Proceedings of The Magnetized Plasma in Galaxy Evolution
Sep. 27th – Oct. 1st 2004, Jagiellonian University, Kraków, Poland
Eds. K.T. Chyży, K. Otmianowska-Mazur, M. Soida and R.-J. Dettmar

Magnetic Fields in Clusters of Galaxies

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Abstract

A brief overview about our knowledge on galaxy cluster magnetic fields is provided. Emphasize is given to the mutual dependence of our knowledge on relativistic particles in galaxy clusters and the magnetic field strength. Furthermore, we describe efforts to measure magnetic field strengths, characteristic length-scales, and power-spectra with reliable accuracy. An interpretation of these results in terms of non-helical dynamo theory is given. If this interpretation turns out to be correct, the understanding of cluster magnetic fields is directly connected to our understanding of intra-cluster turbulence.

1 What do we know?

We know that magnetic fields exist in clusters of galaxies for several reasons. First, in many galaxy clusters we observe the so-called *cluster radio halos* with a spatial distribution which is very similar to that of the intra-cluster gas observed in X-rays. These radio halos are produced by radio-synchrotron emitting relativistic electrons (cosmic ray electrons = CRe) spiraling in magnetic fields. We do not have direct evidence of cosmic ray protons (CRp) probably due to their much weaker radiative interactions. However, in our own Galaxy the CRp energy density outnumbers the CRe energy density by two orders of magnitude, which makes the assumption of a CRp population in galaxy clusters very plausible.

Second, the Faraday rotation of linearly polarized radio emission traversing the intracluster medium (ICM) proves independently the existence of intracluster magnetic fields. It has been debated, if the magnetic fields seen by the Faraday effect exist on cluster scales in the ICM, or in a mixing layer around the radio plasma which emits the polarized emission (Bicknell *et al.* 1990, Rudnick & Blundell 1990). However, there is no valid indication of a source local Faraday effect in the discussed cases (Enßlin *et al.* 2003), and the Faraday rotation signal excess of radio sources behind clusters compared to a field control sample strongly supports the existence of strong magnetic fields in the ICM (Clarke et al. 2001, Johnston-Hollitt & Ekers 2004). The detailed mapping of the Faraday effect of extended radio sources reveals that the ICM magnetic fields are turbulent, with power on a variety of scales, and with a power-spectrum which is Kolmogoroff-type (Sect. 4). All these Faraday rotation measurements support magnetic field strengths of the order of several μG.

The existence of ICM magnetic fields and cosmic rays is not too surprising, since there are plenty of energy sources available, which could have contributed:

- cluster mergers: shock waves and turbulence (*e.g.,* Miniati et al. 2000, 2001),
- active galactic nuclei (*e.g.,* Enßlin *et al.* 1997),
- injection by galactic winds, driven by supernovae (*e.g.,* Völk et al. 1996),
- galactic wakes (*e.g.,* Jaffe 1980, Roland 1981, Ruzmaikin et al. 1989),

- decaying/annihilating dark matter particles (*e.g.,* Colafrancesco & Mele 2001, Boehm et al. 2004).

2 Cosmic ray illumination of magnetic fields

In order to translate cluster radio halo emission into magnetic field estimates one requires some knowledge about the nature and properties of the relativistic electron population. Here, we will discuss the possibility that the radio emitting CRe are secondaries from hadronic interactions of a long-living CRp population within the ICM gas (*e.g.,* Dennison 1980, Vestrand 1982, Blasi & Colafrancesco 1999, Dolag & Enßlin 2000, Pfrommer & Enßlin 2004a): approximately once in a Hubble time, a CRp collides inelastically with a nucleon of the ambient ICM gas of non-cooling core clusters. Within cooling cores, such collisions are much more frequent due to the higher target densities. Such inelastic proton (p) nucleon (N) collisions hadronically produce secondary particles like relativistic electrons, positrons, neutrinos and γ-rays according to the following reaction chain:

$$\begin{aligned} p + N &\rightarrow 2N + \pi^{\pm/0} \\ \pi^{\pm} &\rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu} \rightarrow e^{\pm} + \nu_e/\bar{\nu}_e + \nu_{\mu} + \bar{\nu}_{\mu} \\ \pi^0 &\rightarrow 2\gamma\,. \end{aligned}$$

The resulting γ-rays can be detected directly with current and future γ-ray telescopes. The relativistic electrons and positrons (summarized as CRes) are visible due to two radiation processes: inverse Compton scattering of background photon fields (mainly the CMB, but also starlight photons) and radio synchrotron emission in ICM magnetic fields.

