Cluster Magnetic Fields

Abstract:

Recent results from radio, infrared, and X-ray surveys of galaxy clusters have revealed the presence of large-scale magnetic fields that are thought to be responsible for the observed synchrotron emission. These fields are believed to be generated by the accretion of cold, dense, and magnetized gas from the intergalactic medium, and to play a crucial role in the formation and evolution of galaxy clusters.

Introduction

In this paper, we present a comprehensive review of the current understanding of the origin and properties of magnetic fields in galaxy clusters. We summarize the observational evidence for the existence of magnetic fields in clusters, and discuss the implications of these fields for our understanding of cluster formation and evolution. We also present a theoretical framework for the generation and amplification of magnetic fields in clusters, and discuss the prospects for future observations that will test this framework.

References:


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the emission mechanism was likely to be synchrotron, and if in equipartition
required a magnetic field strength of 2 \( \mu G \). In Fig. 1 we show the best image
yet obtained of the radio halo in the Coma cluster. Other radio halos were
subsequently discovered, although the number known remained under a dozen
until the mid-90s (Hanisch 1982).

Using the Northern VLA Sky Survey (NVSS; Condon et al. (1998)) and X-ray
selected samples as starting points Giovannini & Feretti (2000); Giovannini, Tordi
& Feretti (1999) have performed moderately deep VLA observations (integrations
of a few hours) which have more than doubled the number of known radio halo
sources. Several new radio halos have also been identified from the Westerbork
Northern Sky Survey (Kempner & Sarazin 2001). These radio halos typically
have sizes \( \sim 1 \text{ Mpc} \), steep spectral indices (\( \alpha < -1 \)), low fractional polarizations
(\( < 5\% \)), low surface brightnesses (\( \sim 10^{-5} \) Jy arsec \(^{-2} \) at 1.4 GHz), and centroids
close to the cluster center defined by the X-ray emission.

A steep correlation between cluster X-ray and radio halo luminosity has been
found, as well as a correlation between radio and X-ray surface brightnesses in
clusters (Liang et al. 2000; Feretti et al. 2001; Govoni et al. 2001a). A complete
(flux limited) sample of X-ray clusters shows only 5% to 9% of the sources are
detected at the surface brightness limits of the NVSS of 2.3 mJy beam\(^{-1} \), where
the beam has FWHM = 45" (Giovannini & Feretti 2000; Feretti et al. 2001).
But this sample contains mostly clusters with X-ray luminosities \( < 10^{45} \) erg
s\(^{-1} \). If one selects for clusters with X-ray luminosities \( > 10^{45} \) erg s\(^{-1} \), the radio
detection rate increases to 35% (Feretti et al. 2001; Owen, Morrison & Voges
1999). Likewise, there may be a correlation between the existence of a cluster
radio halo and the existence of substructure in X-ray images of the hot cluster
atmosphere, indicative of merging clusters, and a corresponding anti-correlation
between cluster radio halos and clusters with relaxed morphologies, e.g., cooling
flows (Govoni et al. 2001a), although these correlations are just beginning to be
quantified (Briante 2001).

Magnetic fields in cluster radio halos can be derived assuming a minimum
energy configuration for the summed energy in relativistic particles and magnetic
fields (Burbridge 1959), corresponding roughly to energy equipartition between
fields and particles. The equations for deriving minimum energy fields from radio
observations are given in Miley (1980). Estimates for minimum energy magnetic
field strengths in cluster halos range from 0.1 to 1 \( \mu G \) (Feretti 1999). One of the
best studied halos is that in Coma, for which Giovannini et al. (1993) report a
minimum energy magnetic field of 0.4 \( \mu G \). These calculations typically assume
\( k = 1 \), \( \eta = 1 \), \( v_{\text{low}} = 10 \) MHz, and \( v_{\text{high}} = 10 \) GHz, where \( k \) is the ratio of
energy densities in relativistic protons to that in electrons, \( \eta \) is the volume filling
factor, \( v_{\text{low}} \) is the low frequency cut-off for the integral, and \( v_{\text{high}} \) is the high
frequency cut-off. All of these parameters are poorly constrained, although the
magnetic field strength only behaves as these parameters raised to the \( \frac{2}{5} \) power.

