

A Critical Look at Faraday Rotation Measures of Cluster Magnetic Fields

Lawrence Rudnick¹ and Katherine Blundell²

¹ *University of Minnesota*

² *Oxford University*

Strong magnetic fields (up to 40 μG) have been claimed for the ICM in galaxy clusters, especially those with strong cooling flows, based on studies of radio source rotation measures (RMs). The suggested evidence is of two types—studies of variations in RM across individual radio galaxies embedded in clusters, and statistical studies of background sources. We have re-examined this evidence, and find that no claims for such strong, cluster-wide fields can be supported against likely alternative explanations for the observations. We show that RM variations in embedded sources have a significant contribution from the medium local to the sources themselves, which would have to be removed before seeking evidence for cluster-pervading fields. We find that the statistical conclusions are based not on background sources, but on sources embedded in the clusters and others with unreliable RMs. When such inappropriate sources are eliminated from existing samples, only marginal evidence remains for cluster-wide fields from the RM data. Other indicators of cluster fields, such as radio halos, suggest field strength values at levels of μG or less. At such levels, the magnetic fields probably do not directly affect the dynamics of the intracluster medium, although they may still be important, e.g., for thermal conduction.

1. Introduction

The roles of magnetic fields in cooling flow clusters of galaxies are largely unexplored, partly due to the complications of incorporating them into physical models, and partly due to the lack of a clear observational picture. A recent review article (Carilli & Taylor 2002) and several contributions to these Proceedings (Taylor 2004; Enßlin 2004; DeYoung 2004) seek to clarify this situation.

One of the key techniques used to estimate cluster field strengths and geometries is the use of Faraday rotations of radio galaxies. The Rotation Measure (RM, in units of rad/m^2) is a measure of $\int n_e \vec{B} \cdot d\vec{l}$, determined by the observed change in the polarization position angle along a given line of sight, as a function of observing wavelength. The average RM contains contributions from our own Galaxy, and, if cluster fields are tangled on small scales, would yield zero in any case. Therefore, in the method we term *EMBEDDED*, the spatial variations in RM (i.e. $\langle RM^2 \rangle$ after subtracting $\langle RM \rangle$) across a well-resolved galaxy are used to estimate the strength and characteristic scale size of cluster field fluctuations. A second method, *BACKGROUND*, uses the RM values for sources *behind* the clusters to estimate the cluster fields. Again, $\langle RM \rangle$ should be zero on average, but the dispersion in these values ($\langle RM^2 \rangle$) should be higher for sources seen through the ICM than for control sources not seen through the ICM, if the cluster field dominates over that causing any local effects.

There are magnetic fields in galaxy clusters: We see them in isolated synchrotron-emitting patches of plasma (i.e. radio galaxies) at levels of 10s of μG ; we see them at the μG level in the thermal medium close to or mixed with radio galaxy plasmas on the 50–100 kpc scale (the

Laing-Garrington effect); we see them in the detached “relic” radio sources probably representing energization by shocks in the ICM. We also see them on cluster-wide scales as synchrotron halos. The best estimates for the strengths of cluster-wide magnetic fields, are $\approx \mu\text{G}$ (Carilli & Taylor 2002). However, RM studies cite values for cluster-wide fields up to 10s of μG , (2–3 orders of magnitude higher in magnetic pressure). In this contribution, we briefly outline the flaws in those RM studies.

2. EMBEDDED Studies

The primary flaw in such studies (e.g. Taylor et al. 1993; Feretti et al. 1999) is the *untested assumption* that $\langle RM^2 \rangle$ is dominated by contributions from a magnetic field pervading the overall ICM. A simple, and even likely, alternative is that $\langle RM^2 \rangle$ is dominated by contributions local to the radio source, either a thin skin of dense warm gas mixed into the edges of the radio emitting plasma, or in its immediate surroundings. The criticism is often made that a thin skin of X-ray emitting gas would be insufficient to produce the observed RMs (see the summary, e.g., in Eilek & Owen 2002); however, if the accompanying warm gas is in pressure equilibrium with the hot gas (see the beautiful multi-phase medium, e.g., in Abell 2597, Koekemoer et al. 1999) then the available densities are orders of magnitude higher. The *presumption* that RMs come from the overall ICM, on scales of 100s of kpc, as opposed to the medium immediately surrounding the radio source, is wildly optimistic, given the following well-established facts (also see Figure 1):