3 Hadronic minimum energy criteria

We estimated magnetic field strengths of radio emitting galaxy clusters by minimizing the non-thermal energy density — contained in relativistic electrons, protons, and magnetic fields — with respect to the magnetic field strength (Pfrommer & Enßlin, 2004b). As one boundary condition, the implied synchrotron emissivity is required to match the observed value. Additionally, a second boundary condition is required mathematically which couples CRps and CRes. For the *classical* minimum energy criteria, a constant scaling factor between CRp and CRe energy densities is assumed. However, if the physical connection between CRps and CRes is known or assumed, a physically better motivated criterion can be formulated. As such a case, we introduce the minimum energy criterion within the scenario of *hadronically* generated CRes.

Alongside, we provide theoretically expected tolerance regions which measure the deviation from the minimum energy states by one e-fold: We use logarithmic measures of the curvature radius at the extremal values in order to characterize the 'sharpness' of the minima. These regions have the meaning of a quasi-optimal realization of the particular energy densities.

The philosophy of this approach is to provide a criterion for the energetically least expensive radio synchrotron emission model possible for a given physically motivated scenario. There is no first principle enforcing this minimum state to be realized in nature. However, our minimum energy estimates are interesting in two respects: First, these estimates allow scrutinizing the hadronic model for extended radio synchrotron emission in clusters of galaxies. If

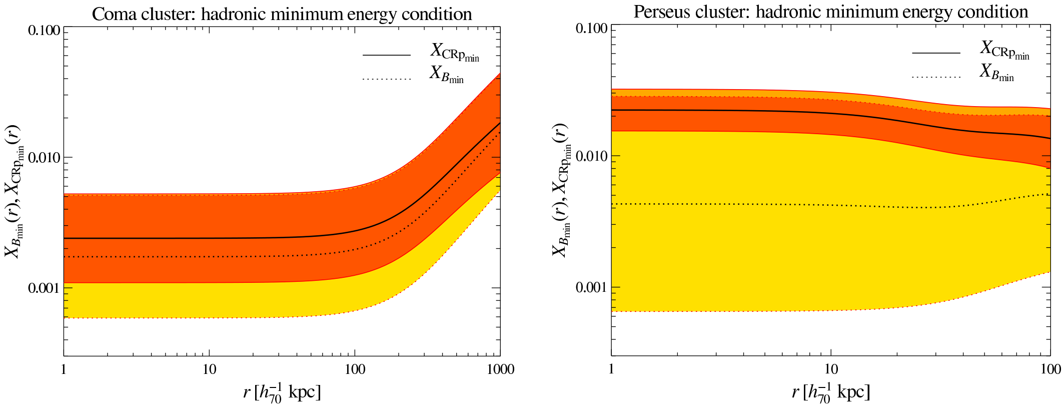

Figure 1: Profiles of the CRp-to-thermal energy density ratio $X_{\mathrm{CRp_{min}}}(r)$ (solid) and magnetic-to-thermal energy density ratio $X_{B_{\min}}(r)$ (dotted) as a function of deprojected radius are shown. The different energy densities are obtained by means of the hadronic minimum energy criterion. The **left panel** shows profiles of the Coma cluster while the **right panel** represents profiles of the Perseus cluster. The light shaded areas represent the logarithmic tolerance regions of $X_{B_{\min}}(r)$ and $X_{\mathrm{CRp_{min}}}(r)$, respectively, while the dark shaded regions indicate the overlap and thus the possible equipartition regions in the quasi-optimal case.

it turns out that the required minimum non-thermal energy densities are too large compared to the thermal energy density, the hadronic scenario will become implausible to account for the extended diffuse radio emission. In this respect, our criteria is a way to test the hadronic model with respect to the observationally available parameter space spanned by the CRp spectral index and the (unknown) distribution of the magnetic field strength (Pfrommer & Enßlin 2004a). Secondly, should the hadronic scenario be confirmed, the minimum energy estimates allow testing for the realization of the minimum energy state for a given independent measurement of the magnetic field strength.

