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FARADAY ROTATION OBSERVATIONS OF MAGNETIC FIELDS IN GALAXY CLUSTERS

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ABSTRACT

The presence of magnetic fields in the intracluster medium in clusters of galaxies has been revealed through several different observational techniques. These fields may be dynamically important in clusters as they will provide additional pressure support to the intracluster medium as well as inhibit transport mechanisms such as thermal conduction. Here, we review the current observational state of Faraday rotation measure studies of the cluster fields. The fields are generally found to be a few to 10 μG in non-cooling core clusters and ordered on scales of $10-20$ kpc. Studies of sources at large impact parameters show that the magnetic fields extend from cluster cores to radii of at least 500 kpc. In central regions of cooling core systems the field strengths are often somewhat higher ($10-40$ μG) and appear to be ordered on smaller scales of a few to 10 kpc. We also review some of the recent work on interpreting Faraday rotation measure observations through theory and numerical simulations. These techniques allow us to build up a much more detailed view of the strength and topology of the fields.

Key words : clusters of galaxies – magnetic fields – Faraday rotation

I. INTRODUCTION

Magnetic fields are common to nearly all astrophysical phenomena, thus it is not surprising to find that they are an important constituent of galaxy clusters, and therefore a major topic for this meeting. Intracluster magnetic fields provide an additional form of pressure support to the cluster gas, as well as inhibiting transport processes such as cosmic ray propagation and thermal conduction in the cluster. The presence of intracluster magnetic fields has been established through a number of observational approaches. This paper concentrates on Faraday rotation measure (RM) observations of the magnetic fields, mainly on the observational status of the RM studies, although we also briefly summarize some of the important work on modeling the fields in the intracluster medium (ICM) based on RM observations. Other techniques to study the intracluster magnetic fields are presented elsewhere in these proceedings. For detailed recent reviews of intracluster magnetic fields, the reader is referred to Govoni & Feretti (2004), Clarke (2003), Carilli & Taylor (2002), Widrow (2002), and Kronberg (1994).

II. FARADAY ROTATION MEASURE OVERVIEW

One of the most direct measurements of intracluster magnetic fields is through the effect of the fields on the propagation of linearly polarized radiation. As the polarized emission from a radio source passes through a magnetized, ionized plasma, the plane of polarization will be rotated due to the different phase velocities of the two opposite-hand polarization modes. This Faraday rotation effect will rotate the intrinsic position angle of the emission by an addition term given by the rotation measure (RM):

$$RM = 811.9 \int_0^L n_{\rm e} B_{\|} d\ell \quad {\rm rad/m}^2 \qquad (1)$$

where $n_{\rm e}$ is the electron density in cm^{-3}, B is the line of sight magnetic field strength in μG, and L is the path length through the Faraday rotating medium in kpc. The change in position angle of the radiation can be written as:

$$\Delta\chi = \chi - \chi_0 = RM\,\lambda^2 \;\; {\rm radians} \qquad (2)$$

where χ is the observed position angle at wavelength λ and χ_0 is the intrinsic position angle of the polarized emission. Faraday rotation measure studies require observations at three or more wavelengths in order to remove the $n\pi$ ambiguity resulting from the fact that measured position angle is only a pseudo-vector lying in the range of $0 < \chi < \pi$ radians. The measurements of this angle are uncertain by $\pm n\pi$ due to the unknown number of half rotations of the polarization angle between the source and observer. By carefully selecting a set of observational wavelengths, it is possible to remove the ambiguities and determine accurate rotation measures. A more detailed discussion of the $n\pi$ ambiguities is given by Ruzmaikin & Sokoloff (1979).