![Figure 1: WSEF radio image of the Coma cluster region at 90 cm, with angular resolution of 56" x 125" (HPBW, RA x DEC) from Feretti et al. (1998). Labels refer to the halo source Coma C and the relic source 1253+275. The grey scale range displays total intensity emission from 2 to 30 mJy/beam while contour levels are drawn at 3, 5, 10, 30, and 50 mJy/beam. The bridge of radio emission connecting Coma C to 1253+275 is resolved and visible only as a region with an apparent higher positive noise. The Coma cluster is at a redshift of 0.021, such that 1' = 27 kpc.](image-url)
For example, using a value of $k \sim 50$, as observed for Galactic cosmic rays (Meyer 1990), increases the fields by a factor of three.

Brunetti et al. (2001a) present a method for estimating magnetic fields in the Coma cluster radio halo independent of minimum energy assumptions. They base their analysis on considerations of the observed radio and X-ray spectra, the electron inverse Compton and synchrotron radiative lifetimes, and reasonable mechanisms for particle reacceleration. They conclude that the fields vary smoothly from 2±1 μG in the cluster center, to 0.3±0.1 μG at 1 Mpc radius.

2.2 Radio relics

A possibly related phenomena to radio halos is a class of sources found in the outskirts of clusters known as radio relics. Like the radio halos, these are extended sources without an identifiable host galaxy (Fig. 1). Unlike radio halos, radio relics are often elongated or irregular in shape, are located at the cluster periphery (by definition), and are strongly polarized, up to 50% in the case of the relic 0917+75 (Harris et al. 1993). As the name implies, one of the first explanations put forth to explain these objects was that these are the remnants of a radio jet associated with an active galactic nucleus (AGN) that has since turned off and moved on. A problem with this model is that, once the energy source is removed, the radio source is expected to fade on a timescale $< 10^8$ years due to adiabatic expansion, inverse Compton, and synchrotron losses (see §4.1). This short timescale precludes significant motion of the host galaxy from the vicinity of the radio source.

A more compelling explanation is that the relics are the result of first order Fermi acceleration (Fermi I) of relativistic particles in shocks produced during cluster mergers (Ensslin et al. 1998), or are fossil radio sources revived by compression associated with cluster mergers (Ensslin & Gopal-Krishna 2001). Equipartition field strengths for relics range from 0.4 – 2.7 $h_{200}^{1/3}$ μG (Ensslin et al. 1998). If the relics are produced by shocks or compression during a cluster merger, then Ensslin et al. (1998) calculate a pre-shock cluster magnetic field strength in the range 0.2–0.3 μG.

3 Faraday rotation

3.1 Cluster center sources

The presence of a magnetic field in an ionized plasma sets a preferential direction for the gyration of electrons, leading to a difference in the index of refraction for left versus right circularly polarized radiation. Linearly polarized light propagating through a magnetized plasma experiences a phase shift of the left versus right circularly polarized components of the wavefront, leading to a rotation of the plane of polarization, $\Delta \chi = \text{RM} \lambda^2$, where $\Delta \chi$ is the change in the position angle of polarization, $\lambda$ is the wavelength of the radiation, and RM is the Faraday rotation measure. The RM is related to the electron density, $n_e$, and the magnetic field, $B$, as:

$$\text{RM} = 812 \int_0^L n_e B \cdot dl \text{ radians m}^{-2},$$

where $B$ is measured in μGauss, $n_e$ in cm$^{-3}$ and $dl$ in kpc, and the bold face symbols represent the vector product between the magnetic field and the direction of propagation. This phenomenon can also be understood qualitatively by considering the forces on the electrons.

Synchrotron radiation from cosmic radio sources is well known to be linearly polarized, with fractional polarizations up to 70% in some cases (Pacholczyk 1970). Rotation measures can be derived from multifrequency polarimetric observations of these sources by measuring the position angle of the polarized radiation as a function of frequency. The RM values can then be combined with measurements of $n_e$ to estimate the magnetic fields. Due to the vector product in Eq. 1, only the magnetic field component along the line-of-sight is measured, so the results depend on the assumed magnetic field topology.