Application to the radio halo of the Coma cluster and the radio mini-halo of the Perseus cluster yields equipartition between cosmic rays and magnetic fields within the expected tolerance regions. In the hadronic scenario, the inferred central magnetic field strength ranges from 2.4 μG (Coma) to 8.8 μG (Perseus), while the optimal CRp energy density is constrained to $2\% \pm 1\%$ of the thermal energy density (Perseus) (cf. Fig. 1). Pfrommer & Enßlin (2004b) discuss the possibility of a hadronic origin of the Coma radio halo while current observations favor such a scenario for the Perseus radio mini-halo. Combining future expected detections of radio synchrotron, hard X-ray inverse Compton, and hadronically induced γ-ray emission should allow an estimate of volume averaged cluster magnetic fields and provide information about their dynamical state.

4 Faraday rotation and magnetic power spectra

The estimates of the magnetic field strength of different methods differ significantly. Sub-micro-Gauss fields are obtained when analyzing the reported Extreme Ultraviolet (EUV) and Energy X-ray (HEX) excesses of the Coma cluster in terms of Inverse Compton (IC) scattering of CMB photons into theses bands (Lieu *et al.* 1996, Hwang 1997, Enßlin & Biermann 1998,

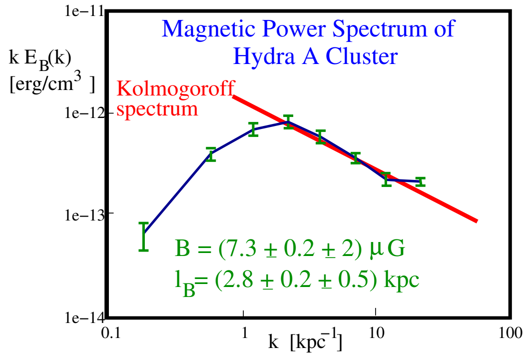

Figure 2: Magnetic power spectrum within the cooling flow region of the Hydra A cluster of galaxies (Vogt & Enßlin, submitted). The last data-point at large k-values is likely affected by map noise and should be discarded.

Fusco-Femiano *et al.* 1996, 2004, but see Rosetti & Molendi 2004, who do not find a significant HEX excess signal). Super-micro-Gauss fields are assumed in the context of the interpretation of Faraday rotation signals.

Both methods of field estimates have their weak points. The inverse Compton argumentation can only provide strict lower limits to magnetic fields strength. The used observed EUV or HEX flux could have (partially) resulted from a different source or could be a measurement artefact. Therefore, the number of relativistic electrons could be smaller than assumed in the estimate, requiring stronger magnetic fields in order to provide the same amount of observed synchrotron emission.

Faraday rotation based field estimates are also not straightforward, since magnetic field reversals along the line of sight partially cancel each other's Faraday signal. What is left as a typical cluster Faraday signal is the result of a random walk in rotation measure (RM) in the case of turbulent magnetic fields. The statistical RM signal depends on the statistical magnetic field strength times the square root of the magnetic autocorrelation length. The latter is unknown, and thus the Faraday based field estimates suffer from this uncertainty. However, the statistical properties of Faraday maps may allow to measure the magnetic autocorrelation length under relative reasonable assumptions of statistical isotropy and homogeneity of the magnetic fields (see Enßlin & Vogt 2003).

The Faraday rotation based field estimates can not be accommodated by sub-micro-Gauss field strength. For a typical cluster like Coma, $3 - 5\,\mu$G are reproducing the Faraday signal if a magnetic length-scale of 10 kpc is assumed. Lowering the magnetic field strength by one order of magnitude – as suggested by the IC based field estimates (in the case of the HEX excess) – would require an increase of the magnetic length scale to $\sim$ Mpc in order to reproduce the Faraday signal strength. But fields ordered on the cluster size would produce a nearly homogeneous RM signal, and not exhibit the many sign reversals observed in clusters.

For the Faraday rotation measurements an analysis would be highly desirable which shows if and how observational artefacts influence our field estimates. In order to go into this direction, methods to quantify the level of noise and artefacts in Faraday maps were developed (Enßlin *et al.* 2003). They were used to verify the improved quality of Faraday maps and even the accuracy of Faraday error maps generated with the new *Polarization Angle Correcting rotation Measure Analysis* (PACMAN) algorithm (Dolag et al. 2004, Vogt *et al.* 2004). These maps were then analyzed with a maximum likelihood power spectrum estimator (Vogt & Enßlin, submitted), which is based on the cross correlation of Faraday signals in pixel pairs, as expected for a given magnetic power spectrum and galaxy cluster geometry (Enßlin & Vogt 2003, Vogt & Enßlin 2003).

