The origin and evolution of cluster magnetism

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Abstract. Random motions can occur in the intergalactic gas of galaxy clusters at all stages of their evolution. Depending on the poorly known value of the Reynolds number, these motions can or cannot become turbulent, but in any case they can generate random magnetic fields via dynamo action. We argue that magnetic fields inferred observationally for the intracluster medium require dynamo action, and then estimate parameters of random flows and magnetic fields at various stages of the cluster evolution. Polarization in cluster radio halos predicted by the model would be detectable with the SKA.

Key words: Galaxies: clusters: general – galaxies: intergalactic medium – galaxies: magnetic fields – MHD – turbulence

1. Introduction

We witness the epoch when galaxy clusters are being formed. Galaxies and smaller-size structures have generally achieved (quasi-)steady states in their evolution, whereas structures of larger scales keep evolving. There is abundant evidence of formation processes in galaxy clusters, including the merger of large masses comparable to the cluster mass. Relaxed, symmetric galaxy clusters are rare. Thus, most constituents of the clusters keep evolving. Our particular interest here is with motions of the gas and magnetic fields in the intergalactic space of evolving galaxy clusters. The epoch of major mergers is notable for widespread, intense random motions, followed by a period of decaying flows. In a steady state, random motions can be confined to the wakes produced by the cluster galaxies and smaller mass subcluster clumps that continue falling into the cluster; as we argue here, these motions are likely to occupy a small fraction of the total volume.

The high electrical conductivity of the intracluster gas is not sufficient to ensure the survival of a magnetic field captured by the forming cluster. The reason is that the intracluster gas is very viscous, and any inhomogeneous magnetic field would drive gas motions which will rapidly decay, thereby converting magnetic energy into heat. Even for a small viscosity, the field would decay by driving decaying MHD turbulence. On the other hand, random gas motions of the intracluster gas can be efficient generators of (random) magnetic fields via a process known as the fluctuation dynamo.

The origin and properties of magnetic field in the intracluster plasma cannot be understood without knowing the nature and parameters of the plasma motions. The reason is that the magnetic Reynolds number in the intracluster gas is large, hence magnetic induction effects are strong for any plausible speed of gas motion. Our model of gas motions and magnetic fields in galaxy clusters, presented and justified in detail by Subramanian et al. (2006), is in close agreement with the available data. It predicts that magnetic field in the intracluster gas is represented by magnetic sheets of a thickness 20–30 kpc, with magnetic field strength about 2–$4\,\mu$G within the sheets. These structures fill about 20% of the volume of a single turbulent cell. Apart from this intermittent component, magnetic field also has a weaker, widely distributed part.

We propose that, at late stages of cluster evolution, turbulence is confined to the wakes of galaxies and infalling mass clumps, and does not fill the volume. However, the area covering factor of the wakes can be close to unity, so most lines of sight pass through a turbulent region. This can help to reconcile the available evidence of turbulence in such clusters as Perseus with the existence of long filaments in the intracluster gas that seem to be inconsistent with pervasive turbulence.

Since typical lines of sight through a cluster pass through a small number of turbulent cells, synchrotron emission from galaxy clusters can show a detectable degree of polarization at wavelengths 3–6 cm.

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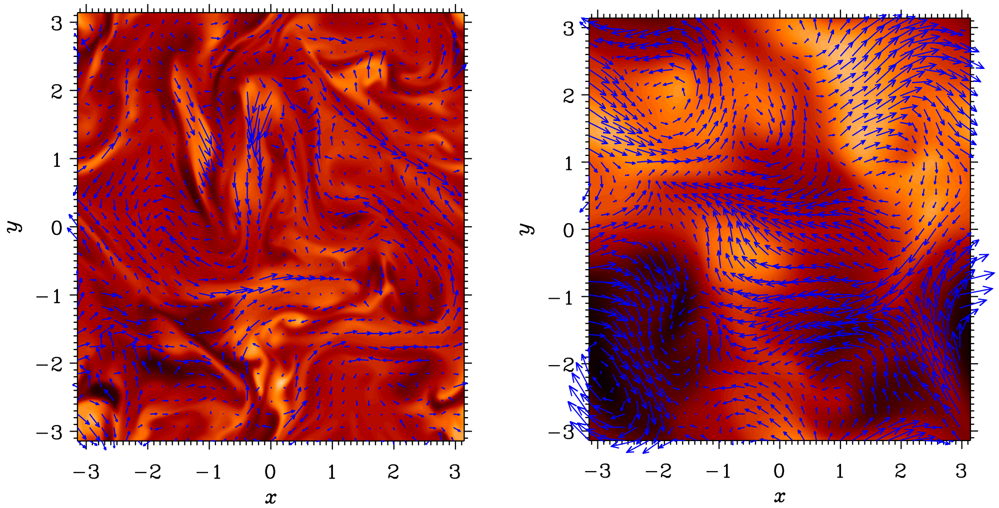

