TURBULENCE AND MAGNETIC FIELDS IN CLUSTERS OF GALAXIES

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Abstract. We consider turbulence generated by galaxies moving transonically through the intracluster gas. We show that neither the gravitational drag nor the gas stripping from the galaxies are able, by themselves, to generate turbulence at a level required to feed the dynamo in the intracluster gas. Some implications for cluster radio halos are discussed.

1. Introduction

Many clusters of galaxies have been searched for extended radio halos. Magnetic fields in the hot (10^8 K), ionized intracluster medium (ICM) are revealed by diffuse radio emission, by excess of Faraday rotation and by asymmetric depolarization of radio sources embedded in the cluster (Kronberg 1994). There are two separate problems with no current consensus: the acceleration of relativistic electrons and the amplification of the magnetic field in the ICM (e.g. Sarazin 1986). Here we will focus on the second one.

Polarization measurements give information on the mean line-of-sight component of the field weighted by the gas density. It is inferred that magnetic fields in the ICM are random, tangled at scales 10–20 kpc, and are detected out to 500 kpc in radius, considerably larger than the cluster core. In the core, the observed local magnetic field strengths are 0.2–8 μG for different clusters (e.g. Feretti et al. 1995; Henriksen 1998).

It seems plausible that the magnetic field in the ICM should be maintained by some turbulent small-scale dynamo capable to convert kinetic energy of intracluster turbulence into magnetic energy. Two different sources have been suggested to produce the required turbulence: disturbances from the cluster galaxies, and ongoing merger of other cluster substructures. The energy released in a major merger event is certainly sufficient to maintain

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the observed magnetic fields. Still, it is quite natural to ask if the cluster galaxies are able to magnetise the cluster medium up to a few μG, or otherwise, a recent merger event is a necessary condition for the existence of radio halos (Tribble 1993).

The r.m.s. turbulent velocity v_0 required to explain the observed magnetic field H can be roughly estimated from equipartition between kinetic and magnetic energies as $v_0 \simeq H/\sqrt{4\pi\rho}$, where ρ is the gas density. For $H = 1\,\mu$G and ρ corresponding to 10^{-3} particles/cm^3, we obtain $v_0 \simeq 250$ km/s.

2. Stirring of the ICM by cluster galaxies

The origin of the sources of turbulence in the ICM has received considerable attention to explain not only the magnetic fields but also the reacceleration of relativistic electrons, the properties of radio sources in clusters or the heating of the central cooling core.

Galaxies may produce turbulent motions in the ICM mainly by two different interactions. Firstly, every galaxy produces a gravitational wake behind it, with the subsequent drag heating of the cluster gas and, secondly, the gas in galactic halos can be stripped by ram pressure and thereby contributes to turbulence. The high metallicities found in the ICM provide clear indication that significant amounts of interstellar gas have been removed to the intergalactic space.

For the dynamo action proposed by Jaffe (1980) and Ruzmaikin et al. (1989), the turbulent motions in the cluster gas generated by the merged turbulent wakes control the magnetic field strength. Hence it is necessary to estimate the typical scale l_0 and the velocity v_0 of the turbulence in a steady state.

Independently of the model of turbulence and regardless of the nature of the interaction, we require that at least one galaxy must have come across any volume of size l_0^3 in the eddy turnover time, i.e.

$$n_{\rm G} l_0^2 v_{\rm G} \approx v_0/l_0, \tag{1}$$

where $n_{\rm G}$ is the number density of galaxies, and $v_{\rm G}$ is the typical velocity of a galaxy with respect to the ICM (Goldman & Rephaeli 1991). Further, the rate of energy transfer into turbulence must be equal to that injected by the galaxies, $\dot{E}_{\rm G}$, thus

$$\dot{E}_{\rm G} \approx \frac{1}{2}\frac{\rho v_0^3}{l_0}, \tag{2}$$

where ρ is the gas density of the ICM. Our aim is to estimate $\dot{E}_{\rm G}$ for both the gravitational disturbances and the gas pressure stripping, and then to obtain l_0 and v_0 from Eqs. (1) and (2).

