Magnetism in the Early Universe

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Abstract. Blazar observations point toward the possible presence of magnetic fields over inter-galactic scales of the order of up to $\sim 1\,\mathrm{Mpc}$, with strengths of at least $\sim 10^{-16}\,\mathrm{G}$. Understanding the origin of these large-scale magnetic fields is a challenge for modern astrophysics. Here we discuss the cosmological scenario, focussing on the following questions: (i) How and when was this magnetic field generated? (ii) How does it evolve during the expansion of the universe? (iii) Are the amplitude and statistical properties of this field such that they can explain the strengths and correlation lengths of observed magnetic fields? We also discuss the possibility of observing primordial turbulence through direct detection of stochastic gravitational waves in the mHz range accessible to LISA.

Keywords. Early Universe, Cosmic Magnetic Fields, Turbulence, Gravitational Waves

1. Introduction

Magnetic fields of strengths of the order of $\sim 10^{-16}\,\mathrm{G}$ are thought to be present in the voids between galaxy clusters; see Neronov & Vovk (2010) for the pioneering work and Durrer & Neronov (2013) for a review and references therein. These are thought to be the result of the amplification of the seed magnetic field, with two scenarios of the origin currently under discussion; see Subramanian (2016) for a review: a bottom-up (astrophysical) scenario, where the seed is typically very weak and magnetic field is transferred from local sources within galaxies to larger scales, and a top-down (cosmological) scenario where a magnetic field is generated prior to galaxy formation in the early universe on scales that are large at the present epoch. We discuss two different scenarios of primordial magnetogenesis: magnetic fields produced during inflation or during cosmological phase transitions. We address cosmic magnetohydrodynamic (MHD) turbulence, in order to understand the magnetic field evolution. Turbulent motions can also affect cosmological phase transitions. We argue that even a small total energy density in turbulence (less than 10% of the total thermal energy density) can have substantial effects because of strong nonlinearity of the relevant physical processes; see also Vazza *et al.* (2017).

2. Overview

The evolution of a primordial magnetic field is determined by various physical processes that result in amplification and damping of the field. Complexities arise in the problem due to the strong coupling between magnetic field and plasma motions (Kahniashvili *et al.* 2010), producing MHD turbulence, which then undergoes free decay after the forcing is

switched off (Brandenburg *et al.* 1996; Dimopoulos & Davis 1997; Jedamzik *et al.* 1998; Subramanian & Barrow 1998); see Kahniashvili *et al.* (2016) for a recent overview. The presence of initial kinetic and/or magnetic helicity strongly affects the development of turbulence. In several models of phase transition magnetogenesis, parity (mirror symmetry) violation leads to a non-zero chirality (helicity) of the field (Cornwall 1997; Giovannini & Shaposhnikov 1998; Field & Carroll 2000; Giovannini 2000; Vachaspati 2001). We also underline the importance of possible kinetic helicity: our recent simulations have shown that through the decay of hydromagnetic turbulence with initial kinetic helicity, a weak nonhelical magnetic field eventually becomes fully helical (Brandenburg *et al.* 2017).

The anisotropic stresses of the resulting turbulent magnetic and kinetic fields are a source of gravitational waves, as already pointed out by Deryagin *et al.* (1986). The amplitude of the gravitational wave spectrum depends on the strength of the turbulence, and its characteristic wavelength depends on the energy scale at which the gravitational wave source is generated (Gogoberidze *et al.* 2007).

3. Results

Understanding the mechanisms for generating primordial turbulence is a major focus of our investigation. Turbulence may be produced during cosmological phase transitions when the latent heat of the phase transition is partially converted to kinetic energy of the plasma as the bubbles expand, collide, and source plasma turbulence (Christensson *et al.* 2001). The two phase transitions of interest in the early universe are (i) the electroweak phase transition occurring at a temperature of $T \sim 100\,\mathrm{GeV}$, and (ii) the QCD phase transition occurring at $T \sim 150\,\mathrm{MeV}$. Turbulence at the electroweak phase transition scale is more interesting for the gravitational wave detection prospects, since the characteristic frequency of the resulting stochastic gravitational wave background, set by the Hubble length at the time of the phase transition, falls in the Laser Interferometer Space Antenna (LISA) frequency band; see Kamionkowski *et al.* (1994), and Kosowsky *et al.* (2002) for pioneering studies, and Caprini & Figueroa (2018) for a recent review.

Since the electroweak phase transition is probably a smooth crossover in the Standard Model of particle physics, it would not proceed through bubble collisions and follow up turbulence. However, our knowledge of electroweak scale physics is incomplete; at least two lines of reasoning point toward a first-order phase transition in the very early universe. First, such a transition can provide the out-of-equilibrium environment necessary for successful baryogenesis; see, e.g., Morrissey & Ramsey-Musolf (2012). Secondly, as discussed above, turbulence induced in a first-order transition naturally amplifies the seed magnetic fields which can explain the magnetic fields that might be present in cosmic voids; see Fig. 1 and Brandenburg *et al.* (2017). Arguments in favor of a primordial origin of such fields were also given by Dolag *et al.* (2011).

