X-ray + Radio Analysis of Magnetic Fields in Clusters of Galaxies

T. E. Clarke and P. P. Kronberg
Department of Astronomy, 60 St. George Street, University of Toronto, M5S 3H8, Canada

ABSTRACT

Clusters of galaxies provide a unique laboratory in which to study plasma physics. The intracluster plasma is composed of hot gas mixed with cosmic rays and magnetic fields. Very little is known about the strength and orientation of the magnetic fields in clusters although they may be dynamically important in the central regions.

We present an overview of the areas in which magnetic fields can affect the dynamics of galaxy clusters. The various methods used to measure cluster magnetic fields are presented along with typical results. We also briefly discuss our current project which is the most detailed radio and X-ray study of cluster magnetic fields. We consider XMM's future potential for furthering this area of research.

Subject headings: galaxies: clusters: general — magnetic fields — X-rays: general

1. Introduction

Clusters of galaxies are the largest known gravitationally bound systems in the universe. The principal components of clusters are galaxies, hot gas, dark matter, cosmic rays and magnetic fields. A cluster can contain thousands of galaxy members and is generally characterized by the morphology of the central galaxy and a 'richness' parameter (number of galaxies visible down to a limiting magnitude) (e.g. Struble & Rood 1987). X-ray observations detected the signature of hot intracluster gas in the early 1970's (Gursky & Schwartz 1977). This hot gas emits both spectral-line and thermal free-free emission. The typical mass of the hot cluster gas and galaxies is $\sim 30\%$ of the total cluster mass. Most of the remaining fraction ($\sim 70\%$) of the intracluster medium (ICM) appears to be in the form of dark matter (Böhringer 1995).

2. Magnetic Field Interactions

2.1. The Baryon Crisis

The hot, X-ray emitting gas in the intracluster medium traces the cluster potential. Through a study of the angular distribution of the surface brightness of this gas, it is possible to estimate the mass of hot gas within a cluster. A measurement of the total gravitational cluster mass is obtained by imposing thermal hydrostatic equilibrium requirements.

Comparing the gas mass and total mass within clusters will allow us to determine their baryon to dark matter ratios. These ratios are found to be $\sim$ 10-30% (Schindler 1996). If clusters are indeed representative of the Universe as a whole, this ratio would be in conflict with the nucleosynthesis predictions for Ω_o=1. This has been termed the "baryon crisis" (Steigman & Felten 1995; White & Fabian 1995). The addition of a magnetic pressure support to the ICM would bring in another term in the hydrostatic equation and thus increase the measurement of the total mass within clusters, but it would leave the baryonic mass unchanged. This would lead to a higher estimate of Ω_o and reduce the "crisis". An additional cosmic-ray proton component in the ICM would bring the ratio even closer to the predicted values (Ensslin *et al.* 1997).

2.2. Thermal Conduction

X-ray temperature profiles of several clusters reveal the presence of cooler gas in the core regions of the clusters (Arnaud 1988). This is difficult to understand since thermal conduction should be extremely efficient in the hot ICM. Heat will be transferred to the cooler regions (David & Bregman 1989) and remove any temperature gradients. Over a very short timescale, the central regions of the clusters should become isothermal. The observations of cool central gas indicate that there must be a mechanism in place that suppresses the thermal conduction. This suppression can be accomplished by the presence of tangled magnetic fields within the ICM. These fields will confine the electrons (Tribble 1989), forcing them to travel further along the tangled fields to reach regions of different temperature. This extra path-length produces an increase of the thermal conduction timescale which can allow temperature gradients to persist.

An interesting consequence of having cooler gas in the center of clusters is that the gas must flow inward from the outer regions of the cluster to maintain the core pressure support against the outer gas. This radial motion will stretch and compress frozen-in magnetic fields. This will result in an amplification of the magnetic field strength in the centers of cooling flow clusters (Soker & Sarazin 1988). Cooling flow models show that this mechanism can lead to dynamically important magnetic fields within the central regions of clusters (Soker & Sarazin 1990).

2.3. Particle Acceleration

Once magnetic fields have been amplified to the regime where the magnetic and thermal pressures are comparable, there are rapid field line reconnection processes that can occur (Soker & Sarazin 1990). This reconnection will release energy into the ICM which can lead to the acceleration of particles to relativistic energies. The observed cluster-wide synchrotron halos may be tracing the interaction region of these particles and the magnetic fields.

