Magnetic fields in the first galaxies: Dynamo amplification and limits from reionization

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Abstract

We discuss the amplification of magnetic fields by the small-scale dynamo, a process that could efficiently produce strong magnetic fields in the first galaxies. In addition, we derive constraints on the primordial field strength from the epoch of reionization.

1 Introduction

In the local Universe, magnetic fields are observed on virtually all scales (e.g. Beck et al., 1996), and observations confirm the presence of magnetic fields also at high redshift. Such evidence has been found through the Faraday Rotation imprint of line-of-sight galaxies on distant QSOs (Bernet et al., 2008; Kronberg et al., 2008), as well as through the far-infrared - radio correlation (Murphy, 2009). They further exist in the intergalactic medium (IGM). For instance, galaxy clusters exhibit $\mu$G fields (Clarke et al., 2001) that require non-negligible initial seeds (Banerjee & Jedamzik, 2003; Ryu et al., 2008; Miniati & Martin, 2011).

Even in cosmic voids, weak magnetic fields seem to exist, as suggested by recent gamma-ray experiments (Neronov & Vovk, 2010; Tavecchio et al., 2010; Taylor et al., 2011), but see Broderick et al. (2011). Various astrophysical mechanisms have been proposed for the origin of intergalactic and cosmological magnetic fields (Miniati & Bell, 2011; Bertone et al., 2006; Gnedin et al., 2000; Ando et al., 2010). In particular, the model in Miniati & Bell (2011) makes consistent predictions for the magnetic fields observed in the cosmic voids, providing a relevant seed for subsequent dynamo amplification.

Primordial models of magnetogenesis (e.g. Grasso & Rubinstein, 2001) provide an alternative scenario. Magnetic fields from the early universe could be potentially strong, and need to be constrained observationally. This concerns in particular inflationary scenarios (Turner & Widrow, 1988), the electroweak phase transition (Baym et al., 1996), or the QCD phase transition (Quashnock et al., 1989; Cheng & Olinto, 1994; Sigl et al., 1997).

In this contribution, we discuss the amplification of magnetic fields via the small-scale dynamo, which may provide a strong tangled magnetic field already in the first galaxies (e.g. Schleicher et al., 2010; Sur et al., 2010; Federrath et al., 2011). We further describe upper limits on the primordial field strength from recent reionization data (Schleicher & Miniati, 2011).

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The small-scale dynamo for different turbulence models

The small-scale dynamo provides an efficient amplification mechanism of magnetic fields in the presence of turbulence. It was originally proposed by Kazantsev (1968), and subsequently explored by various authors using analytical models and numerical simulations (e.g. Subramanian, 1997, 1999; Schekochihin et al., 2002; Haugen et al., 2004a,b; Schekochihin et al., 2004). To calculate the growth rate of the magnetic field, the induction equation, given as

$$ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{v} \times \mathbf{B} - \eta \nabla \times \nabla \times \mathbf{B}, \quad (1) $$

can be rewritten in terms of the so-called Kazantsev equation

$$ - \kappa_{\text{diff}}(r) \frac{d^2 \psi(r)}{d^2 r} + U \psi(r) = - \Gamma \psi(r), \quad (2) $$

where $\psi$ is related to the spatial dependence of the magnetic field correlation function, $\kappa_{\text{diff}}$ denotes the turbulent diffusion coefficient and $U$ denotes a function depending on the properties of turbulence. In a recent study by Schober et al. (2011), we solved this equation and derived the dependence of the growth rate on the turbulence model, the magnetic Prandtl number and the Reynolds number. For this purpose, we considered the turbulence models given in Table 1, where we also provide the critical magnetic Reynolds number for magnetic field amplification, as well as the growth rate, which is normalized in terms of the eddy timescale. In Fig. 1, we show the dependence of the growth rate on the turbulence model, the Prandtl and the Reynolds number. The interested reader is referred to Schober et al. (2011) for the derivation of these results.

### Table 1: The critical magnetic Reynolds number $Rm_{\text{crit}}$ and the normalised growth rate of the small-scale dynamo $\dot{\Gamma}$ in the limit of infinite magnetic Prandtl numbers.

| Model/Reference | $\vartheta$ | $Rm_{\text{crit}}$ | $\dot{\Gamma}$ $(Pm \to \infty)$ |
|-----------------|-------------|----------------------|-------------------------------|
| Kolmogorov (1941) | $1/3$ | $\sim 107$ | $\frac{37}{36} Re^{1/2}$ |
| intermittency of Kolmogorov turbulence (She & Leveque, 1994) | $0.35$ | $\sim 118$ | $0.94 Re^{0.48}$ |
| driven supersonic MHD-turbulence (Boldyrev et al., 2002) | $0.37$ | $\sim 137$ | $0.84 Re^{0.46}$ |
| observation in molecular clouds (Larson, 1981) | $0.38$ | $\sim 149$ | $0.79 Re^{0.45}$ |
| solenoidal forcing of the turbulence (Federrath et al., 2010) | $0.43$ | $\sim 227$ | $0.54 Re^{0.40}$ |
| compressive forcing of the turbulence (Federrath et al., 2010) | $0.47$ | $\sim 697$ | $0.34 Re^{0.36}$ |
| observations in molecular clouds (Ossenkopf & Mac Low, 2002) | $0.43$ | $\sim 2718$ | $\frac{11}{60} Re^{1/3}$ |
| Burgers (1948) | $1/2$ | | |