- Many of the sources with high RMs have radii < 30 kpc (e.g. see Table 3 in Taylor, Fabian & Allen 2002: Virgo A, PKS 1246-410 [Centaurus], 3C295,

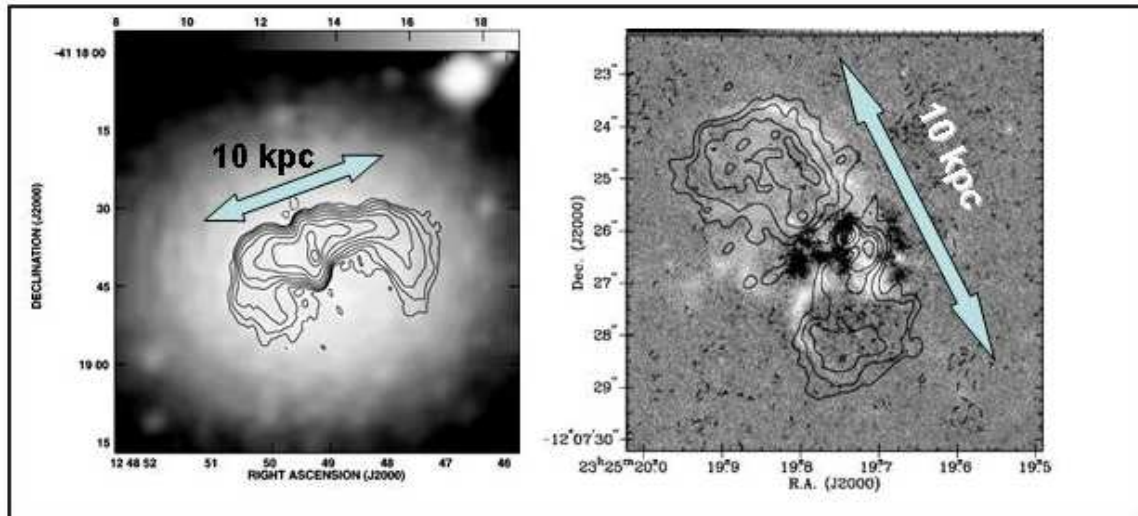


FIG. 1.— Illustration of flaws in the use of *embedded* sources for cluster-wide field determinations – small sizes, and interactions with dense warm material. Left: PKS1246–410 in the Centaurus cluster, radio source overlaid on Digital Sky Survey image, annotated version of figure from Taylor, Fabian & Allen (2002). Right: The bright compact radio galaxy in Abell 2597 overlaid on a galaxy-subtracted F702W image, annotated version of figure in Koekemoer et al. (1999).

3C317 [Abell 2052], 4C26.42 [Abell 1795], 2322-123 [Abell 2597]) so the measurements may tell us something about their ISMs, but the relevance to large-scale ICM fields is dubious.

- Warm dense gas is common around radio galaxies, (Heckman 1981; van Breugel, Heckman & Miley 1984; van Breugel et al. 1985; McCarthy et al. 1987; Giraud et al. 1996; Clark et al. 1998; Tadhunter et al. 2000; Bicknell et al. 2000), often showing signs of interactions (Koekemoer et al. 1999; Solórzano-Iñarrea & Tadhunter 2003), and even extending out to hundreds of kpc (Reuland et al. 2003)
- The presence of dense, warm gas is associated with depolarization (i.e. extreme Faraday rotation; Pedelty et al. 1989a,b; McCarthy & van Breugel 1989; Liu & Pooley 1991).

Faraday rotations originating *local* to the radio galaxy are therefore a very plausible alternative to cluster-wide fields to explain the RMs of cluster-embedded sources. In order to justify a claim that cluster-wide fields have been detected, it would therefore be necessary to rule out effects local to the radio galaxy. Therefore, the spurious argument is sometimes advanced that because the observed RM structure is not clearly related to the radio source *brightness* distribution, that the RM must be due to the unrelated intervening cluster medium. This argument ignores the fact that, if the RM comes from the source itself, changes in the source magnetic field orientation can change the synchrotron polarization angle and the RM *without any change in the total intensity*. Therefore, a proper way to look for a connection between the magnetic fields intrinsic to a radio source and its observed RM would be through the polarization angle.

