Magnetic turbulence in cool cores of galaxy clusters

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Abstract. The analysis of Faraday rotation measurements (RM) gives insight into the properties of cluster magnetic fields. Recently, Kolmogorov-like magnetic turbulence was reported for the cool core of the Hydra A galaxy cluster which was derived using a maximum likelihood analysis of an RM map of this cluster (Vogt & Enßlin 2005). Here, we present our understanding of this power spectrum by kinetic energy injection through active galaxies which drive a turbulent non-helical magnetic dynamo. We develop an analytical model of the turbulence in cool cores and show that it fits well to Faraday rotation measurements for a number of cool core clusters. Moreover, our model allows predictions for magnetic fields in clusters in which the appropriate observational information is still missing, and allows predictions for yet unobserved quantities like the hydrodynamical turbulence velocity and characteristic length scale, and suggests some level of magnetic intermittency and large-scale hydrodynamic viscosity.

Key words: galaxies: clusters: general – cooling flows – galaxies: magnetic fields

1. Introduction

It was a surprise when it was found that the strongest magnetic fields seem to be located in the centres of those clusters which were dynamically the most relaxed, since the last major merger was long ago. These *cooling flow* (now *cool core*) clusters had time to develop a cool, dense central region due to the cooling instability of optically thin X-ray emission of cooling gas. The magnetic fields reported for those cooling flow regions inferred by Faraday rotation studies were extraordinary strong (up to $50\,\mu$G) compared to the few μG fields reported for non-cooling flow clusters (for recent reviews see Carilli & Taylor 2002; Govoni & Ferretti 2004).

Magnetic fields in normal clusters and cool core clusters have revealed their existence by the diffuse radio halo emission in many clusters and radio mini-halos in cool core regions. Furthermore, the Faraday rotation of linearly polarised radio emission traversing the intra-cluster medium proves independently the existence of intra-cluster magnetic fields. If the Faraday active medium is external to the source of the polarised emission, one expects the change in polarisation angle to be proportional to the squared wavelength. The proportionality factor is called the rotation measure (RM). This quantity can be evaluated in terms of the line of sight integral over the product of the electron density and the magnetic field component along the line of sight.

For the case of the well studied cool core cluster Hydra A, a high quality Faraday rotation map of the northern lobe of its central radio source produced by the novel PACERMAN algorithm (Dolag, Vogt & Enßlin 2005; Vogt, Dolag & Enßlin 2005) based on the data of Taylor & Perley (1993) was analysed by Vogt & Enßlin (2005). They used a maximum likelihood estimator for the derivation of the magnetic power spectra, based on the theory of turbulent Faraday screens (Enßlin & Vogt 2003; Vogt & Enßlin 2003), and also using the most up-to-date gas density profile of the cool core, which turned out to make a crucial difference. Thereby, a magnetic field strength of $7 \pm 2\mu$G was found in the centre of the cool core region of the Hydra A cluster, which is still a significantly larger field than reported for non-cool core clusters. Vogt & Enßlin (2005) measured the detailed magnetic power spectrum from the Hydra A dataset, which revealed a Kolmogorov-type spectrum on small scales indicating turbulence (see Fig. 1).

The purpose of the work presented here is to propose a cool core working scenario which could explain the origin of this Kolmogorov-like power spectrum in the cool core of the galaxy cluster Hydra A. Furthermore, it is investigated if this working scenario could be applied also for other cool core clusters.

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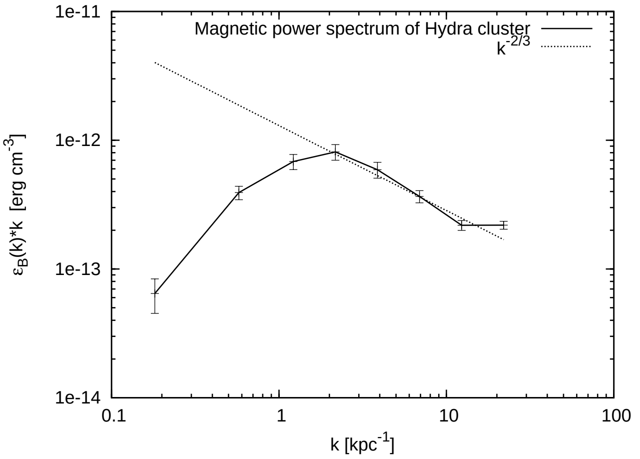

Fig. 1. Magnetic turbulence in the centre of the cool core cluster Hydra A as derived from the Faraday rotation map of the northern radio lobe of Hydra A by Vogt & Enßlin (2005). An angle of 45° between the line of sight and the approaching north-lobe was assumed in this figure. Variation of this angle changes the overall normalisation of the spectrum, but not its shape. The right-most data point is likely to be contaminated by observational noise in the Faraday map. A central root-mean-square magnetic field strength of $B_{\rm rms} = 7.3 \pm 0.2 \pm 2\,\mu$G and a magnetic autocorrelation length of $\lambda_B = 2.8 \pm 0.2 \pm 0.5$ kpc was derived by Vogt & Enßlin (2005). The first errors are the statistical uncertainties due to the limited statistics, whereas the systematic error is reflecting the uncertainties in the geometry of the radio source and the Faraday screen.

