Magnetic fields in Clusters of Galaxies

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An important area of study of cosmic magnetic fields is on the largest scales, those of clusters of galaxies. In the last decade it has become clear that the intra-cluster medium (ICM) in clusters of galaxies is magnetized and that magnetic fields play a critical role in the cluster formation and evolution. The observational evidence for the existence of cluster magnetic fields is obtained by the diffuse cluster-wide synchrotron radio emission and from rotation measure (RM) studies of extragalactic radio sources located within or behind the clusters. A significant breakthrough in the knowledge of the cluster magnetic fields will be reached through the SKA, owing to its capabilities, in particular the deep sensitivity and the polarization purity.

1. INTRODUCTION

Unlike electromagnetic radiation from astrophysical sources, distant magnetic fields are difficult to detect. Nonetheless, recent measurements have begun to reveal that such fields exist at significant strengths, and on surprisingly large scales, in the extragalactic universe. Observations have shown that magnetic fields are ubiquitous in cluster atmospheres, playing a critical role in the cluster formation and evolution, in determining the energy balance in cluster gas through their effect on heat conduction, and in some cases, perhaps even becoming dynamically important.

Our knowledge of the magnetic field properties in galaxy clusters and of how they relate to other cluster properties is limited by the sensitivity and resolution of current instruments. In particular, several questions are still unanswered: are the fields filamentary, what are the coherence scales, to what extent do the thermal and non-thermal plasmas mix in cluster atmospheres, what is the radial dependence of the field strength, how does the field depend on cluster parameters such as the gas temperature, metallicity, mass, substructure and density profile, how do the fields evolve with cosmic time, how do the fields extend and finally how were these fields generated?

Magnetic fields associated with the intracluster medium (ICM) in galaxy clusters are investigated in the radio band through studies of the rotation measure and of the synchrotron emission of both individual radio galaxies and radio halos and relics. Other techniques include X-ray studies of the inverse Compton emission and of cold fronts, and hydrodynamic simulations. The studies in the radio band are, however, the most relevant and provide the most accurate field estimates. The SKA's high sensitivity, high resolution, multifrequency capability, and polarization purity will be crucial to these studies.

2. CURRENT RESULTS FROM RM STUDIES

Cluster surveys of the Faraday rotation measures of polarized radio sources both within and behind clusters provide an important probe of the existence of intracluster magnetic fields, as the radio waves traversing the magnetized intracluster medium show depolarization and rotation of the polarization position angle as a function of wavelength.

The RM values derived from multifrequency polarimetric observations of background or em-
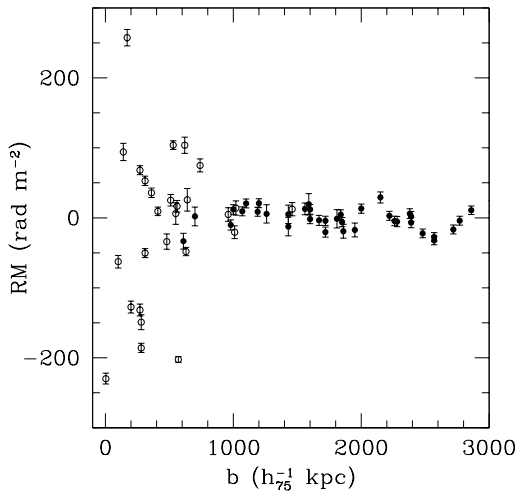
Figure 1. Galaxy-corrected rotation measure plotted as a function of source impact parameter in kiloparsecs for the sample of sources from [5]. Open dots refer to cluster sources, closed dots to control sources.

bedded cluster sources are of the order of tens to thousands rad m^{-2}. These have to be combined with measurements of the thermal gas density, $n_{\rm e}$, to estimate the cluster magnetic field along the line of sight. The observing strategy to derive information on the magnetic field intensity and structure is twofold: i) obtain the average value of the RM of sources located at different impact parameters of the cluster, ii) derive maps of the RM of extended radio sources, to evaluate the σ of the RM distribution.

Part of the difficulty of investigating cluster magnetic fields through Faraday rotation is that at present such a study may only be undertaken statistically over a large number of clusters. This is due, in part, to the lack of available RMs which are limited by current instrument sensitivity and by the vectorial nature of the RMs themselves. Since every measured RM is the vectorial addition of all contributing Faraday screens along the line of sight it is impossible to disentangle the cluster rotation measure components from either inter-

nal rotation in the source, or a Galactic rotation measure component without a sufficient number of RMs available.