Fig. 1. Snapshots of magnetic field in a cross-section through the middle of the computational domain in a numerical simulation of turbulence driven by an imposed random force and its dynamo action. The left-hand panel shows a statistically steady state at a time $t/t_{0\mathrm{i}} = 0.30$ whereas the right-hand panel illustrates magnetic field structures in turbulence at a late stage of decay, $t/t_{0\mathrm{i}} \approx 60$. Here $t_{0\mathrm{i}}$ is the eddy turnover time before the start of the turbulence decay (given in Table 1). The dimensionless energy injection scale in these simulations is about 4 (with the domain size of 2π), so each frame contains a few turbulent cells. The strongest magnetic field within the frame is close to the equipartition value with respect to the turbulent energy. The magnitude of the field component perpendicular to the plane of the figure is shown color coded (in shades of grey) with black corresponding to field pointing into the figure plane, and lighter shades, to field pointing out of the plane. The field in the plane of the figure is shown with vectors whose length is proportional to the field strength.

2. Three evolutionary stages

2.1. The epoch of major mergers

Theories of hierarchical structure formation suggest that clusters of galaxies have been assembled relatively recently. N-body simulations indicate that the clusters form at the intersection of dark matter filaments in the large-scale structure, and result from both major mergers of objects of comparable mass (of order $10^{15} M_\odot$) and the accretion of smaller clumps onto massive protoclusters. It is likely that intense random vortical flows, if not turbulence, are produced in the merger events. Their plausible properties are summarized in Table 1. The structure of magnetic field at this stage is illustrated in the left-hand panel of Fig. 1. What is shown is the statistically steady state of magnetic field produced by dynamo action in turbulent flow with the Reynolds number about 400 and the magnetic Prandtl number equal to unity. Similar magnetic structure plausibly occur in the turbulent wakes of subclusters and galaxies as well.

It is not quite clear whether random flows driven during major merger events and at later stages of evolution will develop into turbulence. The nature of the flow depends on the value the Reynolds number which is difficult to estimate reliably for the collisionless, magnetized plasma of the intracluster space where plasma instabilities can be responsible for anomalous viscosity and resistivity (Schekochihin et al. 2005). The problem is further complicated by the possibility of dynamo action, since the magnetic field can affect both viscosity and magnetic diffusivity. This may lead to the growth of the magnetic diffusivity and reduction of viscosity as the magnetic field is being amplified by the dynamo, so that the magnetic Prandtl number tends to unity.

2.2. Decaying turbulence

Random flows produced by major mergers decay after the end of the merger event. Unlike a laminar flow that decays exponentially in time due to viscosity, turbulent kinetic energy decays slower, as a power law (e.g., Landau & Lifshitz 1975; Frisch 1995). The reason for this is that kinetic energy mainly decays at small scales, to where it is constantly supplied by the turbulent cascade. As a result, the energy decay rate depends nonlinearly on the energy itself, which makes the decay a power law in time. Our simulations confirm that the power-law decay occurs even for the Reynolds number as small as $\mathrm{Re} \approx 100$. At this stage of evolution, the turbulent scale l_0 grows with time, whereas turbulent energy density E reduces, together with the turbulent speed v_0, typically as

$$E \simeq \tfrac{1}{2} v_0^2 \propto (t/t_{0\mathrm{i}})^{-6/5}, \quad l_0 \propto (t/t_{0\mathrm{i}})^{2/5} \quad \text{for } t/t_{0\mathrm{i}} \gg 1 ,$$

where subscript ‘i’ refers to the start of the evolution, $t_{0\mathrm{i}}$ is a certain dynamical time scale, which can be identified with the initial turnover time of the energy-containing eddies, $t_{0\mathrm{i}} = l_{0\mathrm{i}}/v_{0\mathrm{i}}$, subscript ‘0’ refers to the energy-range (correlation) scale of the motion. The structure of magnetic field in the decaying flow is shown in the right-hand panel of Fig. 1, and parameters of the flow and magnetic field are shown in the second line of Table 1.