The observed rotation measure is a linear sum of all contributions along the line of sight between the radio source and the observer. Contributions to the observed RM are mainly limited to the region local to the radio

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source, the intracluster medium, and the Milky Way galaxy. Since it is the cluster contribution which we are interested in, it is important to understand (and limit) the contributions from the other sources of Faraday rotation. The Galactic rotation measure has been studied by many authors, including a recent study by Frick et al. (2001). In general, these studies find that the Galactic contribution to the RM can be up to a few hundred radians m^{-2} at low galactic latitudes, but this contribution quickly drops to the level of a few radians m^{-2} above a Galactic latitude of $\sim 20°$. The contribution local to the source appears to be generally small based on observations such as the Laing-Garrington effect where the more distant radio lobe is more depolarized than the lobe pointing toward us (Laing 1988, Garrington et al. 1988, 1991), as well as the radial trend seen in statistical Faraday studies (see § IV), and the results of gradient alignment statistics (Enßlin et al. 2003). For observations limited to high Galactic latitudes, the majority of the observed Faraday rotation for sources viewed through galaxy clusters will be contributed by the intracluster magnetic fields.

An estimate of the magnetic field strength from Equation 1 requires some assumptions to be made about the geometry of the intracluster fields. The simplest case would be a uniform slab geometry where both the direction and strength of the magnetic field are constant through the cluster medium. This geometry provides a lower limit on the magnetic field strength. As discussed in § III, Faraday maps of extended sources often show fluctuations on scales much smaller than the radio source extent. An alternative approach to the field topology is to assume that the cluster is composed of cells of uniform strength but random field orientation along the line of sight. Generally the magnetic field scale length for this tangled cell model is taken to be the observed RM fluctuation scale. Note, however, that recent work by Enßlin & Vogt (2003) and Vogt & Enßlin (2003) has shown that the RM fluctuation scale overestimates the true field coherence length, and hence underestimates the field strength in this simple model.

III. EXTENDED AND POLARIZED RADIO SOURCES

(a) Faraday Mapping

Details on the topology of the Faraday rotating medium require high resolution Faraday mapping of extended, polarized radio sources. The majority of these studies have been undertaken for extended sources embedded in the cores of cooling flow clusters (Ge & Owen 1993, 1994; Taylor & Perley 1993; Taylor, Fabian, & Allen 2002).

One of the first objects targeted for high resolution Faraday studies was Cygnus A located in the core of a dense cluster. Dreher, Carilli & Perley (1987) found large rotation measure gradients of up to 600 radians

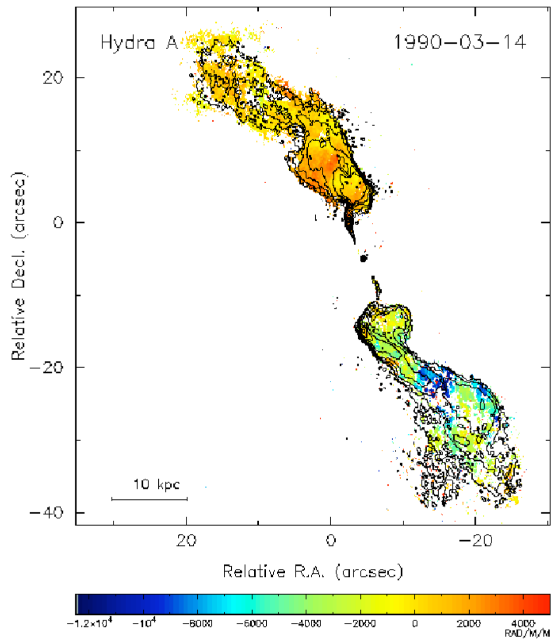

Fig. 1.— Faraday rotation measure map of Hydra A in color with total intensity contours overlaid (Taylor & Perley 1993). The northern lobe is mainly positive (field toward observer) while the southern lobe is mainly negative (field away from observer) indicating organized structures on scales of 50 kpc. The map also shows small scale fluctuations on scales of $5-10$ kpc, indicating the presence of a tangled field component.

m^{-2} across the lobes of the radio galaxy, conclusively ruling out the possibility of a Galactic origin to the RMs. Perhaps more important was the fact that they found the position angle varied by more than π radians and was well fit to a λ^2 relation over a very large range of frequencies. Combining that with the fact that the polarization fraction remained constant over the region allowed them to rule out the possibility that the RMs were due to thermal gas mixed into the radio emitting plasma. These were the first observations to conclusively show that the observed RMs must be coming mainly from an external Faraday screen which could not be Galactic. After an analysis of a number of possibilities, Dreher et al. (1987) concluded that the most likely origin for the RMs was the intracluster medium. Based on simple assumptions of field topology, they estimate the intracluster magnetic field strength to be $2-10$ μG for this cluster.