This is illustrated in Figure 2, based on Rudnick & Blundell (2003a). In that paper, we report such an investigation of the PA-RM relationship, both developing

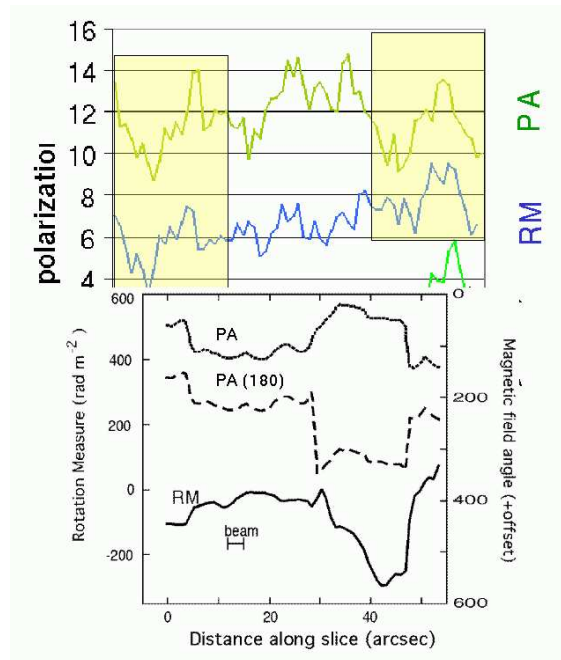


FIG. 2.— Cartoon of expected relationship between polarization angle (PA) and RM, both plotted as a function of position along a radio source. A simple Monte Carlo simulation was done with the vector magnetic field and the thermal density varying as a function of position. If the field vector components are independent, no correlation is seen. Here we impose a correlation between the variations in the several vector field components, resulting in a visible correlation between PA and RM in some locations (shaded). The bottom plot is from Rudnick & Blundell (2003a), showing a slice in a selected region showing good correlation in the tailed radio galaxy 3C75, using the data of Eilek & Owen (2002). The PA plot is shown for two choices for the 180° phase ambiguity. Note that the beam size is much smaller than the coherence length of the PA and RM, so this correlation is not due to random fluctuations.

a new test to examine the RM–source magnetic field correlation statistically, and also a more subjective search for correlated changes in other cluster sources. Our conclusion was that RMs in a number of sources are quite plausibly caused by the mixing of source magnetic fields with a local thermal plasma, without any need to invoke high cluster-wide fields. Enßlin et al. (2003) then pointed out, as we had suggested, that some sophisticated, *ad hoc*, classes of cluster magnetic field distributions could explain our results on PKS1246–410. They could not, however, develop any arguments *against* the hypothesis of RMs originating local to the source. The case for RMs as high as those claimed (e.g. Feretti et al. 1995, 1999; Dolag et al. 2001; Taylor, Fabian & Allen 2002), arising from the large-scale ICM over and above those due to local effects remains to be demonstrated.

2.1. Statistical Trends

A variety of statistical trends, such as increasing $\langle RM^2 \rangle$ with increasing X-ray surface brightness, or with decreasing distance to the cluster center are used to argue in favor of large-scale cluster field contributions to the RMs (Dolag et al. 2001; Govoni et al. 2001). However, higher densities near the cluster center, especially if there is pressure balance with the warm, dense gas mixing in with the *magnetic field of the radio source* would produce the same statistical effect. Another relationship suggested by Taylor, Fabian & Allen (2002) is between the RM and the overall “cooling flow” rate, again pointing to cluster-wide fields. However, as referenced earlier, most of these sources are quite small, with only three out of thirteen with radii larger than 50 kpc, and can establish only what is happening in their own respective ISMs.