Table 1. Summary of turbulence and magnetic field parameters at various stages of cluster evolution: duration of the stage (the last two stages represent steady states), the r.m.s. velocity v_0 and scale l_0 of turbulence and eddy turnover time $t_0 = l_0/v_0$ (for the decaying turbulence, values for the middle of the decay stage are given, 2 Gyr after its start), the equipartition magnetic field $B_{\rm eq} = (4\pi\rho v_0^2)^{1/2}$ with ρ the gas density (i.e., maximum field strength within a turbulent cell), thickness of magnetic filaments and sheets l_B for the statistically steady state of the dynamo, the r.m.s. magnetic field within a turbulent cell $B_{\rm rms}$, and finally the standard deviation of the Faraday rotation measure $\sigma_{\rm RM}$ (calculated for the volume filling turbulence along path length of $750\,{\rm kpc}$ through the central parts of a cluster in the first two lines, and assuming one transverse wake along the line of sight in the last two lines). A subcluster mass of $3\times10^{13}M_\odot$ has been assumed.

Evolution stage	Duration (Gyr)	v_0 $({\rm km\,s^{-1}})$	l_0 (kpc)	t_0 (Gyr)	$B_{\rm eq}$ (μG)	l_B (kpc)	$B_{\rm rms}$ (μG)	$\sigma_{\rm RM}$ $({\rm rad\,m^{-2}})$
Major mergers	4	300	150	0.5	4	25	1.8	200
Decaying turbulence	5	130	260	2.0	2	44	0.8	120
Subcluster wakes		260	200	0.8	4	34	1.6	110
Galactic wakes		300	8	0.03	4	1.4	1.6	5

2.3. Turbulent wakes of subclusters and galaxies

At the final stage of the evolution, when the cluster enters a steady state, turbulence is maintained only in the wakes of galaxies and smaller mass clumps that continue to accrete onto the cluster. The wakes become weaker as the gas within the clumps or galaxies is stripped by the ram pressure of intracluster gas. The radius of a wake at its head is close to the radius within which gas of the mass clump or galaxy remains intact. We estimate the stripping radius as $R_0 \simeq 100\,{\rm kpc}$ for clumps of a mass $10^{13}M_\odot$ (which fall into a cluster every 3 Gyr) and $R_0 = 3$–$5\,{\rm kpc}$ for massive elliptical galaxies. If the flow within the wake becomes turbulent (so that it can be described in terms of Prandtl's theory of turbulent wakes), the wake length X is controlled by the magnitude of the Reynolds number via

$$X/R_0 \simeq ({\rm Re_i}/{\rm Re_{cr}})^3 ,$$

where ${\rm Re_{cr}} \approx 400$ (Tomboulides & Orszag 2000) is the marginal Reynolds number with respect to the onset of turbulence. This value of ${\rm Re_{cr}}$ was obtained for a flow around a solid sphere; ${\rm Re_{cr}}$ for gas spheres is not known. The strong dependence of the wake parameters on the Reynolds number makes the estimates somewhat uncertain. On the other hand, it implies that galactic wakes can be very sensitive to the detailed parameters of the galactic motion and intergalactic gas, so that clusters with very similar parameters can have vastly different wake structures.

