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.

[1] http://www.pa.msu.edu/astro/MC2/accept/

IV. References

[1] C.L. Sarazin. *Reviews of Modern Physics*, 58:1–115, Jan. 1986.
[2] G.M. Voit. *Reviews of Modern Physics*, 77:207–258, Apr. 2005.
[3] J.F. Navarro et al. *MNRAS*, 275:56–66, Jul. 1995.
[4] Proceedings of *Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution*, 2004.
[5] A.C. Fabian. *ARA&A*, 32:277–318, 1994.
[6] J.R. Peterson & A.C. Fabian. *Phys. Rep.*, 427:1–39, Apr. 2006.
[7] B.R. McNamara & P.E.J. Nulsen. *ARA&A*, 45:117–175, Sept. 2007.
[8] D.S. De Young. *ApJ*, 710:743–754, Feb. 2010.
[9] S. Heinz et al. *MNRAS*, 373:L65–L69, Nov. 2006.
[10] G.M. Voit et al. *ApJ*, 681:L5–L8, Jul. 2008.
[11] F. Guo et al. *ApJ*, 688:859–874, Dec. 2008.
[12] P. Sharma et al. *ApJ*, 699:348–361, Jul. 2009.
[13] T. Bogdanović et al. *ApJ*, 704:211–225, Oct. 2009.
[14] I.J. Parrish et al. *ApJ*, 712:L194–L198, Apr. 2010.
[15] M. Ruszkowski & S.P. Oh. *ApJ*, 713:1332–1342, Apr. 2010.
[16] M.W. Kunz et al. *arXiv e-prints: 1003.2719*, Mar. 2010.
[17] M. Ruszkowski et al. *arXiv e-prints: 1010.2277*, Oct. 2010.
[18] L.M. Voigt & A.C. Fabian. *MNRAS*, 347:1130–1149, Feb. 2004.
[19] K.W. Cavagnolo et al. *ApJ*, 683:L107–L110, Aug. 2008.
[20] E.T. Million et al. *MNRAS*, 407:2046–2062, Oct. 2010.
[21] S.A. Balbus. *ApJ*, 534:420–427, May 2000.
[22] E. Quataert. *ApJ*, 673:758–762, Feb. 2008.
[23] T.E. Clarke et al. *ApJ*, 547:L111–L114, Feb. 2001.
[24] F. Govoni et al. *arXiv e-prints: 1007.5207*, Jul. 2010.
[25] D. Grasso & H.R. Rubinstein. *Phys. Rep.*, 348:163–266, Jul. 2001.
[26] C. Ferrari et al. *Space Science Reviews*, 134:93–118, Feb. 2008.
[27] T.H. Reiprich. PhD thesis, Jul. 2001.
[28] H. Böhringer et al. *A&A*, 469:363–377, Jul. 2007.
[29] A. Bonafede et al. *A&A*, 513:A30+, Apr. 2010.
[30] C. Pfrommer & L. Jonathan Dursi. *Nature Physics*, 6:520–526, Jul. 2010.
[31] U. Keshet & A. Loeb. *ApJ*, 722:737–749, Oct. 2010.
[32] C. Vogt & T.A. Enßlin. *A&A*, 412:373–385, Dec. 2003.
[33] M. Murgia et al. *A&A*, 424:429–446, Sept. 2004.
[34] M.A. Brentjens & A.G. de Bruyn. *A&A*, 441:1217–1228, Oct. 2005.
[35] P. Sharma et al. *ApJ*, 720:652–665, Sept. 2010.
[36] N. Werner et al. *MNRAS*, 407:2063–2074, Oct. 2010.
[37] M. McDonald et al. *ApJ*, 721:1262–1283, Oct. 2010.
[38] C.L. Carilli & G.B. Taylor. *ARA&A*, 40:319–348, 2002.
[39] J. Donnert et al. *MNRAS*, 392:1008–1021, Jan. 2009.
[40] K. Dolag et al. *A&A*, 387:383–395, May 2002.
[41] A. Vikhlinin et al. *ApJ*, 692:1060–1074, Feb. 2009.
[42] M. Arnaud et al. *A&A*, 517:A92+, Jul. 2010.
[43] R. Athreya. *ApJ*, 696:885–890, May 2009.