The result of this exercise is not only a magnetic power spectrum, which is corrected for the complicated geometry of the used radio galaxy and of the Faraday screen, but also an assessment of the errors, and even the cross correlation of the errors. The power spectrum of the Hydra A cluster cool core region, which is displayed in Fig. 2, exhibits a Kolmogoroff-like power law on small scales, a concentration of magnetic power on a scale of 3 kpc (the magnetic auto-correlation length) and a total field strength of $7 \pm 2\,\mu$G. The given error is the systematic error due to uncertainties in the Faraday screen geometry. The statistical error is lower by one order of magnitude.

5 Is a consistent picture possible?

Here, we are attempting to draw a consistent picture, which may explain at least a significant subset of the observational information:

- the Faraday rotation observations, which point towards turbulent fields strength of several μG strength: in the cool core region of the Hydra A cluster a field strength of 7μG correlated on 3 kpc; in non-cooling flow clusters like Coma somewhat lower fields (say 3μG) with a somewhat larger correlation length (say 10-30 kpc).
- the radio halo synchrotron emission of CRe in Coma
- the EUV excess of the Coma cluster, which may be understood as being inverse Compton scattered CMB light, and would favor field strength about $1.4\,\mu$G (e.g. Enßlin & Biermann 1998).

The Faraday measurements provide us with volume averaged magnetic energy densities, since the RM dispersion scales as $\langle \mathrm{RM}^2 \rangle \propto \langle B^2 \rangle_{\mathrm{Vol}}$. The synchrotron emission is also (approximately) proportional to the magnetic energy density, but weighted with the CRe population around 10 GeV: $L_{\mathrm{radio}} \propto \langle B^2\, n_{\mathrm{CRe}} \rangle_{\mathrm{Vol}}$. Finally, the IC flux is a direct measurement of the number density of CRe (of the appropriate energy to produce photons of the observational frequency): $L_{\mathrm{IC}} \propto \langle n_{\mathrm{CRe}} \rangle_{\mathrm{Vol}}$. Combining the latter two measurements provides a magnetic field estimate (for a given or assumed electron spectral slope), which is weighted with the CRe density: $\langle B^2 \rangle_{\mathrm{CRe}} = \frac{\langle B^2\, n_{\mathrm{CRe}} \rangle_{\mathrm{Vol}}}{\langle n_{\mathrm{CRe}} \rangle_{\mathrm{Vol}}} \propto \frac{L_{\mathrm{radio}}}{L_{\mathrm{IC}}}$

The magnetic energy density derived from the combination of synchrotron and inverse Compton flux is significantly lower than the one derived from RM measurements. This discrepancy might be reconciled if there is a significant difference between volume and CRe weighted averages. This would require inhomogeneous or intermittent magnetic fields, and a process which anti-correlates the CRe density with respect to the magnetic energy density. The latter could be synchrotron cooling in inhomogeneous magnetic fields. In case of an injection rate of CRe which is un-correlated with the field strength, as it is expected for the hadronic electron injection, the equilibrium electron density is $n_{\mathrm{CRe}} \propto (B^2 + B_{\mathrm{CMB}}^2)^{-1}$. Here $B_{\mathrm{CMB}} \approx 3.2\mu$G describes the field strength equivalent to the CMB energy density.

For illustration, we assume that only a small fraction $f_B = 0.1$ of the volume is significantly magnetized with a field strength of $10\,\mu$G, and the rest with only $1\,\mu$G. We will see later that $f_B = 0.1$ may be a plausible number. The volume average would give $\langle B^2 \rangle_{\mathrm{Vol}}^{1/2} = 3.3\,\mu$G, whereas the CRe average gives $\langle B^2 \rangle_{\mathrm{CRe}}^{1/2} = 1.5\,\mu$G. These numbers are in good agreement with the corresponding field estimates for the Coma cluster based on Faraday rotation and

IC/synchrotron measurements, respectively. A larger ratio in magnetic field estimates could even be accommodated since the EUV emitting electrons are at energies below the synchrotron electrons. A spectral bump of an old accumulated electron population at these energies is therefore possible, and even plausible due to the minimum in the electron cooling rate at these energies (Sarazin 1999).

It remains to be shown that there is also a natural mechanism producing intermittent magnetic fields. The Kolmogoroff-like magnetic power spectrum in the cool core of the Hydra A cluster indicates that the magnetic fields are shaped and probably amplified by hydrodynamical turbulence (*e.g.,* De Young 1992). Therefore, we have to look into the predictions of the theories of turbulent dynamo theories.