One argument cited in support of large scale fields outside of radio galaxies is the Laing-Garrington effect (Garrington et al. 1988; Laing 1988; Garrington & Conway 1991), whereby the radio source lobe which is pointed towards us (as determined by the presence of a Doppler-boosted jet) is less depolarized, on average, than the lobe pointing away. The standard interpretation is that this is due to a halo of thermal gas, threaded by a turbulent magnetic field, surrounding the radio galaxy. The path length through this plasma, and therefore the amount of depolarization, would be larger for the more distant lobe.

The result is statistically significant for some samples, but its relevance for a global ICM field is unclear. It is important to remember that this effect measures the medium centered on the radio galaxy, and on the scale size of the radio galaxy. Garrington & Conway (1991) derive values of $\langle B_0 n_0 \rangle \approx 1(40) \times 10^{-3} \mu\text{G cm}^{-3}$ at low (high) redshifts, with halo radii on the order of 50 kpc, decreasing with redshift. This leads them to estimates of $\langle B_0 \rangle \approx 1 \mu\text{G}$ for $z > 1$. Morganti et al. (1997) use a sample of low-luminosity galaxies to derive numbers that they describe as agreeing well with Garrington & Conway (1991), although their halo radii, determined by Monte Carlo simulations, come out larger, at 150 kpc.

Detailed mapping of three distant, powerful classical double sources by Johnson et al. (1995) note consistency with the Laing-Garrington effect, but also show that the

most important trend is for increasing depolarizations closer to the center of *each galaxy*, as expected if the thermal material were entrained in the lobes. There are also other indications of *intrinsic*, as opposed to external, causes for some depolarization asymmetries (Ishwara-Chandra et al. 1999). The Laing-Garrington effect is thus clearly important in some cases, but may or may not be telling us anything about the ICM beyond the radio galaxy itself.

2.2. Large-Scale Field Examples?

Some individual cases of depolarization asymmetry are quite striking, even on very large scales, drawing people to the conclusion that global ICM fields are responsible. One such case is Hercules A, most recently mapped at multiple frequencies by Gizani & Leahy (2003). Although their full polarization analysis is not yet available, these authors preview their support for a magnetized cluster halo. However, they do not mention the dramatic change in depolarization at the same position as a change in the *intrinsic* polarization properties (see their Figure 16, at $+60''$), a clear indicator of source-related (not global ICM) effects.

Taylor, Fabian & Allen (2002) cite Hydra A as perhaps the most extreme signpost of a cluster-wide field, with an inferred strength of $35 \mu\text{G}$, and extending for hundreds of kpc from the center. However, Chandra observations have shown a bright rim of cooler X-ray emitting gas around the radio galaxy (Nulsen et al. 2002). They explore the relationship between the radio and X-ray plasmas, and suggest, for example, that moderately strong hydrodynamic shocks increase the local relative magnetic field. Another possibility involves relic fields from previous radio galaxy activity. The important physics for the fields around Hydra A is the radio galaxy/ICM interactions, *not* the unjustified leap to some global cluster field.

The strong Faraday effects local to radio galaxies thus make it very difficult to use them as reliable probes of cluster-wide fields. This leads us to the second class of RM cluster studies, that of background sources.

3. Background RM Studies

If one had an unbiased sample of background sources, themselves not in clusters of galaxies, it would be possible to look for the effects of the ICM on the distribution of RMs. Specifically, one would search for an increased dispersion in RM where the background sources are seen through a cluster medium. Hennessy, Owen & Eilek (1989, hereafter HOE) detected no cluster influence, although several studies purport to have seen such an effect (Kim et al. 1990; Kim, Kronberg & Tribble 1991; Clarke, Kronberg & Böhringer 2001). Unfortunately, these studies suffer from fundamental design errors, as well as other problems.