2. Turbulent magnetic dynamo

The Kolmogorov-like magnetic power spectrum in the cool core of the Hydra A cluster (Fig. 1) indicates that the magnetic fields are shaped and probably amplified by hydrodynamical turbulence (e.g. De Young 1992). Therefore, it seems most promising to us to seek the origin of the observed magnetic power spectrum in the theories of turbulent dynamos.

Since cool cores of galaxy clusters are not believed to rotate, the gas flow is probably non-helical and the galactic dynamo theories do not apply here. Instead, the non-helical turbulent dynamo (also called small-scale dynamo) should operate if the gas flow is sufficiently random, as it would be in the case of developed turbulence.

The random gas motion would stretch and fold any initial seed magnetic fields and lead to an exponential growth of the magnetic energy density with time with the characteristic time scale being the eddy turnover time. This proceeds as long as the dynamical back-reaction of the magnetic field is unimportant. The folding operations of the flow form small-scale magnetic reversals perpendicular to the local field directions (Schekochihin et al. 2002). Magnetic diffusivity limits the scales to be of the order of $\lambda_B \sim \lambda_{\rm T}\, R_{\rm m}^{-1/2}$, where $\lambda_{\rm T}$ is the turbulence injection scale, and $R_{\rm m}$ is the magnetic Reynolds number (Ruzmaikin, Sokoloff & Shukurov 1989). The typical bending radius of the fields should be of the order of the turbulence length scale $\lambda_{\rm T}$.

As soon as the Lorentz force becomes sufficiently strong, the fields do not follow the flow passively, but start to try to disentangle themselves. This back-reaction motion leads to an increase in the effective magnetic diffusivity, and therefore to a lower, renormalised magnetic Reynolds number implying fields to become organised on larger scales. The Reynolds number decreases until it reaches a critical value $R_{\rm c} \sim 10-100$ below which the turbulent dynamo would stop to operate. The system reaches a saturated state in which the magnetic correlation length scale $\lambda_B \sim \lambda_{\rm T}\, R_{\rm c}^{-1/2}$ is solely determined by the turbulence length scale and the critical Reynolds number.

Since various geometries of the magnetic structures in the saturated state have been proposed (e.g. Ruzmaikin, Sokoloff, & Shukurov 1989; Zeldovich, Ruzmaikin & Sokoloff 1990; Subramanian 1999; Subramanian, Shukurov & Haugen 2005), we assume that they are effectively d-dimensional.

Under the steady-state conditions of the saturated dynamo, the hydrodynamical dissipation of turbulent energy on scale $\lambda_{\rm T}$ and the relaxation of magnetic structures bent on the same scales $\lambda_{\rm T}$ should have the same time scales ($\tau_B \sim \tau_{\rm T}$). This implies that the magnetic fields within the structures are in equipartition with the environmental turbulent energy density ($\varepsilon_{\rm T}$), and the volume averaged magnetic energy density (ε_B) is therefore lower than these by the magnetic volume filling factor:

$$\varepsilon_B \sim \varepsilon_{\rm T}\, f_B \sim \varepsilon_{\rm T}\, R_{\rm c}^{-\frac{3-d}{2}}\,, \tag{1}$$

where f_B is the fraction of volume which is filled by magnetic fields. Thus, with the knowledge or assumption of the critical Reynolds number $R_{\rm c}$, and the effective dimensionality d of the magnetised regions, it is possible to translate properties of the hydrodynamical turbulence to the magnetic turbulence and vice versa, under the assumption that the system is in the saturated dynamo state.

3. Magneto-hydrodynamical turbulence in cool cores

Chandra and XMM observations revealed that the standard cooling flow picture, in which unheated gas cools down to neutral gas temperatures, must be incorrect, since the expected amount of line emission of cold (< 0.3 keV) gas or the expected number of stars formed from the condensing gas was not detected (e.g. Edge & Frayer 2003; Salomé & Combes 2003; and many others). Therefore a heat source has to be present which balances the cooling of the coldest gas. The energy losses of the cool core have to be balanced by a similar energy injection.

In this work, we adopt a scenario in which the central radio galaxy balances the radiative energy losses of the cool core which provides naturally fine tuning in form of a self-adapting feedback mechanism: If the radio galaxy activity is triggered by cold gas condensing out of the cool core onto the central galaxy, the galaxy activity increases until it disrupts further accretion (Churazov et al. 2001). We assume this scenario, not only since it is – at least in our view – theoretically more compelling, but also because it predicts a certain level of hydrodynamical turbulence, which can be compared to the level required to explain the cool core magnetic fields by magnetic dynamo theory.