Observations of Hydra A by Taylor & Perley (1993) show mainly positive RMs in the northern lobe and negative values across the southern lobe (Figure 1). This RM structure requires a field geometry that is ordered on scales of 50 kpc in the cluster. The Faraday map of Hydra A also shows small scale fluctuations (scale of $5-10$ kpc) superimposed on the lobes. Based on these observations Taylor & Perley (1993) estimate the uniform component of the field to be ~ 7 μG and the

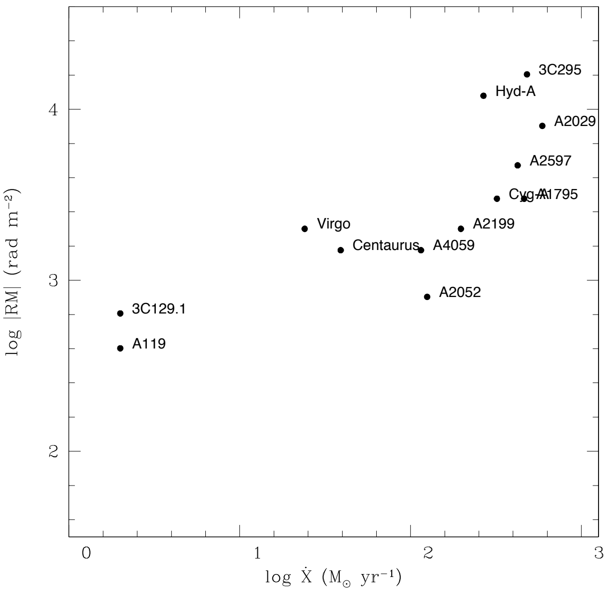

Fig. 2.— Plot of maximum absolute rotation measure as a function of the cluster cooling rate from Taylor, Fabian, & Allen (2002). They point out that all known high rotation measure sources at z < 0.4 are included in this sample. These data are also consistent with all radio sources embedded in cooling core clusters having extreme RMs.

tangled component to be ~ 40 μG.

More generally, the Faraday studies of cooling core sources find very high rotation measures ($|RM| > 800$ rad/m^2), with the magnitude of the RMs appearing roughly proportional to the cooling flow rate ($\dot{X}$) (Taylor et al. 2002). This correlation (shown in Figure 2) is expected as both the RM and $\dot{X}$ depend on the electron density to positive powers. The RM fluctuations seen in maps of cooling core clusters are on scales of a few to 10 kpc, resulting in a tangled cell estimate of $10-40$ μG (Carilli & Taylor 2002).

Extended, polarized radio sources have also been studied in non-cooling core clusters. Eilek & Owen (2002) studied the RM properties of 3C 75 in the core of Abell 400, and 3C 465 in the core of Abell 2634. Both radio sources extend > 100 kpc in the cluster cores and were observed with resolutions ~ 2 kpc. The Faraday maps show patches of RM fluctuations on scales of order $10-20$ kpc. If this scale is taken to be the tangled magnetic field reversal scale, Eilek & Owen estimate that the cluster core magnetic field strength is in the range of $1-4$ μG.

A more detailed picture of magnetic fields in a single cluster can be obtained by mapping several polarized radio sources viewed at different impact parameters to the cluster core. In Abell 119, Feretti et al. (1999) studied the rotation measures of 3 extended polarized sources located within the cluster at impact parameters of 115, 300, 1010 kpc. Overall they found that the magnitude of the maximum RM, the dispersion in the RM, and the depolarization at long wavelengths all decrease with increasing distance from the cluster center. This is consistent with the idea that the Faraday screen in front of the sources is tangled on small scales (< 4 kpc) in the central regions of the cluster. From a tangled cell analysis they estimate the magnetic field strength to be in the range of $12-17$ μG, although they note that such a field strength is unlikely for the source at the largest impact parameter as the magnetic pressure would exceed the thermal pressure in this region. Indeed, a re-analysis of the Abell 119 data by Dolag et al. (2001) finds that the fields scale as $n_e^{0.9}$, significantly steeper than the $n_e^{0.5}$ expected for constant scaling between the thermal and magnetic pressures in the ICM.