Nevertheless, studies on both statistical samples and individual clusters have been carried out (see the review [4] and references therein). Kim et al.[18] analyzed the RM of 53 radio sources in and behind clusters and 99 sources in a control sample. This study contains the largest cluster sample to date. It demonstrated that μG level fields are widespread in the ICM, regardless of whether there is the direct evidence for the existence of magnetic fields from the presence of diffuse radio emission. In a more recent statistical study, Clarke et al.[5] analyzed the RMs for a representative sample of 27 cluster sources, plus a control sample, and found a statistically significant broadening of the RM distribution in the cluster sample, and a clear increase in the width of the RM distribution toward smaller impact parameter (see Fig. 1). They derived that the ICM is permeated with a high filling factor by magnetic fields at levels of 4 - 8 μG and with a correlation length of $\sim$15 kpc, up to $\sim$0.75 Mpc from the cluster center.

The first detailed studies of RM have been performed on cooling core clusters, owing to the extremely high RMs of the powerful radio galaxies at their centers (e.g., Hydra A [21] & 3C295 [1]). High values of the magnetic fields, up to tens of μG, have been obtained, but they only refer to the innermost cluster regions.

Studies on larger areas of clusters have been carried out e.g. for Coma [9], A119 [10], A514 [13] and 3C129 [22]. However, because of the limited sensitivity of current instruments, reliable maps of the RM can be obtained only for the strongest sources (total flux $\gtrsim$50 mJy) and only in the regions of high radio surface brightness (see e.g. Fig. 2). The number of targeted sources per cluster is on average 1-2, with a maximum of 3-5 in a few clusters.

Overall, the data are consistent with cluster atmospheres containing μG fields, with perhaps an order of magnitude scatter in field strength between clusters, or within a given cluster, and with extreme field values in cluster cooling cores. The RM distribution is generally patchy, indicat-
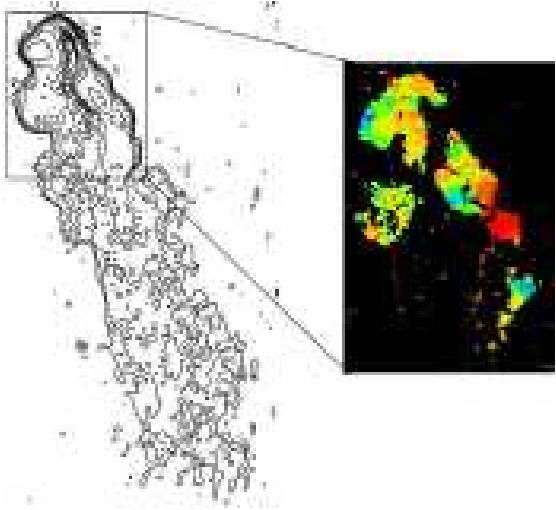
Figure 2. VLA contour plot of the tailed radio galaxy 0053-015 in A119 at 1.4 GHz (left), and RM image (right). The RM information has only been derived for the brightest source region [10].

ing that large scale magnetic fields are not regularly ordered on cluster scales, but have coherence scales between 1 and 10 kpc. The estimates of the magnetic field strength crucially depend on the magnetic field structure and geometry, thus accurate maps of RM are needed. We note that in the Coma cluster the presence of a weaker field component of 0.1-0.2 μG, ordered on a scale of about one cluster core radius, was inferred in addition to the stronger tangled magnetic field component [9].

A caveat in the interpretation of RM data is the possible existence of local RM enhancements, produced by the compression of the ICM fields by a radio galaxy. In this case the RM would not be indicative of the cluster magnetic field, leading to overestimates of the ICM magnetic field strength [20]. This difficulty can be overcome by sensitive observations at very high resolution, which cannot be obtained with the presently available instruments.

The observations are often interpreted in terms of the simplest possible model, i.e. in this case a constant field throughout the whole cluster. However, a decline with radius is expected if the intensity of the magnetic field results from the compression of the thermal plasma during the cluster gravitational collapse. According to this model, a correlation between observable parameters, the RM and the X-ray surface brightness, is expected to reflect the correlation between the physical quantities, magnetic field and gas density. The application of this approach has been possible so far only in A119, giving the radial profile of the magnetic field as $B \propto n_e^{0.9}$ [7] in this cluster. In addition, Beck et al.[2] pointed out that field estimates derived from RM may be too large in the case of a turbulent medium where small-scale fluctuations in the magnetic field and the electron density are highly correlated.

