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 the cluster 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, the strength & structure of CMFs must be measured in detail for large samples of clusters spanning a broad-range of evolutionary & dynamical states and then compared with model predictions (see Figs. 1–3 for individual examples). Unfortunately, measuring CMF properties is notoriously difficult [*e.g.* 23], which has limited our knowledge of CMF demographics to a handful of clusters [*e.g.* 24]. Additionally, there is no consensus on 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 detect the faint ICM synchrotron emission and numerous, weak radio sources needed to probe CMFs [26]. **As a Jansky fellow, I propose to use radio polarimetry in conjunction with optical & X-ray imaging to map CMFs (magnitudes, orientations, power spectra, 3D structure) and evaluate their relationship with ICM thermal properties (*e.g.* temperature, entropy, pressure).** 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 radio and 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 the increased polarimetry bandwidth and frequency accessibility of *EVLA* to obtain uniform, deep ($\sigma_{\rm rms} \lesssim 10\ \mu$Jy beam^{-1}) full Stokes continuum observations of each cluster. The observations will enable measurements of: 1) rotation measures (RM) of embedded & background radio sources [see 29, for method], 2) coherent polarized emission (CPE) from orbiting cluster member galaxies [see 30, for method], and 3) low-surface brightness polarized emission associated with synchrotron halos [see 31, for method]. Combined with the archival X-ray data for each source, the following outstanding issues regarding the relation between CMFs and the ICM will be investigated.

A. Testing Models of ICM Heating: The EPiCS campaign will produce data of sufficient quality to estimate CMF radial amplitude profiles, directly reconstruct CMF power spectra, and model 3D CMF structure using RM synthesis [methods in 32–34]. Numerous MHD models make predictions regarding the CMF strengths and configurations (*e.g.* being preferentially radial, declining in strength with radius) and each of the above properties will be directly compared with these models to determine which input physics are replicated and which are incomplete. This will help address which microphysical processes participate in heating the ICM. Since AGN feedback is the likely progenitor of heating, I will also investigate possible correlations between CMF properties and signatures of feedback and heating such as the cool/non-cool core dichotomy, jet powers for systems with cavities, 2D thermal distributions, and central AGN activity. 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 & ICM 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 scales of tens of kpc, 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 magnetic structures being 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, and are they dynamically important? Just like ICM heating, this question has been addressed extensively in the theoretical domain, but poorly observationally because we lack samples of CMF measurements. The most prevalent hypotheses for CMF origins are a cosmic seed field amplified as structure forms, the Biermann battery process, and protocluster seeding by AGN or galactic outflows [38]. The CMF strength & structure measurements determined in this project are relevant to tackling these issues. 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 the extent to which dynamo processes dominate over secondary processes like late-time turbulent amplification [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 a significant amount of this support, then cluster mass estimates may be overestimated – though lensing and X-ray derived masses tend to agree – which would have 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. Tool and Software Development: 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 lengthiest steps in radio analysis, and to allevaite this tension, a python version of the 'RfiX' rejection algorithm [43] has been written and is being tested. To widen this proposal's impact, all code, software, and results produced will be made freely available to the research community.

III. Host Institution and Timeline

The University of Wisconsin-Madison (UW) is an ideal host for this project. The proposed work is ambitious, requiring a team of observational & theoretical experts to interpret the data, distribute results, and propose new projects motivated by this work. The UW Astronomy and Physics Departments, Center for Plasma Theory & Computation, and the Center for Magnetic Self-Organization are hosts to (to name but a few) Sebastian Heinz (the sponsor), Alex Lazarian, Leonid Malyshkin, Dan McCammon, Eric Wilcots, and Ellen Zweibel, all of whom are experts in one, or several, of the areas of AGN feedback, computational modeling, magnetic field polarimetry, plasma physics, and X-ray instrumentation. At UW I will have access to this broad community of experts whom can provide invaluable expertise in evaluating and interpreting the observational results. UW is also part of the Great Lakes network of institutions (*e.g.* MSU, UM, OSU, UMinn, UChicago) which have groups actively involved in the topics of this proposal. And it cannot be ignored that UW and MSU have guaranteed time on the WIYN and SOAR telescopes, which will be used over the course of this project.

In year one of the fellowship: radio and optical data acquisition will begin, the archival project will continue, and tool development will proceed. I will initiate a collaboration with the plasma physics group and help determine the best strategy for executing new simulations to probe 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 and the ICM temperature and density profiles? In year two: data acquisition will continue, the first round of results using archival data will be published, and comparisons between observations and model predictions will begin. In year three,

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

data acquisition and analysis for the REXCESS sample will conclude, a second round of results will be published, and the investigation of CMF origins and non-thermal pressure support will be underway.