(b) Theory and Simulations

Recently, significant effort has been put into extending the analysis of Faraday maps beyond the uniform slab and tangled cell models described above. Detailed cosmological simulations including magnetic fields are discussed elsewhere in these proceedings by Dolag. Here, we concentrate on a brief description of methods that are being applied to observational Faraday maps.

Enßlin & Vogt (2003) describe the details of a real space and Fourier space analysis of high resolution Faraday rotation measure maps. Using the techniques they describe, they are able to to determine the strength, energy spectrum, and magnetic field autocorrelation length (λ_B) from observational data. They find that λ_B can differ from the (observed) RM fluctuation scale that is commonly equated to the magnetic field scale length. In a typical astrophysical plasma they find that the RM scale length is generally larger than λ_B, thus the field strengths may be underestimated in the simple tangled cell model. Vogt & Enßlin (2003) applied their techniques to Faraday maps of 3C 75, 3C 465, and Hydra A, and found that the RM fluctuation scale is generally $2-4$ times larger than λ_B for these sources. They determine magnetic to thermal pressures between 1% and 20% in the cores of these clusters, and conclude that the magnetic fields may have an impact on the cluster dynamics. The reader is referred to the contribution by Vogt & Enßlin in these proceedings for further details.

Improvements in the modeling of the intracluster magnetic fields have also been made recently. Work by Murgia et al. (2004) has applied Monte Carlo methods to simulate random 3D magnetic fields in clusters. They select systems which contain details of the polarization structure of several radio galaxies viewed through the cluster and, in some cases, clusters which also have information on the total intensity distribution of diffuse radio halos. They study the different power spectrum spectral indices to determine what value provides the best fit to the polarization characteristics of the sources as well as the surface brightness distribution and polarization limits of the diffuse radio halo emission if applicable. Based on their analysis of Abell 119, they find mean intracluster magnetic field strengths of 2 μG are required to reproduce the observed RM structure of the embedded sources. Murgia et al. (2004) also find that the data require a relatively flat power spectrum of $n = 2$, indicating that much of the magnetic field energy density is on small scales in the intracluster medium. They also find that the field analysis using the power spectrum results in a field strength that is a factor of roughly 2 lower than that obtained from the standard RM fluctuation scale analysis.

IV. STATISTICAL FARADAY STUDIES

Ideally, the radial distribution of the strength and topology of intracluster magnetic fields would be studied on an individual cluster basis with a large number of Faraday probes at different cluster impact parameters. Unfortunately, the analysis of a large number of clusters with many RM probes per cluster is currently unfeasible due to the sensitivity limits of available radio telescopes. An alternative approach to studying the distribution of intracluster magnetic fields is to obtain the RM for a number of probes viewed through a carefully selected sample of galaxy clusters. By choosing a sample of clusters with similar characteristics (e.g. the lack of a central cooling core), a statistical approach can be taken to study the magnetic fields. In addition to the Faraday observations, the statistical analysis requires details of the distribution of the thermal gas in each cluster. Until recently, this type of analysis was difficult due to a paucity of X-ray data required to obtain individual electron density measurements for the target clusters. Statistical studies such as those by Lawler & Dennison (1982) or Kim, Tribble, & Kronberg (1991) used average properties over a sample of clusters to determine the electron density distribution as many of the systems under study did not have X-ray observations available. This approach is not ideal since the clusters covered a very large range of richness and morphology, thus the true electron density along a line of sight could be significantly different from the assumed universal profile. The era of sensitive, long-lived X-ray satellites such as *ROSAT*, *Chandra* and *XMM* is now providing the necessary details of individual cluster electron density distributions for determining the magnetic field strength along individual sight-lines through a large number of galaxy clusters.