A cool core is a condensation of cold gas of mass $M_{\rm cc}$, which dropped out of the hot phase of a galaxy cluster due to the faster radiative cooling of denser gas. The observables of the cool core, which can be used for diagnostics of the physical parameters, are the bolometric X-ray luminosity of the cool core $L_{\rm cc}$, its temperature $T_{\rm cc}$, and its radius $r_{\rm cc}$, from which the central electron density $n_{\rm cc}$ can be deduced.

In our picture, the injection from radio galaxies is the dominant heating mechanism. When a radio bubble raises buoyantly in the cool core atmosphere, the environmental gas is flowing around it, which leads to injection of kinetic energy from the central radio galaxy into the cool core. This injected kinetic energy is dissipated through a Kolmogorov-cascade within an eddy turnover time. Furthermore, since the turbulence is stirred by the movement of buoyant radio plasma bubbles, the turbulence injection scale should be of the order of the radius of the bubbles.

Using this simplified description, equations can be derived (Enßlin & Vogt 2005) which allow the determination of the turbulent energy density $\varepsilon_{\rm T}$. The energy density of the magnetic turbulence ε_B is lower by a factor $f_B \sim 0.05\ldots 0.2$ (see Eq. (1)). The length scale is also smaller by a factor $R_{\rm c}^{-1/2}$. Thus, one can make rough estimates for the magnetic energy density in a cool core if the values of observables (i.e. $L_{\rm cc}, M_{\rm cc}, r_{\rm cc}, T_{\rm cc}$) are known from X-ray measurements and a cool core scenario as described here is assumed.

One can go one step further and try to predict the Faraday rotation measure (RM) dispersion caused by such a magnetic energy. This can be done if one knows the depth of the Faraday screen $r_{\rm cc}$, the magnetic field strength $\langle B^2\rangle^{1/2}$, and the magnetic autocorrelation length λ_B, assuming an isotropic distribution of magnetic field strengths and the help of Eq. (40) of Enßlin & Vogt (2003).

A more detailed discussion and derivation is given in Enßlin & Vogt (2005).

4. Application to cool cores

In the following, we apply our model to a number of cool core clusters. Here, we assume a magnetic field topology where the magnetic fields are organised in flux tubes (d = 1, $R_{\rm c}$ = 20). The input parameters of our calculations are the central electron density $n_{\rm cc}$, the central gas temperature $T_{\rm cc}$, and the core radius $r_{\rm cc}$ of the cool core. The numbers are taken from the literature and the corresponding references are given in the caption of Tab. 1. The cluster parameters and the derived properties are summarised in Tab. 1.

The other quantities in Tab. 1 are calculated according to the formulae given in Enßlin & Vogt (2005). Only the observed rotation measure dispersion $RM_{\rm rms}^{\rm obs}$ is taken from the literature and its references are given in the caption of Tab. 1. Note that our expected $RM_{\rm rms}^{\rm exp}$ is calculated for a polarised synchrotron source in the middle of the cool core, whereas the real radio emitting volume may be displaced due to an inclination between radio jet and line-of-sight, and/or due to a non-central position. This will cause some deviation of our expectations from the observations and usually biases the observational values to be lower.

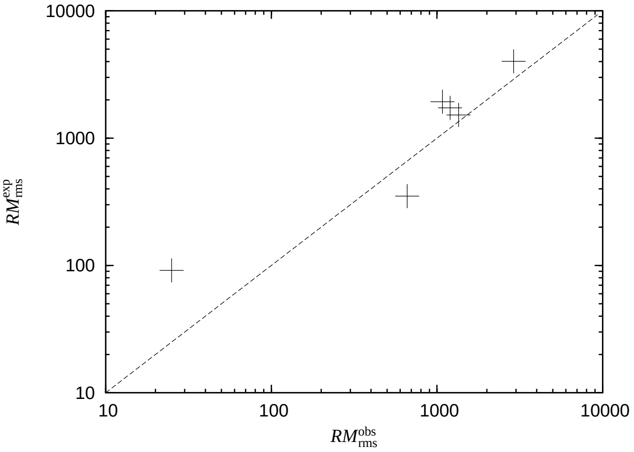

Fig. 2. Comparison of observed (cross) and theoretically expected (case $d = 1$, $R_{\rm c} = 20$) (dashed line) root-mean-squared RM signal. Note that the expected RM is calculated for a radio source located at the centre of the cluster, whereas most RM measurements are somewhat off-centre, probably leading to a reduced observed signal.