2 The small-scale dynamo for different turbulence models

3 The Mach number dependence of magnetic field amplification
Figure 1: Left: Normalized growth rate for different turbulence models as a function of the Reynolds number, in the limit of an infinite magnetic Prandtl number. Right: Normalized growth rate as a function of the magnetic Prandtl number in the case of incompressible (Kolmogorov) turbulence, for different Reynolds numbers.

| $\Gamma \left[ \hat{t}_{ed}^{-1} \right]$ | $(E_m/E_k)_{sat}$ | $E_{sol}/E_{tot}$ |
|-----------------|-----------------|-----------------|
| (sol) | (comp) | (sol) | (comp) | (sol) | (comp) |
| $p_0$ | -18.71 | 2.251 | 0.020 | 0.037 | 0.808 | 0.423 |
| $p_1$ | 0.051 | 0.119 | 2.340 | 1.982 | 2.850 | 1.970 |
| $p_2$ | -1.059 | -0.802 | 23.33 | -0.027 | 1.238 | 0.003 |
| $p_3$ | 2.921 | 25.53 | 2.340 | 3.601 | 2.850 | 1.970 |
| $p_4$ | 1.350 | 1.686 | 1 | 0.395 | 1 | 0.535 |
| $p_5$ | 0.313 | 0.139 | 0 | 0.003 | 0 | 0 |
| $p_6$ | 1/3 | 1/3 | 0 | 0 | 0 | 0 |

Table 2: Parameters in Eq. (3) for the fits in Fig. 2

We considerably extended the range of Mach numbers in a recent study, exploring the range from Mach 0.02 up to Mach 20, using both solenoidal and compressive driving schemes (Federrath et al., 2011). Our results for the growth rate, the saturation level and the amount of solenoidal turbulent energy are shown in Fig. 2. We derived analytic fits using the fit function

$$f(x) = \left( p_0 \frac{x^{p_1} + p_2}{x^{p_3} + p_4} + p_5 \right) x^{p_6},$$

with the fit parameters given in Table 2. In the regime of low Mach numbers, all quantities depend considerably on the driving scheme, with solenoidal driving leading to more efficient amplification. Also at high Mach numbers, solenoidal driving is more efficient, but the difference is less pronounced. For the growth rate of the magnetic field, a transition seems to occur at about Mach 1, where the growth rate drops considerably in the presence of shocks. Towards even larger Mach numbers, we observe an approximate scaling as $M^{1/3}$ for both types of driving. Overall, our results show that the small-scale dynamo works for a large range of Mach numbers, as well as for compressively driven and solenoidally driven turbulence.
Figure 2: Growth rate (top), saturation level (middle), and solenoidal ratio (bottom) as a function of Mach number, for all runs with solenoidal (crosses) and compressive forcing (diamonds). The solid lines show empirical fits given by Federrath et al. (2011).

4 Upper limits on the primordial field strength

If strong primordial fields have been created in the early Universe, they will subsequently affect structure formation via the magnetic Jeans mass, which is given as (Subramanian & Barrow 1998; Schleicher et al. 2009)

\[ M^B_J = 10^{10} M_\odot \left( \frac{B_0}{3 \, nG} \right)^3 \]

(4)

with \( B_0 \) the co-moving field strength. The latter is related to the physical field strength \( B \) via \( B_0 = B/(1+z)^2 \). To explore the implications for the epoch of reionization, we follow the time evolution of the ionized volume fraction \( Q_{HII} \) as Madau et al. (1999), yielding

\[ \frac{dQ_{HII}}{dt} = - \frac{Q_{HII}}{t_{rec}} + \frac{SFR(z)f_{esc} 10^{53.2}}{n_H(0)}, \]

(5)
with $t_{\text{rec}}$ the recombination timescale, $f_{\text{esc}}$ the escape fraction, $n_H(0)$ the co-moving number density. The star formation rate is calculated from the observed Schechter function provided by Bouwens et al. (2011). The further details of this approach are given by Schleicher & Miniati (2011). From the ionized volume fraction as well as the ionized fraction in the neutral component, we calculate the effective ionization degree $x_{\text{eff}}$ and the reionization optical depth

$$
\tau_e = \frac{n_H(0)c}{H_0} \int_{z=0}^{z=z_s} x_{\text{eff}}(z)\sigma_T \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} dz,
$$

with $c$ the speed of light, $H_0$ the Hubble constant, $\sigma_T$ the Thompson scattering optical depth and the cosmological density parameters $\Omega_\Lambda$ and $\Omega_m$. We explore the uncertainties due to the cosmological parameters, the reionization parameters as well as the uncertainty in the observed Schechter function on the reionization optical depth, and the ionization degree at different redshifts. Some of our results are given in Fig. 3 and additional details are provided by Schleicher & Miniati (2011). Overall, they lead to a 2$\sigma$ constraint of $\sim 2$ nG on the co-moving field strength.

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