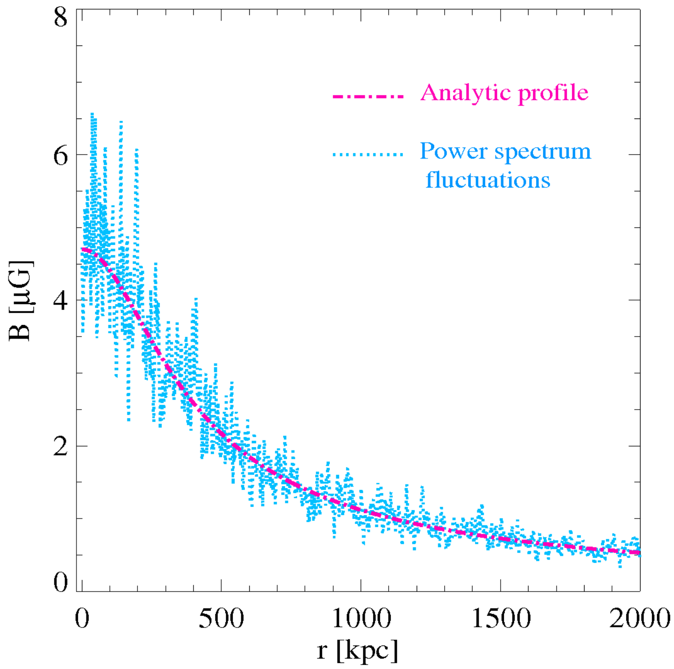

Figure 1: Radial profile and power spectrum of the Coma CMF derived from 3D simulations which reproduce observed RMs of embedded and background radio sources (taken from Bonafede et al. 2010 [29]). If one assumes the CMF and ICM thermal radial distributions trace each, then comparison of observed RM 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.

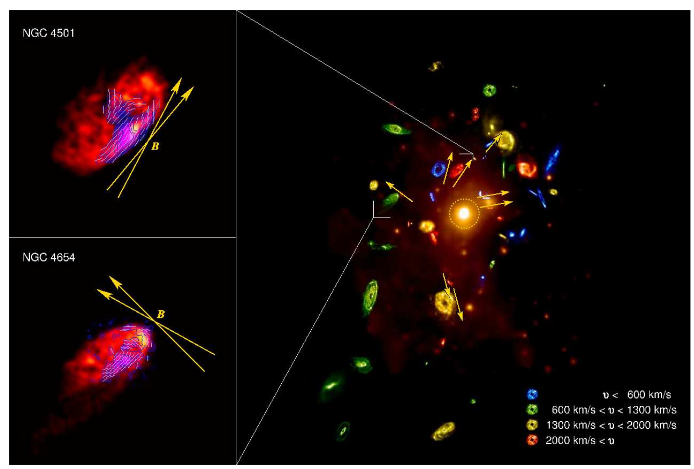

Figure 2: Virgo CMF orientations (yellow arrows) taken from Pfrommer & Dursi 2010 [30] where they argue draping of CMF lines at the ICM-infalling galaxy interface explains the CPE (left panel at 5 GHz). The CPE results from galactic cosmic rays gyrating around regularly compressed field lines. The authors 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.

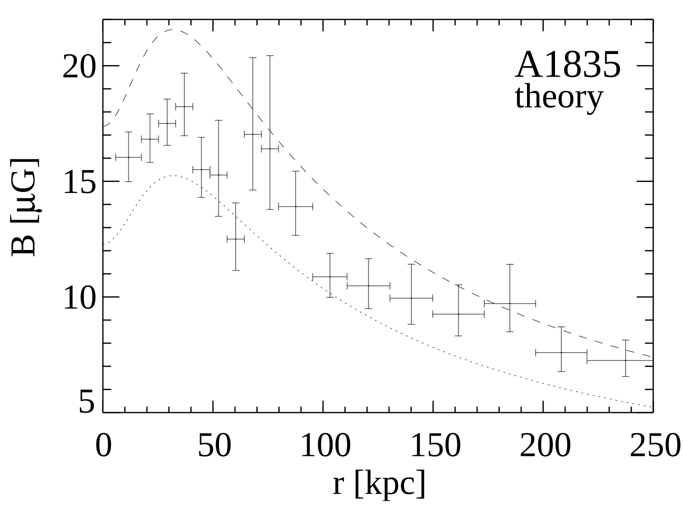

Figure 3: Predicted CMF strength of Abell 1835 from model of Kunz et al. 2010 [16] which heats the ICM *only* via viscous dissipation of turbulent ICM motions. The Kunz et al. model takes in X-ray derived ICM density and temperature measurements alone and returns estimates of field strengths. These profiles 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.