New generation instruments are rather promising and establish a clear connection between radio astronomical techniques and the improvement in the knowledge of the X-ray sky. There are various satellite missions which will map the X-ray sky at low energies in the next years. These will provide a more precise knowledge of the X-ray surface brightness of clusters, i.e. of their thermal gas density, allowing a more accurate and correct interpretation of the sensitive RM measurements. The accurate experimental determination of large scale magnetic fields in the intracluster medium will thus be possible.

3. DIFFUSE SYNCHROTRON EMISSION

The presence of magnetic fields in clusters is directly demonstrated by the existence of the radio halos and relics, i.e. diffuse cluster-wide synchrotron radio sources, as revealed in Coma (Fig. 3) and some other clusters [12]. Under the assumption that the energy density within radio sources is minimum (equipartition condition), magnetic field values in the range 0.1-1 μG are derived for the radio emitting regions, i.e. on scales as large as ~ 1 Mpc. These calculations typically assume equal energy in relativistic protons and electrons, a magnetic field entirely filling the radio source volume, a low frequency cut-off

of 10 MHz, and a high frequency cut-off of 10 GHz. The magnetic field values derived in this way are consistent with those suggested from the recent detection of Inverse Compton hard X-ray emission in clusters with halos or relics [16].

The number of clusters presently known to host halos and relics is around 50, i.e. $\sim 10\%$ of rich clusters. Indeed, the typically low surface brightness of cluster radio halos and their steep spectrum makes it difficult to image them accurately with the current resources. Further, at lower resolution, where beam averaging enhances the detectability of extended radio emission, true diffuse emission is sometimes difficult to distinguish from a blend of weak, discrete radio sources.

The observations of clusters with the SKA will allow a dramatic improvement of the knowledge of halos and relics. It will be possible to detect new halos and relics, and study these sources in great detail (see detailed discussion Feretti, Burigana, & Ensslin, this volume). In particular, polarimetric studies will be of crucial importance, to give direct information on the magnetic field orientation, degree of ordering, and overall structure.

The detection of synchrotron radiation at the lowest possible levels will allow the measurement of magnetic fields in even more rarefied regions of the intergalactic space, and investigations of the relation between the formation of magnetic fields and the formation of the large scale structure in the universe.

4. RECONCILING MAGNETIC FIELD VALUES

The cluster magnetic field values obtained from RM arguments are about an order of magnitude higher than the estimates, typically of 0.2 to 1 μG, derived from both the synchrotron diffuse radio emission [12] and the inverse Compton hard X-ray emission [16]. The discrepancy can be alleviated by taking into account that i) the values deduced from radio synchrotron emission and from inverse Compton refer to averages over large volumes, whereas the RM estimates give a weighted average of the field along the line of sight; ii) the magnetic field intensity is likely to
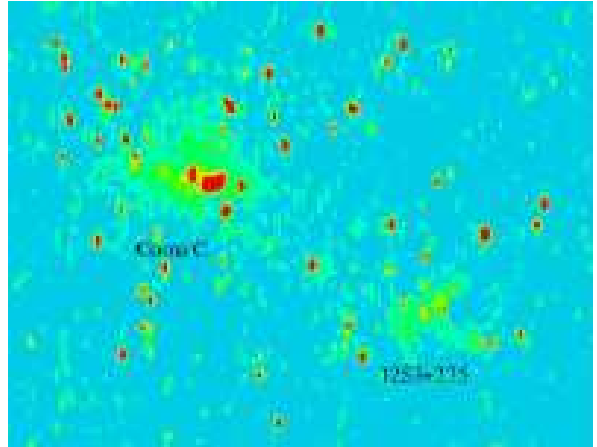

Figure 3. Radio image of the Coma cluster region at 90 cm, with angular resolution of $55'' \times 125''$ (HPBW, RA $\times$ DEC), showing the halo source Coma C at the cluster center and the relic source 1253+275 at the cluster periphery.

decline with the distance from the cluster center; iii) the magnetic field may show complex structure, as filamentation and/or substructure with a range of coherence scales. Therefore, the RM data should be interpreted using realistic models of the cluster magnetic fields, as shown by a recent investigation performed using a numerical approach [14,19].