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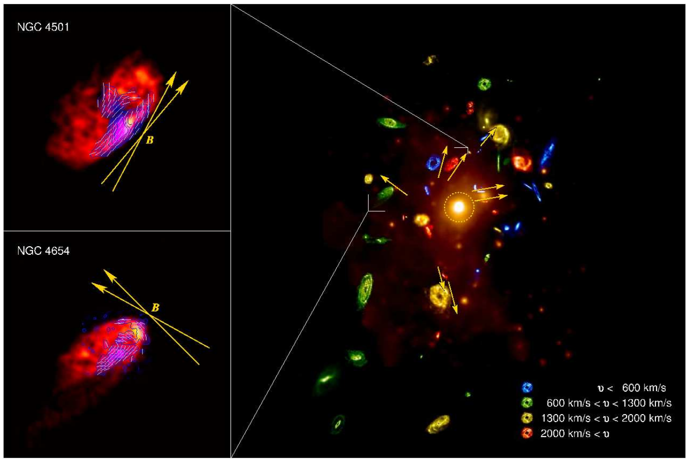

Figure 1: Virgo CMF orientations (yellow arrows) taken from Pfrommer & Dursi 2010 [30] where they argue draping of CMF lines at the ICM-infalling galaxy interface explains the coherent polarized emission (CPE; left panel at 5 GHz). The CPE results from galactic cosmic rays gyrating around regularly compressed 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.

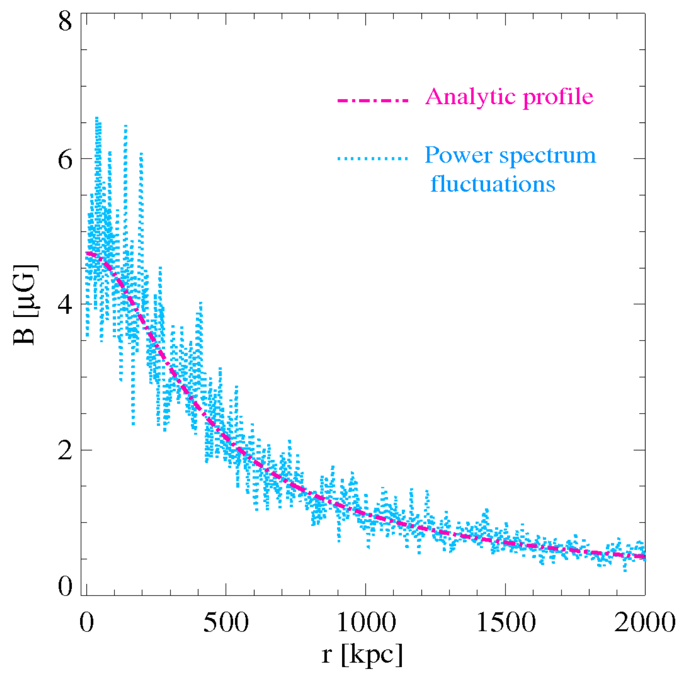

Figure 2: Radial profile and power spectrum of the Coma CMF derived from 3D simulations which reproduce the observed rotation measures (RMs) of embedded and background radio sources (taken from Bonafede et al. 2010 [29]). If one assumes the CMF and ICM thermal radial distributions trace each, then comparison 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.

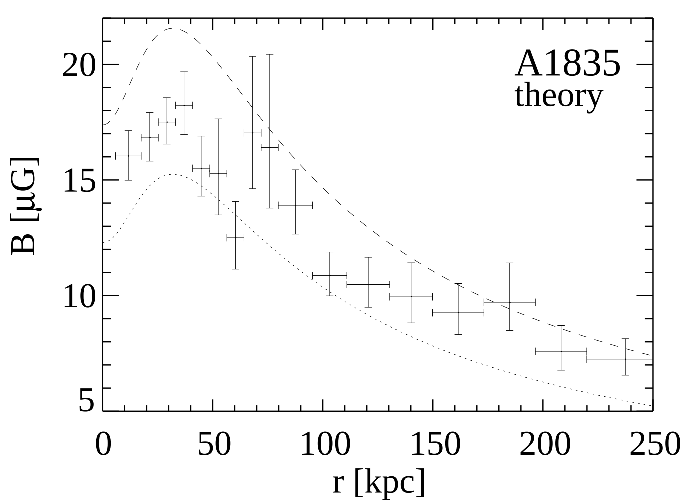

Figure 3: Predicted CMF strength of Abell 1835 from model of Kunz et al. 2010 [16] which heats the ICM *only* via viscous dissipation of turbulent ICM motions. The Kunz et al. model takes in X-ray derived ICM density and temperature measurements alone and returns estimates of field strengths. These profiles have already been derived for over 300 clusters using the *Chandra* archival project, and will be compared with the results of the EPiCS program (see Fig. 2) 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.

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