have recently formed the Joint Space-Sciences Institute (JSI); its first focus is high-energy astrophysics and indeed the first JSI hire was Prof. Richard Mushotzky, one of the most prolific high-energy astronomers in the world and noted expert on clusters of galaxies. Other scientists associated with Maryland with very close interests include Tamar Bogdanovic, Sylvain Veilleux, and Keith Arnaud. He would also connect with our Center for Theory and Computation (CTC) is a highly interactive group of faculty, postdocs, and students; Dr. Cavagnolo would have access to the Beowolf cluster operated by the group.

Also, Neal Miller (former Jansky Fellow) is on our staff and is expert in VLA studies of clusters. In addition, the faculty and staff of our Laboratory for Millimeter-wave Astronomy has considerable expertise in radio interferometry. Finally, staff at NRL successfully supervise our graduate students, and so I am confident that Dr. Cavagnolo would be able to work closely with the NRL scientists identified in his proposal, Dr. Tracy Clarke and Dr. Namir Kassim.

In summary, Dr. Cavagnolo's research program closely aligns with ongoing efforts in our astronomy department. We would be happy to host him at Maryland and mentor his program.

Sincerely yours,

Stuart M Vogel

Stuart Vogel
Professor & Chair
Department of Astronomy