Additionally, evidence suggests that the magnetic field strength will vary depending on the dynamical history and location within the cluster. A striking example of the variation of magnetic field strength estimates for various methods and in various locations throughout the cluster is given in Table 1 for the post merger cluster A3667 (at z = 0.055). The results of each estimation, are consistent with a typical 1–2 μG field, tangled on scales of 10 to 100 kpc, pervading the cluster's central region. This field has been further enhanced in the region of the observed central X-ray cold front to a level of 7–16 μG [23] and to around 3–5 μG in the region of the Mpc-scaled radio relic in the northern part of the cluster [17]. As the relic emission is currently thought to be

Table 1
Magnetic field estimates derived from various methods for the galaxy cluster A3667. Column 1 gives the method used to estimate the field strength, Column 2 the value of the magnetic field in μG, Column 3 describes the location in the cluster at which this estimation is made and Column 4 gives the reference.

Method	Field Estimate (μG)	Location in the cluster	Reference
Inverse Compton	≥ 0.4	cluster core	[15]
Kelvin-Helmholtz	7-16	along the cold front	[23]
Faraday Rotation	1-2	cluster core	[17]
Faraday Rotation	3-5	NW radio emission region	[17]
Equipartition	1.5-2.5	NW radio emission region	[17]

the result of a cluster merger it is likely that the central field would be compressed and elevated by a factor of 3–4 in the region of the shock accelerated relic.

As shown in Table 1 the observational data needed to obtain sufficiently detailed information about the cluster magnetic field strength and structure can only be achieved by a new generation instrument.

5. RELEVANCE OF STUDIES WITH SKA

Although several interesting results have been obtained in recent years about the cluster magnetic fields, such studies are still limited to works on a few clusters, and on a few radio sources, as reported in the previous sections. Magnetic field strengths of the order of ~ 1 μG are found to be common in clusters. However, estimates obtained with different approaches may differ (Sec. 4), thus detailed information on the cluster field is still needed.

The main goals to pursue with SKA are the following:

• obtain the RM of large samples of radio sources within or behind clusters;

• derive detailed RM maps at high resolution, to resolve small scale features in the foreground screens, in particular those due to turbulence and other local effects;

• distinguish the external Faraday rotation measure from that arising internally in a radio source, in order to get careful information on the cluster magnetic field (and on the radio source too);

• investigate the ICM magnetic field structure, the existence of components with different coherence lengths (power spectrum), the magnetic field filling factor;

• analyze the correlation between the magnetic field intensity and the gas density, get information on the magnetic field profile,

• test models of magnetic field formation from the study of distant objects and the effect of density inhomogeneities on their Faraday RM.

The SKA specifications to these aims are

• a frequency range 1 - 10 GHz with a large number of channels[6], to get reliable information on the RM, solving the ambiguity related to its computation and disentangling various contributions;

• an angular resolution of 0.5″ at 1.4 GHz to allow structures of 1 kpc at z $\lesssim$0.5 to be resolved; a resolution of 0.1″ is needed for the distant clusters.

• polarization purity of -40 dB at the field center to allow measurement of the polarization parameters for submJy sources.

The All Sky RM survey (SKA Key Project on Magnetic Fields [3]), will provide the RM for $\gtrsim 10^7$ compact polarized extragalactic sources, expanding the sample of RM measurements by five orders of magnitude over current data sets. When combined with redshift and X-ray information from future instruments, such a data-base will allow a statistical analysis of the RM of sources within or behind clusters, leading to a great im-

provement of the knowledge of the strength of the magnetic field in clusters. For example in the case of A3667 illustrated above only 3 reliable RMs were obtained after over 100 hours of observations on present day instruments. With the All Sky RM Survey, it will be possible to obtain about 1000 RM measurements through lines of sight in this cluster, and generally in clusters at similar distances. Additionally, we will detect at least 20 RMs through clusters up to redshifts of 3.5 giving the first opportunity to perform detailed analysis of the evolution of cluster magnetic fields.

Deep multifrequency surveys, targeting individual clusters, will allow the investigation of the intensity and structure of the ICM magnetic fields. Low surface brightness radio features such as relics and halos should be detected in their thousands [8] allowing us to explore the role of dynamically important magnetic fields in merging clusters and providing vital clues to the origin of cluster magnetic fields.

Using the described techniques, magnetic fields can also be observed and studied in the jets and lobes of radio galaxies. The largely improved sensitivity and resolution of SKA will allow the study of faint objects and of the low brightness components of extended radio sources, the distinction of local features, the discrimination between internal and external Faraday dispersion, the connection between magnetic fields within the radio galaxies and the cosmological magnetic fields.

ACKNOWLEDGMENTS

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