3. Measuring Cluster Magnetic Fields

3.1. Inverse Compton

The hot, ionized gas within galaxy clusters can induce inverse Compton (IC) scattering of the infrared and cosmic microwave background photons. This scattering process depends on the energy density of cosmic ray electrons and will scatter the low energy (3K) photons to much higher energies. These photons are then visible as diffuse, hard X-ray emission (Schlickeiser & Rephaeli 1990). Diffuse radio emission within clusters originates from the synchrotron process which depends on the product of the magnetic field strength and the energy density of cosmic ray electrons. Upper limits on Inverse Compton (IC) emission in a synchrotron halo cluster provide a lower limit on the magnetic field strength. A detection of the IC emission (e.g. Fusco-Femiano *et al.* 1998) from synchrotron halo clusters leads to a direct estimate of the magnetic field strength. The magnetic field probed by the inverse Compton process is the volume-averaged intracluster magnetic field and is found to be of the order of 0.2 μG.

3.2. Energy Equipartition

The assumption that energy equipartition exists between the relativistic particle energy ($E_p \propto B^{-3/2}$) and the magnetic field energy ($E_B \propto B^2$) within a synchrotron halo cluster can be used to estimate the equipartition magnetic field strength. This estimate is weakly dependent on k (ratio of heavy particle energy to electron energy) and ϕ (halo filling factor of the magnetic fields and relativistic particles) but is strongly dependent on the radius of the emitting region (Pacholczky 1970). An energy equipartition estimate for Coma leads to a field strength of order 1 μG (Kim *et al.* 1990).

3.3. Faraday Rotation Mapping

Linearly polarized emission passing through a magnetized, ionized medium will have its plane of polarization rotated through the Faraday effect. The amount of rotation depends on the product of the electron density through the ionized plasma and the line of sight component of the magnetic field. Using the technique of high resolution mapping of extended polarized radio sources located within the intracluster medium one can trace the cluster magnetic field. This method yields both the structure and strength of the line of sight component of the magnetic field over the region probed by the radio source. Typical field estimates are a few μG, tangled on scales of order a kpc (Feretti *et al.* 1995).

3.4. Statistical Faraday Rotation

This method relies on building a database of "cluster" radio sources that are observed along lines of sight through the hot intracluster medium and a second database of "control" radio sources whose lines of sight pass near (but not through) the cluster. Comparing the observed Faraday rotation of the "cluster" and "control" samples, one can search for effects due to the ICM magnetic field. This signature would be a broadening of the Faraday rotation measure for the "cluster" sources compared to the "control" sources. Combining the rotation measures with the line of sight electron column density to each source yields the line of sight magnetic field strength at the radius of the source. The field strengths are generally in good agreement with those from the Faraday rotation mapping technique (Kim *et al.* 1991).

4. Current Project

We have undertaken a detailed statistical analysis of the magnetic field strength and radial extent within a sample of Abell clusters (Clarke *et al.* 1998). This analysis draws heavily on observations in both the radio (VLA) and X-ray (ROSAT) regimes.

The rotation measure (RM) is defined as:

$$RM = \frac{\Delta\Phi}{(\Delta\lambda)^2} \;\propto \int n_e B_{\|} d\ell$$

where Φ is the position angle of the polarized emission, n_e is the electron density along the line of sight to the source, $B_{\|}$ is the line of sight magnetic field strength. Until the recent era of long lived X-ray satellites, it was difficult to obtain electron column density profiles for large numbers of galaxy clusters. Researchers using the statistical method to study intracluster magnetic fields would determine the electron column density through a King profile parameterized by 'average' cluster properties. This method is not sensitive to the enormous variation that appears in the X-ray profiles of galaxy clusters and thus leads to an increased uncertainty in the field strengths. Our project involves measuring the electron column densities for each of our clusters.

4.1. Observations

The NRAO[1] Very Large Array (VLA) in Socorro, New Mexico was used to obtain polarimetry of radio sources beside and behind a sample of 24 Abell clusters. The radio data provides the position angle of the polarized emission (Φ) at each observed wavelength. This data is fit to the above equation to provide a rotation measure for each source. Combining this rotation measure

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

with the cluster's electron column density determined from ROSAT images will allow us to measure the line of sight magnetic field strength toward each source.