The first large statistical Faraday study to obtain individual electron density profiles toward each target cluster was undertaken by Clarke, Kronberg, & Böhringer (2001). Their study contained 16 low redshift clusters which were selected to have bright ($L_x > 5 \times 10^{42}$ ergs s^{-1}), extended X-ray emission in the ROSAT $0.1-2.4$ keV band. The cluster sample was further limited to high Galactic latitudes ($|b| \geq 20°$) to avoid contamination by the Galactic magnetic field, low redshift ($z \leq 0.1$) to provide a large angular extent on the sky for obtaining RM probes, and each cluster was required to contain at least one linearly polarized radio source viewed through the X-ray emitting ICM. In addition to these *cluster* probes viewed through the ICM, a second set of polarized *control* sources was observed toward each cluster at impact parameters beyond the detectable X-ray emission in order to help determine the Galactic contribution in the direction of each cluster. Target radio sources were further constrained to provide sight-lines probing a large range of cluster impact parameters in order to investigate the radial extent of intracluster magnetic fields. Radio sources in the *cluster* and *control* samples were observed with the NRAO VLA at four to six wavelengths each within the 20 and 6 cm bands. The observing wavelengths were selected to provide unambiguous RMs within the range $|RM| \leq 2600$ rad m^{-2}. X-ray observations of each cluster were retrieved from the ROSAT Data Archive. Thirteen of the clusters were observed in Pointed Observation mode, while the remaining three clusters were extracted from the ROSAT All-Sky Survey (RASS) archive. Details of the cluster sample including radio and X-ray reductions are presented in Clarke et al. (2001).

The distribution of Faraday rotation measures (corrected for the Galactic rotation measure contribution) is shown in Figure 3. This figure clearly shows a broad-

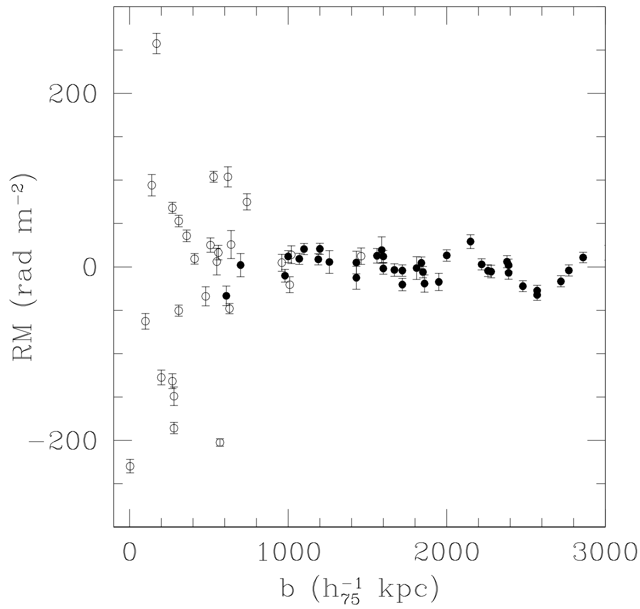

Fig. 3.— Rotation measure (corrected for the Galactic contribution) plotted as a function of source impact parameter in kiloparsecs for 16 clusters from Clarke et al. (2001). Open points are the *cluster* probes while filled points show the *control* sample. Note the clear increase in the width of the RM distribution toward smaller impact parameter, indicating the presence of intracluster magnetic fields.

ening of the RM distribution toward small impact parameter, consistent with excess Faraday rotation in the cluster sample out to impact parameters of more than 500 kpc. Using a simple uniform slab model for the cluster field provided lower limits on the field estimates of $0.5 - 3.0$ μG. Analysis of several extended radio sources in the sample revealed RM fluctuation scales of order $10 - 20$ kpc, resulting in tangled cell field estimates of $5 - 10$ μG.

Statistical studies also allow us to address the question of the location of the Faraday rotating medium. Although the majority of the observational evidence points toward fields located in the intracluster medium (Carilli & Taylor 2002), a contribution from a region local to embedded radio sources cannot be completely ruled out (Bicknell, Cameron, & Gingold 1990, Rudnick & Blundell 2003, Rudnick these proceedings; but also see Carilli & Taylor 2002, and Enßlin et al. 2003). Clarke et al. (in preparation) have expanded the statistical Faraday sample to include high redshift background radio probes viewed through low redshift clusters. Although redshifts are not available for all targets, it is possible to tag individual sources as possible clusters members or background sources based on the Second Generation Palomar Survey images. For each candidate which did not have a redshift, a source was only labeled background if all candidate optical counterparts would have $M_R > -21$ if they were at the redshift of the cluster (F. Owen, private communication). In fact, all unidentified sources would have $M_R > -19.5$ if they were cluster members, thus their identification as background sources is expected to be reliable. This approach to separating embedded and background probes is conservative, and will likely overestimate the number of embedded sources. The F-test rejects the null hypothesis of similar variances for the embedded (or background) and control samples, thus indicating that both the embedded and background samples are seeing excess intracluster Faraday rotation.