If significant magnetic fields exist after the phase transitions, they can source turbulence for long durations, extending even until recombination. For these sources, the damping due to the expansion of the universe cannot be neglected. Numerical simulations show only a slow decay of turbulent energy, especially at the large-scale end of the spectrum, along with the generation of significant energy density in velocity fields; see Fig. 4 of Kahniashvili *et al.* (2010), and Brandenburg & Kahniashvili (2017). Turbulence in the early universe can also be generated during inflation, whereby the magnetic field energy is injected into primordial plasma ensuring a strong coupling between the magnetic field and fluid motions. The correlation scale of induced turbulent motions is limited by the Hubble scale, as required by causality; see Kahniashvili *et al.* (2012) for the non-helical case and Kahniashvili *et al.* (2017) for the helical case, while the magnetic field stays frozen-in at superhorizon scales. The strength of the turbulent motions is determined by the total energy density of the magnetic field; a sufficiently strong field can lead to a detectable gravitational wave signal (Kahniashvili *et al.* 2008).
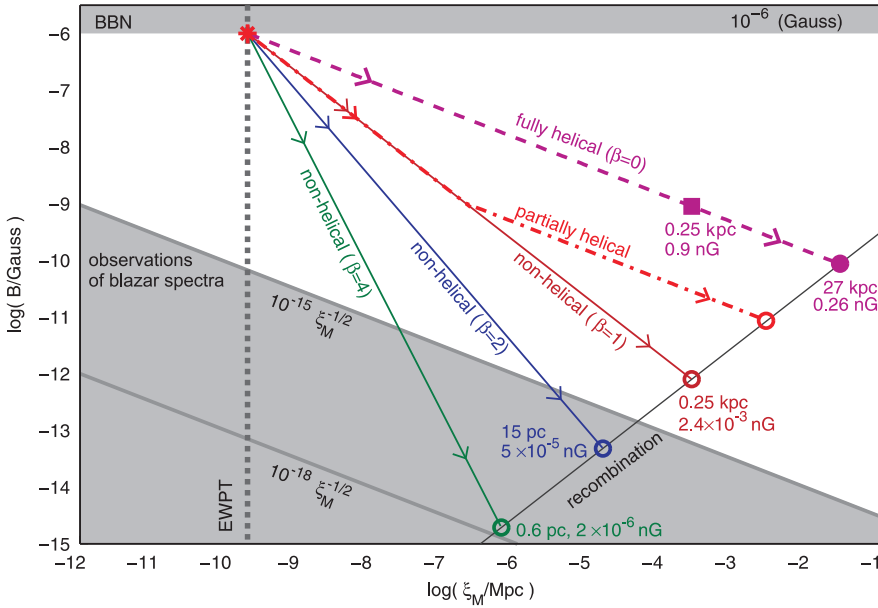
Figure 1. Turbulent evolution of the strength B_{rms} and correlation length ξ_M of the magnetic field starting from their upper limits given by the Big Bang Nucleosynthesis (BBN) bound and the horizon scale at the electroweak phase transitions (from Brandenburg *et al.* 2017, Fig. 11).
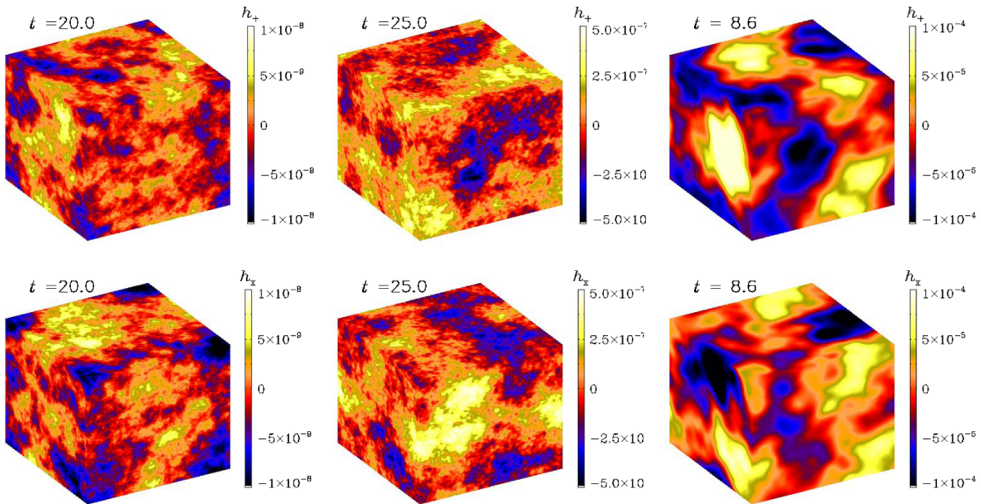
Figure 2. Visualizations of h_+ (top) and $h_\times$ (bottom) on the periphery of the computational domain for different positions of the initial turbulent spectrum peak frequency $k_f/k_H = 300$, 60, 2 from left to right respectively. (in press)

The PENCIL CODE (Brandenburg & Dobler 2002) is a general public domain tool box to solve sets of partial differential equations on large, massively parallel platforms. It has recently been applied to early universe simulations of mesh size up to 2304^3 (Brandenburg & Kahniashvili 2017), which was necessary for modeling turbulence at the phase transitions (Brandenburg *et al.* 2017) and the inflationary stage (Kahniashvili *et al.* 2017). We have recently added a module to evolve the gravitational waves in the simulation domain from the dynamically evolving MHD stresses. Details of the numerical

simulations can be found in Roper Pol *et al.* (2019a). Our first results are presented in Roper Pol *et al.* (2019b) and in Fig. 2, where we plot the gravitational wave strain components h_+ and $h_\times$ sourced by fully helical hydromagnetic turbulence. It must be highlighted that the presence of initial magnetic helicity significantly affects the detection prospects. However, the detection of the circular polarization degree by LISA seems to be problematic (Smith & Caldwell 2017).

Acknowledgments

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