The area covering and volume filling factors, f_S and f_V, respectively, of $N = 5$ wakes, produced by $10^{13}M_\odot$ subclusters, within the virial radius $r \approx 3\,{\rm Mpc}$, are estimated as

$$f_S \simeq 0.15\,\frac{N}{5}\,\left(\frac{R_0}{100\,{\rm kpc}}\right)^6\left(\frac{\rm Re_{cr}}{400}\right)^{-4}\left(\frac{\tilde\lambda}{1\,{\rm kpc}}\right)^{-4} ,$$

$$f_V \simeq 0.02\,\frac{N}{5}\,\left(\frac{R_0}{100\,{\rm kpc}}\right)^8\left(\frac{\rm Re_{cr}}{400}\right)^{-5}\left(\frac{\tilde\lambda}{1{\rm kpc}}\right)^{-5} ,$$

where $N \approx 5$ is consistent with models of hierarchical structure formation, and $\tilde\lambda$ is an effective mean free path in the intracluster gas (its introduction is an attempt to allow for our insufficient understanding of viscosity mechanisms). The covering and filling factors strongly depend on $\tilde\lambda$ and ${\rm Re_{cr}}$. Furthermore, both f_S and f_V depend on high powers of another poorly known parameter, the stripping radius R_0. Hence, as noted above, properties of the subcluster wakes can be rather different in apparently similar clusters. In addition, numerical simulations of turbulent wakes should be treated with caution as otherwise reasonable approximations, numerical resolution, and numerical viscosities can strongly affect the results. On the other hand, it is plausible that $f_S = O(1)$ but $f_V \ll 1$, so that a typical line of sight through the cluster intersects at least one turbulent region (where our estimate of the r.m.s. turbulent speed is 200–$300\,{\rm km\,s^{-1}}$) despite the fact that turbulence occurs only in a small fraction of the cluster volume. Thus the presence of long Hα filaments observed by Fabian et al. (2003, 2006) in the core of the Perseus cluster may not be inconsistent with various evidence for random motions in this cluster core (Churazov et al. 2004; Rebusco et al. 2006). A possible signature of such spatially intermittent turbulence could be a specific shape of spectral lines, with a narrow core, produced in quiescent regions, accompanied by nonthermally broadened wings.

The area covering factor of galactic wakes within the gas core radius, 180 kpc, is unity if

$$X/R_0 \simeq 30\text{–}15\,, \quad X \simeq 100\text{–}70\,{\rm kpc}\,, \tag{1}$$

and the volume filling factor of such wakes is $f_V \simeq 0.07$. The length of galactic wakes required to cover the projected cluster area, given by Eq. (1), does not seem to be unrealistic. For example, Sakelliou et al. (2005) have observed a wake behind a massive elliptical galaxy (mass of order $2\times10^{12}M_\odot$) moving through the intracluster gas at a speed about $v_{\rm c} \simeq 1000\,{\rm km\,s^{-1}}$. The length of the detectable wake is about $X \simeq 130\,{\rm kpc}$ (assuming that it lies in the sky plane), and its mean radius is $40\,{\rm kpc}$ (obtained from the quoted volume of about $2\times10^6\,{\rm kpc}^3$). The projected area of the wake is about $10^4\,{\rm kpc}^2$, as compared to $10^3\,{\rm kpc}^2$ for the wake parameters derived above. This wake has been detected only because it is exceptionally strong, and it is not implausible that weaker but more numerous galactic wakes can cover the projected area of the central parts of galaxy clusters.

We conclude that subcluster wakes are likely to be turbulent, but galactic wakes can be laminar if the viscosity of the intracluster gas is as large as Spitzer's value. Given the uncertainty of the physical nature (and hence, estimates) of the viscosity of the magnetized intracluster plasma, we suggest that turbulent galactic wakes remain a viable possibility. Both types of wake have low volume filling factor but can have an area covering factor of order unity. Parameters of turbulence and magnetic fields produced within the wakes are given in the last two lines of Table 1.

3. Intracluster magnetic fields and their observational signatures

A random flow of electrically conducting fluid (either turbulent or not) can generate and maintain magnetic field if the magnetic Reynolds number $R_{\rm m} = v_0 l_0/\eta$ exceeds a certain critical value, $R_{\rm m} > R_{\rm m,cr}$ where $R_{\rm m,cr}$ depends on the statistical properties of the flow and usually remains within the range $R_{\rm m,cr} = 30$–100 (here η is the magnetic diffusivity). This condition is undoubtedly satisfied in the intracluster plasma, where $R_{\rm m} \gg 1$ (unlike the kinematic Reynolds number $\rm Re$ which may be quite modest), and so the dynamo action in galaxy clusters is more than plausible. This type of dynamo, known as the fluctuation dynamo because it produces fluctuating magnetic fields with zero mean value, does not require any overall rotation, density stratification, α-effect, etc. Reviews of fluctuation dynamos can be found in Zeldovich et al. (1990) and Brandenburg & Subramanian (2005).