Fig. 2 compares the expected RM dispersion with the observed one. It can be seen that they usually do not deviate by more than a factor of two. To summarise our results, we find that the scenario described here predicts rotation measures which are of the same order of magnitude as the observed ones. In cases where observational estimates for field strength and length scales existed, there is also a better than order of magnitude agreement. We would not expect our model to be more accurate than within a factor of two.

5. Conclusion

We propose a steady state scenario for the hydrodynamical and magnetic turbulence, assuming that the turbulent feedback from the central radio source compensates for the cool core radiative losses. This scenario predicts turbulent length scales and energy densities which can be compared to observations.

For a sample of prominent cool core clusters, we calculate the expected hydro- and magnetic-turbulence, and the predicted RM dispersion. We find that our estimates reproduce the observed magnitude of the Faraday dispersion over roughly two orders of magnitude in RM (or four in $\langle RM^2\rangle$). On average, our predictions are a factor of two higher than the measurements, which is not too surprising, since the actual data sample larger cluster radii, whereas our estimates are aiming for a radio source at the cluster centre.

The critical reader might wonder about the amount of fine tuning which went into our model. The answer is: nearly none, but this is probably a mere coincidence rather than a proof for the investigated scenario. There are various places in the calculation where factors of order one could or should have been introduced. An uncertain area are the adopted parameters of the dynamo theory, which have also not fully been settled in the literature yet.

Nevertheless, we have shown that the straight-forward application of current concepts of turbulent magnetic dynamos,

Cluster properties	Hydr.	Cent.	Cygn.	A1958	A2597	3C31
$\mathrm{n_{cc}}$ $[10^{-3}\,\mathrm{cm^{-3}}]$	56.1	80.6	153	189	73.5	180
$\mathrm{T_{cc}}$ [keV]	2.7	2.2	6.5	3.7	1.3	0.7
$\mathrm{r_{cc}}$ [kpc]	35.5	8.57	10.7	13.4	28	1.2
$\mathrm{RM_{rms}^{obs}}$ $[\mathrm{rad\,m^{-2}}]$	1350	660	1200	2900	1080	25
L_{cluster} $[10^{44}\,\mathrm{erg/s}]$	4.61	0.32	1.79	6.22	6.89	0.077
$L(< r_{\mathrm{cooling}})/L_{\mathrm{cluster}}$	0.52	0.41	0.49	–	0.61	–
Hydrodynamical turbulence						
$\lambda_B \sim r_{\mathrm{bub}}$ [kpc]	7.68	1.45	1.7	2.84	7.52	0.2
ε_{T} $[10^{-10}\,\mathrm{erg\,cm^{-3}}]$	0.29	0.16	0.76	1.27	0.35	0.12
v_{T} [km/s]	250	156	244	283	240	87.5
Magnetic turbulence	$d = 1$ (flux ropes) $R_{\mathrm{c}} = 20$					
λ_B [kpc]	1.72	0.32	0.38	0.64	1.68	0.045
B_{rms} $[\mu\mathrm{G}]$	6.06	4.55	9.78	12.6	6.68	3.8
$\mathrm{RM_{rms}^{exp}}$ $[\mathrm{rad\,m^{-2}}]$	1520	351	1730	4010	1930	91.5
$\mathrm{RM_{rms}^{obs}/RM_{rms}^{exp}}$	0.89	1.88	0.69	0.72	0.56	0.27

Table 1. Application of the model to cool cores of the following clusters of galaxies: Hydra A (gas: Mohr & Evrard 1997; Ikebe et al. 1997; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Vogt, Dolag & Enßlin 2005), Centaurus (gas: Mohr, Mathiesen & Evrard 1999; White 2000; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Taylor, Fabian & Allen 2002), Cygnus A (gas: Mohr, Mathiesen & Evrard 1999; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Dreher, Carilli & Perley 1987), A1985 (gas: Allen et al. 2001, 2003; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Allen et al. 2001), A2597 (gas: Pollack, Taylor & Allen 2005; David et al. 1993; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Pollack, Taylor & Allen 2005), 3C31 (gas: Hardcastle et al. 2002; Komossa & Böhringer 1999; $RM_{\mathrm{rms}}^{\mathrm{obs}}$: Laing, private communication). The first part of the table contains the cluster parameters whose values were taken from the literature. The second part describes the expected hydrodynamical turbulence (where v_{T} is the hydrodynamical turbulence velocity). The third part describes the expected magnetic turbulence for the scenario of magnetic flux ropes ($d = 1$).

in combination with the emerging picture of cool core stabilisation via heat injection due to the dissipation of turbulence seeded by radio galaxy feedback, leads to expectations for the Faraday rotation signal which match well with the observed ones. This is the case for a variety of galaxy clusters spanning two orders of magnitude in their X-ray luminosities. Therefore, our picture of cluster cool core heating by radio galaxy feedback and the theory of turbulent magnetic dynamos passed a critical test.

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