Using the identification techniques described above, additional Faraday probes from the sample of Kim, Tribble, & Kronberg (1991) can be added to the Clarke et al. (2001) sample to obtain a combined data set shown in Figure 4. Applying the Kolmogorov-Smirnov test on the combined samples rejects the null hypothesis of the sources being drawn from the control sample at $> 99.7\%$ for the background sample and $> 99.9\%$ for the embedded sample. In addition, the Spearman Rank test shows that the background RM sample is anti-correlated with impact parameter at high probability, again indicating that the excess is due to the intracluster magnetic field. The split RM samples provide strong evidence that both the embedded and background radio probes are sampling intracluster magnetic fields, and not a local Faraday screen in the vicinity of the radio source.

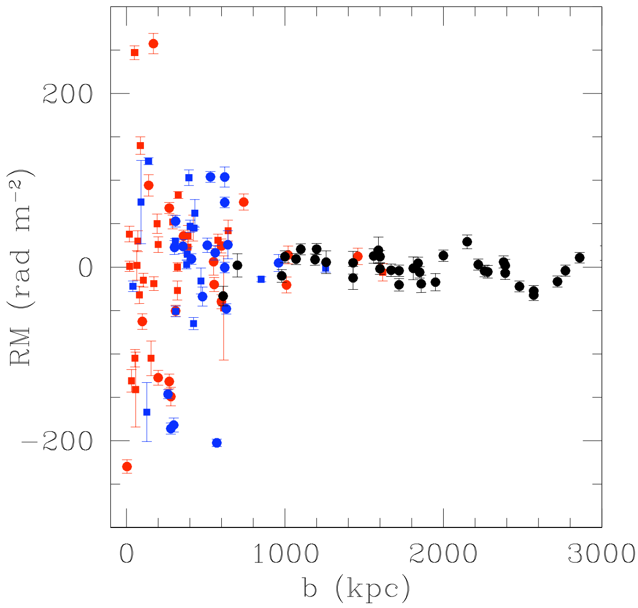

Fig. 4.— Expanded RM sample from Clarke et al. (in preparation) including data from the literature, separated into embedded (red), background (blue), and control (black) samples. The increase in the width of the RM distribution toward smaller impact parameter is clearly visible for both the embedded and the background samples.

V. SUMMARY

Faraday rotation measure probes of intracluster magnetic fields show evidence of cluster fields in both cooling and non-cooling core clusters. In addition, several studies show that the fields extend to distances of at least 500 kpc from the cluster cores. Magnetic field strengths in non-cooling core clusters are generally a few μG and RM maps show fluctuations on scales of $10 - 20$ kpc. Estimates of field strengths in cooling core clusters are generally about an order of magnitude larger, with the RM fluctuation scale being roughly an order of magnitude smaller. The separation of Faraday probes into embedded and background samples shows similar RM distributions for both samples, indicating that the majority of the RM excess is from fields in the intracluster medium. More detailed approaches are being explored to translate the observational data into estimates of the field strength and topology. Depending on the techniques used, these studies suggest that the field scales and estimates from previous work may be off be a factor of 2.

The current instrumentation only allows us to measure the polarimetry of a few background probes viewed through individual clusters due to sensitivity limitations. In the near future, the EVLA will greatly expand our capabilities and allow us to reach dozens of background sources per cluster for many systems. This will permit the study of the radial distribution of the RM properties across single clusters and the comparison of these distributions for clusters in different evolutionary stages to allow us to search for correlations between the magnetic field and cluster properties. Deeper searches will also be possible to detect (or place lower limits on) the polarization associated with diffuse radio halos, and the improved sensitivity and resolution will also allow more detailed studies of extended radio galaxies within and behind clusters

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