It is generally found by a number of researchers that the non-helical turbulent dynamo saturates in a state with a characteristic magnetic field spectrum (*e.g.,* Ruzmaikin *et al.* 1989, Sokolov *et al.* 1990, Subramanian 1999 and many others). The effective magnetic Reynolds number (including magnetic diffusivity due to gas motions caused by magnetic backreactions) reaches a critical value of $R_{\rm c} \approx 20$ ... 60. The magnetic fields should exhibit – more or less pronounced – the following properties:

A. The average magnetic energy density ε_B is lower than the turbulent kinetic energy density $\varepsilon_{\rm kin}$ by $\varepsilon_B \approx \varepsilon_{\rm kin}\, R_{\rm c}^{-1}$.

B. The magnetic fluctuations are concentrated on a scale l, which is smaller than the hydrodynamical turbulence injection scale L by $l \approx L R_{\rm c}^{-1/2}$.

C. Correlations exist up to scale L, turn there into an anti-correlation, and quickly decay on larger scales. This may be understood by Zeldovich's flux rope model, in which magnetic ropes with diameter l are bent on scales of the order L.

D. Within flux ropes, magnetic fields can be in equipartition with the average turbulent kinetic energy density.

E. The magnetic drag of such ropes produces a hydrodynamical viscosity on large scales, which is of the order of 4% of the turbulent diffusivity (Longcope *et al.* 2003).

Turbulent magnetic dynamo theory predicts intermittent magnetic fields, as favored by the proposed explanation of the discrepancy in the different magnetic field estimate methods. Let's see if the other predictions of the theory are in agreement with observations. We assume, that $R_{\rm c}$ is in the range 20 to 60.

A. The expected turbulent energy density in the Hydra A cluster core is of the order of $(0.3\dots1)\,10^{-10}\,{\rm erg\,cm^{-3}}$, which corresponds to turbulent velocities of $v_{\rm turb} \approx (300\dots500)$ km/s. This is comparable to velocities of buoyant radio plasma bubbles (Enßlin & Heinz 2002), which are expected to stir up turbulence (*e.g.,* Churazov *et al.* 2001).

B. The expected turbulence injection scale in the Hydra A cluster core is of the order of $(15\dots25)$ kpc, again consistent with the radio plasma of Hydra A being the source of turbulence. The dynamical connection of the radio source length scale and the magnetic turbulence scale would explain why the Faraday map of Hydra A is conveniently sized to show us the peak of the magnetic power spectrum.

C. Magnetic intermittency in form of flux ropes might have been detected as stripy patterns in the RM map of 3C465 (Eilek & Owen 2002).

D. The fraction of strongly magnetized volume can become as small as $f_{\rm B} = R_{\rm c}^{-1} \approx 0.02...0.05$, a value which is more extreme than what we assumed in our example for the Coma cluster.

E. The expected hydrodynamical viscosity on large scales in the Hydra cluster is of the order of $(1\ldots4)\cdot 10^{28}\,{\rm cm}^2/{\rm s}$. It is interesting to note, that a lower limit on the large scale viscosity of the comparable Perseus cluster cool core of $4\cdot 10^{27}\,{\rm cm}^2/{\rm s}$ was estimated by Fabian et al. (2003). An upper limit on the viscosity in the (somewhat different) Coma cluster of $\sim 3\cdot 10^{29}\,{\rm cm}^2/{\rm s}$ was derived by Schücker *et al.* (2004). Both limits are consistent with our coarse estimate of the large scale viscosity and enclose it.

6 Conclusion

It should have become clear that the existence of strong and possibly intermittent magnetic fields (several μG) in galaxy clusters is strongly supported by the recent detection of a Kolmogoroff-like magnetic power spectra in the Hydra A cluster. Some of the discrepancies between Faraday-based and inverse Compton-based field estimates can be explained by effects caused by magnetic intermittence, which is expected from turbulent dynamo theory.

Furthermore, it is argued that the hadronic generation mechanism of the cluster radio halo emitting electrons is a viable model (among others). This model is providing a number of stringent predictions (like minimal gamma ray fluxes, limits on spectral bending, maximal possible radio luminosities), which allow detailed consistency tests with future sensitive measurements. If this model is correct, the concept of hadronic minimum energy estimates can be introduced, and leads to magnetic field estimates which are well consistent with the ones derived from Faraday rotation measurements.

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