2.1. GRAVITATIONAL DISTURBANCES

For a supersonic galaxy moving through gas of mass density ρ, the energy loss rate is given by Chandrasekhar's formula with the Coulomb logarithm, $\ln \Lambda$, depending on the Mach number:

$$\dot{E} = n_{\mathrm{G}} \frac{4\pi G^2 M_{\mathrm{G}}^2 \rho \ln \Lambda}{v_{\mathrm{G}}} \tag{3}$$

(Rephaeli & Salpeter 1980). If all the energy is transferred into turbulent motions then $v_0 \approx 40$ km/s, where we have used Eqs. (1) and (2), and assuming a typical galactic mass of 10^{11} $\mathrm{M}_\odot$, $v_{\mathrm{G}} \simeq 1500$ km/s and $n_{\mathrm{G}} \simeq 1.4 \times 10^{-6}$ kpc^{-3}. However, the driving force for these motions is potential, so the motions should be irrotational, presumably in the form of sound waves (shocks do not develop if the accretion radius is smaller than the physical size of the galaxy). Irrotational motions are thought to be inefficient in generating magnetic fields at low Mach numbers even if they are random (Kazantsev et al. 1985). So we conclude that gravitational wakes can only contribute negligibly into amplification of intracluster magnetic fields.

2.2. MASS-OUTFLOW DISTURBANCES

Consider galaxies in the cluster as moving solid bodies of effective radius a_{eff}. The turbulent wake dissipates a power of $\frac{1}{2}\lambda_3 \pi \rho v_{\mathrm{G}}^3 a_{\mathrm{eff}}^2$, with λ_3 a parameter of efficiency, which results in $v_0 \approx 150$ km/s for comfortable values of $a_{\mathrm{eff}} \approx 2$ kpc and $\lambda_3 \approx 0.25$. Therefore, it is tempting to identify the galactic gas as the natural source of turbulence.

In fact, it is known that in a short time, a steady state is achieved in which the rate of stripping, for a typical galaxy in cluster, is equal to the rate of gas replenishment by stellar winds within the galaxy (Portnoy et al. 1993). Therefore, the initial gas halo associated with the galaxy does not play any role and only the replenishment of gas at a rate $\dot{\rho}$ is important. In that case, an estimate of the turbulent velocity in the head of the wake, v, is simply given by imposing the conservation of momentum in one dimension as

$$\frac{4}{3}\pi R_{\mathrm{c}}^3 \dot{\rho}\, v_{\mathrm{G}} \approx \rho \pi R_{\mathrm{c}}^2 v_{\mathrm{G}} v, \tag{4}$$

where R_{c} is the core radius of the stellar mass distribution. In the equation above the galactic wind has been neglected. Note that in the inner parts of the galaxy where the gravitational force and cooling are important, Eq. (4) is inapplicable. We may write $v \approx R_{\mathrm{c}}\dot{\rho}/\rho$ and, consequently,

$$\dot{E}_{\mathrm{G}} = \frac{1}{2} n_{\mathrm{G}} \rho \pi R_{\mathrm{c}}^2 v_{\mathrm{G}} v^2 \approx \frac{2}{3} n_{\mathrm{G}} \dot{M} \frac{\dot{\rho}}{\rho} R_{\mathrm{c}} v_{\mathrm{G}}, \tag{5}$$

where $\dot{M}$ is the rate of mass loss by a single galaxy. For typical mean values of $\dot{M} \simeq 0.2\ \mathrm{M}_{\odot}/\mathrm{yr}^{-1}$ and $R_c \simeq 16$ kpc, and using Eqs. (1)–(2), we obtain a mean turbulent velocity of $v_0 \simeq 10$–15 km/s. This velocity corresponds to an equipartition magnetic field $B_{\mathrm{eq}} \equiv \sqrt{4\pi\rho v_0^2} \leq 0.15\ \mu$G. Thus, the mass outflow from galaxies cannot account for the required amplitude of turbulence.

These estimates only apply outside the accretion radius of the galaxy. While gas is stripped from the outer parts of the galaxy, a cooling flow may be formed in the inner parts if there is enough gas replenishment (Balsara, Livio & O'Dea 1994). In that case galaxies can support a bow shock at some radius that we can identify with a_{eff}. Due to the strong dependence of the results on the adopted a_{eff}, the combination of the gravitational potential, gas replenishment and cooling may result in higher levels of turbulence.

3. Conclusions

From the above discussion it is apparent that efficient transfer of energy from galactic motions to intracluster turbulence is required to explain the magnetic fields observed in radio halos. The efficiency depends dramatically on the effective galactic radius adopted. A definite test requires the inclusion of the gravitational and mass outflow disturbances simultaneously into a model allowing for a range of transonic velocities of galactic motion. Turbulence driven by merger events remains an attractive possibility.

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