The most striking flaw is that the samples claiming a cluster effect include many sources actually *embedded* in the clusters, although this is sometimes difficult to ascertain from the papers. As we have seen above, cluster sources often interact with dense material, and in any case, cannot provide an unbiased sample to compare with

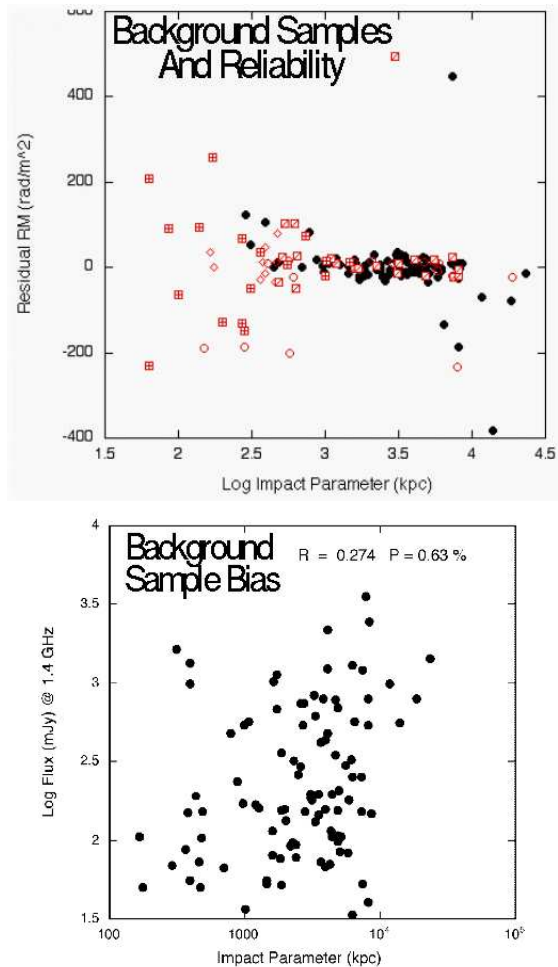


FIG. 3.— Top: RM (corrected for Milky Way contributions) as a function of impact parameter to the cluster center, for the combined sample. Reliable sources are shown in black; the various red symbols show the published results for sources which we found to be problematic, as discussed in the text. Bottom: Flux biases in the sample of true background sources.

distant, presumably non-cluster sources. Cluster sources were presumably included because it is difficult to find sufficient numbers of sufficiently polarized background sources in the directions of clusters. Unfortunately, these embedded cluster sources are also responsible for the bulk of the claimed “cluster excess.”

Other problems with these background studies include improper calculations of errors (Kim et al. 1994), comparisons made between maps with different visibility plane coverage at different frequencies, different resolutions and sets of frequencies for cluster and control sources, and the inclusion of sources with polarization behavior inconsistent with external Faraday rotation (Kim et al. 1990; Kim, Kronberg & Tribble 1991; Clarke, Kronberg & Böhringer 2001).

In order to see what could be salvaged, we combined the data from two samples, those of Clarke, Kronberg & Böhringer (2001, hereafter CKB) and HOE (Rudnick & Blundell 2003b). The HOE experiment, using only actual background sources, found no evidence for a cluster/field difference, although their clusters were not chosen in the same way as the CKB sample. The combination of these two samples, and the elimination of problematic sources, is not ideal; it is however, the most reliable test of the RM contribution from cluster fields *possible at present*.

The initial results from our combined sample are shown in Figure 3. There is no significant effect on the RM dispersion due to a cluster along the line of sight (using only the reliable sources, as shown in black). It is possible to make a variety of different cuts in the data, choosing different impact parameters to distinguish between cluster and field samples, allowing some slightly questionable sources back into the samples, etc. Searching through this parameter space, one can produce a marginally significant cluster effect. This comes at a stiff price, however. First, we find that there is a highly significant difference in the flux densities of sources at high and low impact parameter, as seen in Figure 3 (bottom). This arises largely because HOE had to go to fainter levels to find background sources in the directions of clusters. It is not clear what biases this might cause in the RM distributions. A more serious issue is that the combined samples of true background sources show a highly significant excess of positive RMs in the directions of clusters, whereas a mean of zero is expected. These results will change slightly, when published in Rudnick & Blundell (2003b), after correcting for sources listed in the original papers at high impact parameters where another Abell cluster is at a smaller impact parameter.

Our conclusion is that the high magnetic fields derived in the literature based on RM studies are untrustworthy. Eventually, however, the cluster fields associated with halos and the remnants of dead radio galaxies, should also be detectable through their RM effects. Some progress is possible with the VLA, but the real breakthroughs will probably come with the SKA, and perhaps LOFAR.

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