4.2. Results

The results from our project confirm the presence of magnetic fields within the central regions of non cooling flow clusters. There is a clear excess of Faraday rotation at small radii compared to the outer cluster regions. This excess rotation extends to $R_A > 0.3$ (R > 0.5 Mpc). There is a *strong* indication that *all* clusters contain magnetic fields since there appears to be an exclusion zone of small RRMs at small cluster radii (Clarke *et al.* 1998). This exclusion region gives constraints on the reversal scale within galaxy clusters, and the filling factor of the magnetic field.

5. Future Magnetic Field Prospects with XMM

The X-ray gas in a rich galaxy cluster has a temperature between 2 and 10 keV. This places the peak of the X-ray emission within the X-ray Multi-Mirror (XMM) band (0.1-15 keV). XMM's design of high throughput observations with moderate angular resolution is perfectly suited to detailed studies of these clusters. XMM's sensitivity will trace the diffuse X-ray emission to the outer cluster regions, leading to improved electron column densities. Our current work with ROSAT shows that the magnetic fields exist to large cluster radii. We can probe these fields by combining XMM's sensitivity with Faraday rotation measures.

The presence of substructure within clusters of galaxies will lead to variation in the line of sight electron densities to the polarized radio sources. These density enhancements will modify the position angle of the polarized radio emission. Standard techniques of azimuthal binning to determine radial density profiles overlook these density enhancements. A complete analysis will require sensitive high-resolution measurements of the X-ray gas to outline the substructure. XMM is ideally suited to this type of observation for nearby galaxy clusters.

Clusters of galaxies also show strong evolutionary effects which are probably the result of merger events through the cluster's lifetime. The sensitivity of XMM can be exploited to extend ICM studies to the high redshift (z>1) regime. Combining this data with Faraday probes will permit us to make the first estimates of the magnetic field in these early clusters. These estimates will provide the key to probing the origin of the cluster magnetic fields (and gas) and the effects of mergers on their evolution.

Other areas of cluster research with XMM are covered in these proceedings (e.g. Arnaud 1998 and Romer 1998).

Acknowledgments

T.E.C thanks the organizing committee for partial travel support to attend this conference.

REFERENCES

Arnaud, K.A. 1988, in Cooling Flows in Clusters and Galaxies, ed. A.C. Fabian, (Dordrecht:Kluwer Academic Publishers), 31

Arnaud, M. 1998, these proceedings

Böhringer, Hans 1995, in Reviews in Modern Astronomy, Vol.8, ed. G. Klare, Springer Verlag

Clarke, T.E., Kronberg, P.P., & Böhringer, H. 1998, in preparation

David, L. P. & Bregman, J. N. 1989, ApJ, 337, 97

Ensslin, T.A., Biermann, P.L., Kronberg, P.P., & Wu, X-P 1997, ApJ, 477, 560

Feretti, L., Dallacasa, D., Giovannini, G., & Tagliani, A. 1995, A&A, 302, 680

Fusco-Femiano, R., Dal Flume, D., Feretti, L., Giovannini, G., Matt, G. & Molendi, S. 1998, astro-ph/9808012

Gursky, H. & Schwartz, D. A. 1977, ARA&A, 15, 553

Kim, K.-T., Kronberg, P.P., Dewdney, P.E., & Landecker, T.L. 1990, ApJ, 355, 29

Kim, K.-T., Tribble, P.C., & Kronberg, P.P. 1991, ApJ, 379, 80

Pacholczyk, A.G. 1970, in Radio Astrophysics, eds. G. Burbidge and M. Burbidge (San Francisco:W.H. Freeman and Co.)

Romer, A. K. 1998, these proceedings

Schindler, S. 1996, A&A, 305, 756

Schlickeiser, R. & Rephaeli, Y. 1990, in Galactic and Extragalactic Magnetic Field, ed. R. Beck *et al.*, (Dordrecht: Kluwer Academic Publishers), 487

Soker, N. and Sarazin, C. L. 1988, in Cooling Flows in Clusters and Galaxies, ed. A. C. Fabian, (Dordrecht: Kluwer Academic Publishers), 367

Soker, N. & Sarazin, C. L. 1990, ApJ, 348, 73

Steigman, G. & Felten, J.E. 1995, Space Sci. Rev., 74, 245

Struble, M. F. & Rood, H. J. 1987, ApJS, 63, 555

Tribble, P. 1989, MNRAS, 238, 1247

White, D. A. & Fabian, A. C. 1995, MNRAS, 273, 72

This preprint was prepared with the AAS LaTeX macros v4.0.