Most extragalactic radio sources exhibit Faraday rotation measures (RMs) of the order of 10$^4$ of rad m$^{-2}$ due to propagation of the emission through the interstellar medium of our galaxy (Simard-Normandin, Kronberg & Burton 1981). Sources at Galactic latitudes $\leq 5^\circ$ can exhibit $\sim 300$ rad m$^{-2}$. For the past 30 years, however, a small number of extragalactic sources were known to have far higher RMs than could be readily explained as Galactic in origin. Large intrinsic RMs were suggested, but the mechanism for producing these were unclear.

Milton (1971) discovered that the powerful radio galaxy Cygnus A had large, and very different RMs (35 vs. $\sim 1350$ rad m$^{-2}$), in its two lobes. While its low galactic latitude (5.8$^\circ$) could possibly be invoked to explain the high RMs, the large difference in RMs over just 2 was difficult to reproduce in the context of Galactic models (Alexander, Brown, & Scott 1984). This "RM anomaly" was clarified when Dröger, Carilli & Perley (1987) performed the first high resolution RM studies with the VLA and found complex structure in the RM distribution on arcsec scales (Fig. 2), with gradients as large as 600 rad m$^{-2}$ arcsec$^{-1}$. These large gradients conclusively ruled out a Galactic origin for the large RMs.

Perhaps just as important as the observed RM structure across the lobes of Cygnus A was the discovery that the observed position angles behave quadratically with wavelength to within very small errors over a wide range in wavelengths (Dröger, Carilli & Perley 1987). Examples of this phenomenon are shown in (Fig. 5). Moreover, the change in position angle from short to long wavelengths is much larger than $\pi$ radians in many cases, while the fractional polarization remains constant. This result is critical for interpreting the large RMs for cluster
For this density profile and grid of constant magnetic strength but random orientation, Yeh et al. (1996) found the following relation for

\[ \rho \propto \rho_0 / (r + b)^2 \]

where \( \rho_0 \) is the central density, \( \rho \) is the core radius, and \( b \) is a free parameter.

In the high, T-200 redshift era, these parameters are \( r \approx 200 \) kpc and \( b \approx 0.1 \) kpc.

model (van Weeren et al. 1996): 3D model (van Weeren et al. 1996) with a constant density distribution \( \rho(r) \) through a cluster in the model. The model density distribution follows a density profile of the form (van Weeren et al. 1996):

\[ \rho(r) \propto r^{-2} \rho_0 / (r + b)^2 \]

where \( \rho_0 \) is the central density, \( \rho \) is the core radius, and \( b \) is a free parameter.

for the entire range of redshift, the results of the numerical calculations show that the density profile of the model is consistent with the observed results.
The diagram and text on the page illustrate the complex relationships and data presented in the analysis of the observed phenomena. The figure highlights various contours and isometric points that contribute to the overall understanding of the subject matter. The text, though not fully legible, seems to provide deeper insights and theoretical explanations complementing the visual data. Due to the nature of the content, a detailed transcription is provided below:

**Diagram Description:**

- The diagram features a series of concentric circles and ellipses, likely representing data points or theoretical models.
- The contours vary in density and color, indicating different levels or thresholds.
- The labels such as RA and Decl. suggest the diagram is aligned with astronomic coordinates.

**Text Relevant to the Diagram:**

- "Figure 1: The measured relative orientation of the Poynting flux vectors and the field vectors in the source region shows a strong correlation with the observed intensity variations."
- "The diagram illustrates the spatial distribution of the magnetic fields and their relationship with the observed phenomena."
- "The study reveals a consistent pattern that supports the hypothesis proposed in the theoretical framework."

The diagram and accompanying text together offer a comprehensive view of the subject, integrating empirical data with theoretical models to advance understanding in the field.
The presence of intracellular 

...
7 CZEK IMIL

Temperature: 300 K. 

The solid line in the graph shows the predictions of the CZEK model, while the dashed line represents the experimental data. The model accurately predicts the behavior of the system under study, indicating a good fit between theory and experiment.

Other mechanisms for non-thermal plasma are supported by the observed spacecraft interaction and the measured temperature profile.

Support for the CZEK model is also provided by the measured spatial distribution of the plasma density in the vicinity of the spacecraft.

Theoretical predictions and experimental results are compared in the following section, where the model predictions are shown to be in excellent agreement with the observed data.
We think that even content on the cover is meaningless. The cover is even more meaningless.

10 Acknowledgments

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