At an early stage of the dynamo action, when magnetic fields are still too weak to affect the flow, magnetic energy density grows exponentially. The e-folding time of the r.m.s. magnetic field generated by motions of a scale l and speed v is of the order of $\tau \simeq l/v$. In Kolmogorov turbulence (and in any random flow with a sufficiently steep energy spectrum), the e-folding time is shorter at smaller scales, so that magnetic energy spectrum has maximum at small scales, close to the magnetic diffusion scale $l_\eta = l_0 R_{\rm m}^{-d}$ with $d = 1/2$ (Kazantsev 1967; Zeldovich et al. 1990; Schekochihin et al. 2004) or $d = 3/4$ for the marginal mode in Kolmogorov turbulence (Brandenburg & Subramanian 2005 and references therein). Thus, magnetic field is concentrated into magnetic sheets (and filaments) of thickness l_η and length of order l_0. The field strength within the magnetic structures is, at saturation, close to equipartition with kinetic energy, $B \simeq B_{\rm eq} = (4\pi\rho v_0^2)^{1/2}$, where ρ is the gas density. An application of this theory to galaxy clusters is discussed by Ruzmaikin et al. (1989), although these authors presumed that turbulence produced in galactic wakes can be volume-filling.

The nonlinear stage of the fluctuation dynamo, where the growth of magnetic energy saturates because of the action of the Lorentz force on the flow, is more controversial (Brandenburg & Subramanian 2005). We consider plausible a model of the nonlinear dynamo suggested by Subramanian (1999); this model is consistent with numerical simulations of the fluctuation dynamo, especially for systems with unit magnetic Prandtl number (Subramanian et al. 2006 and references therein). In this model, the thickness of magnetic structures in the saturated dynamo is of the order of the magnetic diffusion scale, but now based on the *critical* value of the magnetic Reynolds number,

$$l_B \simeq l_0 R_{\rm m,cr}^{-1/2} \,.$$

This scale is given in Table 1 for various stages of evolution, together with the magnetic field within magnetic structures, $B_{\rm eq}$ and the resulting r.m.s. magnetic field within a turbulence cell, $B_{\rm rms}$. Table 1 also contains estimates of the r.m.s. value of the Faraday rotation measure, $\sigma_{\rm RM}$ produced in the dynamo-generated magnetic field; the estimates agree with observations fairly well. Our numerical simulations of the fluctuation dynamo, where we directly measure $\sigma_{\rm RM}$, also confirm our semi-analytical estimates.

Our model implies that the correlation scale of random motions in the intracluster gas, l_0, is larger than that assumed earlier. With $l_0 \simeq 150\,{\rm kpc}$ (Table 1), only 5 turbulent cells occur along a path length of $L = 750\,{\rm kpc}$. The resulting degree of polarization of radio emission from clusters with synchrotron halos can be estimated as $p \simeq \frac{1}{2}p_0/n^{1/2} \simeq 0.2$, where $p_0 \approx 0.7$, $n \simeq L/l_0$ is the number of magnetic structures along the line of sight (assuming that one magnetic sheet with well-ordered magnetic field occurs in each turbulent cell and that the linear resolution is better than l_0), and a factor $1/2$ allows, in a very approximate manner, for the volume-filling magnetic field outside the magnetic sheet which only produces unpolarized emission. Depolarization by Faraday dispersion and beam depolarization can reduce the degree of polarization to a fraction of percent at long wavelengths. However, polarization observations at wavelengths 3–6 cm (where Faraday depolarization is sufficiently weak) can reveal magnetic structures produced by the dynamo action if the angular resolution is high enough. Such observations can become feasible for many galaxy clusters with the advent of the SKA (Feretti & Johnston-Hollitt 2004).

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