Magnetic Fields in Clusters of Galaxies

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1. Introduction

Clusters of galaxies contain the spatially largest magnetic fields (MF) in the Universe. It seems that turbulent motion of intra-cluster medium (ICM) is the most important process in MF production. However, a battery of turbulent galaxy motions through ICM may play a similar role. Using simple estimators I demonstrate that modest typical velocities of galaxies v_g (few 100 km sec^{-1}) lead to higher magnetic field strength B (few 0.1 μG) than thought possible to be generated by the turbulent wakes of galaxies.

2. Turbulence Battery from Galaxies

The main idea of the MF production by galactic motion is as follows (e.g. Goldman & Rephaeli 1991): Galaxy movements through the ICM plasma produce turbulent eddies. Then, circular currents are formed that cause the generation of MF. It is widely assumed that galaxies move with v_g of order of 1000 km sec^{-1} or even larger (e.g. Goldman & Rephaeli 1991, Sánchez-Salcedo et al. 1999) which leads to relatively small values of typical turbulent velocities and thus B. However, the studies of structure of clusters of galaxies have shown that v_g is probably of the order of 100 - 700 km sec^{-1} not higher (e.g. Berzins 1998).

The MF production in clusters by turbulent motion will be effective only if the steady state turbulence can be reached, in which case the magnetic field with strength $B \lesssim \sqrt{4\pi\rho v_0^2}$ will be generated, where ρ is the ICM gas mass density and v_0 is the turbulent velocity, or more precisely the Alfven velocity v_A.

A galaxy pass through a volume l_0^3 in a time $\sim (n_g \pi l_0^2 v_g)^{-1}$ where n_g is the number density of galaxies. In the case of steady state, the time scale of production of turbulent eddies is equal to their life time $\sim l_0 v_0^{-1}$. The rate of energy density injected into the turbulence is $\sim \rho v_0^3 l_0^{-1}$. In the same time turbulent eddies are dragging the galaxy causing an energy loss of the rate $\sim n_g \pi a v_g^2 \rho \nu_t(a)$, where a is the characteristic scale of turbulence and ν_t is the turbulent viscosity on the spatial length scale a. Assuming $\nu_t \sim v(a) \cdot a$ and using the Kolmogorov spectrum $v(l) \propto l^{1/3}$, we get:

$$l_0 = a \lambda_1^{3/8} \lambda_2^{-3/16} \left(n_g \pi a^3\right)^{-3/16}, \tag{2.1}$$

$$v_0 = v_g \lambda_1^{1/8} \lambda_2^{-9/16} \left(n_g \pi a^3\right)^{7/16}, \tag{2.2}$$

where the coefficients λ_1 and $\lambda_2 \sim 1$ are introduced and their exact value depend on the form of the spectrum. For details of more formal treatment of this problem see Goldman & Rephaeli (1991). Now we need to estimate the effective size of a galaxy a. Galaxies within the cores of rich clusters are mostly ellipticals. They contain relatively small amount of interstellar medium (hereafter ISM) gas. Thus the radius, at which the ISM and ICM pressures are equal, is expected to be small. There are two cases:

(i) If the ISM pressure is much smaller than the ICM one, the ICM gas gravitational accretion radius of a galaxy is defined as (cf. Goldman & Rephaeli 1991):

$$a = 2GMv_g^{-2} \simeq 0.86 M_{11} v_8^{-2} \qquad \text{kpc}, \tag{2.3}$$

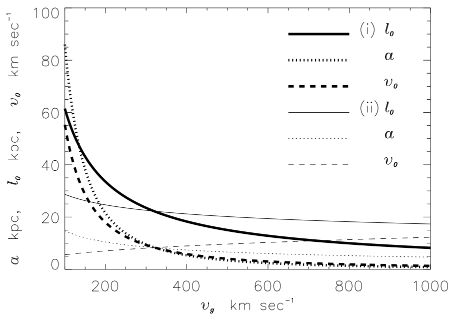

FIGURE 1. Estimates of typical l_0, a and v_0 depending on v_g for cases (i) and (ii).

where G is gravitational constant, M is a mass of galaxy, M_{11} is the mass measured in units of $10^{11} M_\odot$ and v_8 is measured in units of 10^8 cm sec^{-1}. If galaxies move very slowly through the ICM then eq. (2.3) can not be used.

(ii) If the ISM gas pressure is not sufficiently small compared to the ICM pressure (as expected in the case of small v_g) then we have to use another estimate of a instead of eq. (2.3). Taking the slow-down time of galaxies dues to the hydrodynamical drag τ_d to be greater than the age of the Universe (say $> 3 \times 10^{10}$ yr), we can estimate the upper limit of a (note its relatively strong dependence on τ_d; cf. Goldman & Rephaeli 1991):

$$a = \left(\frac{M}{2\rho\tau_d v_g}\right)^{1/2} \simeq 8.1 M_{11}^{1/2} \tau_{10}^{-1/2} v_8^{-1/2} \qquad \text{kpc}, \tag{2.4}$$

where τ_{10} is τ_d measured in units of 10^{10} yr. Our estimates of the largest vortice l_0, the effective size of a galaxy a, and the typical turbulent velocity v_0 are shown in Fig.1. For illustration we will estimate MF using a typical velocity of galaxies $v_g = 200$ km sec^{-1} ($v_0 = 7$ km sec^{-1} and $l_0 = 25$ kpc). Using a typical ICM gas number density of $n = 3 \times 10^{-3}$ cm^{-3}, we obtain a value of $B = 0.18$ μG. The MF will be most likely generated on scales smaller than l_0, thus reducing the value of B. Adopting the reduction efficiency as $v_A = v_0/5$ (cf. Ruzmaikin et al. 1989) we obtain $B = 0.04$ μG. Since this value is only a volume average over cells of size l_0 in the core region of radius r_c, we should apply a modification factor $\sim \sqrt{r_c/l_0}$. Adopting $r_c = 300$ kpc, this leads us to the final estimate of $B \simeq 0.1$ μG. In principle, even larger values of MF strength may be achieved by the battery mechanism of turbulent motions of galaxies through the ICM.

Observations show that magnetic field strengths of $0.2 - 8$ μG appear to be characteristic for galaxy clusters (Henriksen 1998; Sánchez-Salcedo et al. 1999 and references therein). I suggest that both turbulent galaxy motions through the ICM as well as subcluster merging (or large scale ICM flows) are responsible for MF generation in clusters of galaxies.

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