宇宙初期磁場と21cmシグナル

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ABSTRACT

Recent discoveries of magnetic fields in intergalactic void regions and in high redshift galaxies may indicate that large scale magnetic fields have a primordial origin. If primordial magnetic fields were present soon after the recombination epoch, they would induce density fluctuations on the one hand and dissipate their energy into the primordial gas on the other, and thereby significantly alter the thermal history of the universe. Here we consider both the effects and calculate the brightness temperature fluctuations of the 21cm line using simple Monte-Carlo simulations because analytic manipulation is difficult due to complicated non-linearities. We find that fluctuations of 21cm line from the energy dissipation appear only on very small scales and those from the density fluctuations always dominate on the observationally relevant angular scales probed by SKA.

Introduction

Recent discoveries of magnetic fields in galaxies at high redshift [1], and in void regions [2], may support the hypothesis that the seed fields are primordial origin. If this is the case, the primordial magnetic fields have influenced many kinds of cosmological processes, such as the Big Bang Nucleosynthesis, Cosmic Microwave Background Anisotropies, and the formation of large scale structure of the universe (see [3] and references therein). Recently, Planck collaboration placed limits on primordial magnetic fields as $B_\lambda < 3.4$ nG and $n_B < 0$ from the temperature anisotropies at large and small angular scales.

In this paper, we consider the effect of primordial magnetic fields on the evolution of cosmological perturbations after the cosmological recombination. In particular, we investigate the thermal history of the primordial hydrogen gas in the universe by taking into account the heat injection due to the ambipolar diffusion of the magnetic fields [4]. We improve the analysis in [4], taking the fluctuations of the heat injection into account using Monte Carlo simulations.

The heat injection from the magnetic fields into the weakly ionized primordial gas will leave unique signature in the future 21cm observations. If the heating rises the gas temperature and hence the spin temperature high above the background CMB temperature, the 21cm signal comes as emission even at redshift $z \gtrsim 20$, while the signal is expected to be absorption in the standard thermal history of the universe.

Ambipolar Diffusion

The energy dissipation rate due to ambipolar diffusion is given by

$$\Gamma(\mathbf{x}) = \frac{|(\nabla\times\mathbf{B})\times\mathbf{B}|^2}{16\pi^2\chi\rho_b^2 x_i}\,, \tag{1}$$

where ρ_b is baryon energy density and $\chi = 3.5\times 10^{13}\mathrm{cm}^3\mathrm{g}^{-1}\mathrm{s}^{-1}$ denotes the drag coefficient. The evolutions of the hydrogen gas temperature $T_{\rm gas}$ and ionization fraction x_i is given by [4]

$$\frac{dT_{\rm gas}}{dt} = -2HT_{\rm gas} + \frac{x_i}{1+x_i}\frac{8\rho_\gamma\sigma_T}{3m_e c}(T_\gamma - T_{\rm gas}) + \frac{\Gamma}{1.5k_B n_H}, \tag{2}$$

where k_B, ρ_γ, H, x_i, n_e m_e and σ_T denote the Boltzmann constant, photon energy density, the Hubble parameter, the ionization fraction, electron number density and mass, and cross section of Thomson scattering, respectively.

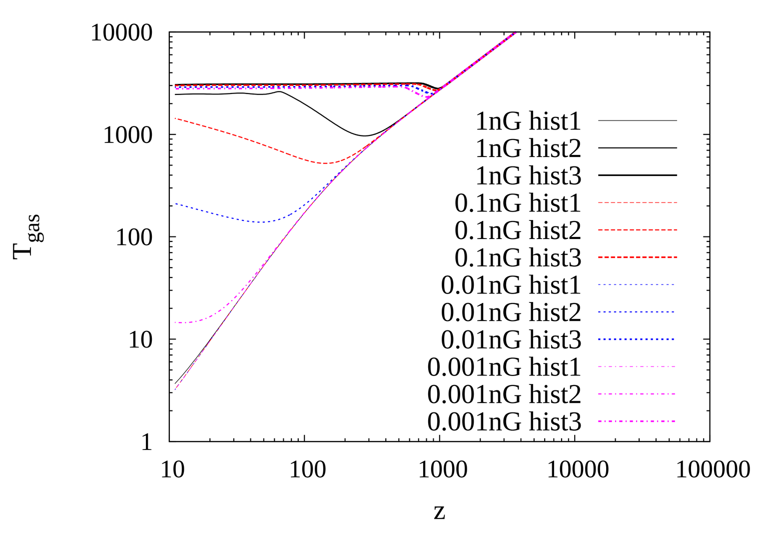

Figure 1: Typical time evolutions of IGM. Different colors correspond to different pixels in the simulation box. Primordial magnetic field parameters are taken as $B_\lambda = 3.0$ nG and $n_B = 0.0$.

Since the spin temperature of the IGM is determined by the balance among absorption of CMB photons, thermal collisional excitation, we can obtain the spin temperature from

$$T_s = \frac{T_\gamma + y_k T_{gas}}{1+y_k}, \tag{3}$$

where y_k is the kinetic coupling strength. For a given frequency, the differential brightness temperature is given by

$$\delta T_{21} = \frac{T_s(z) - T_\gamma(z)}{1+z}(1-e^{-\tau(z)}), \tag{4}$$

where z is the redshift corresponding to the frequency of observation, $1+z = \nu_{21}/\nu$, $T_s(z)$ is the spin temperature and $\tau(z)$ is the optical depth of the IGM at z.

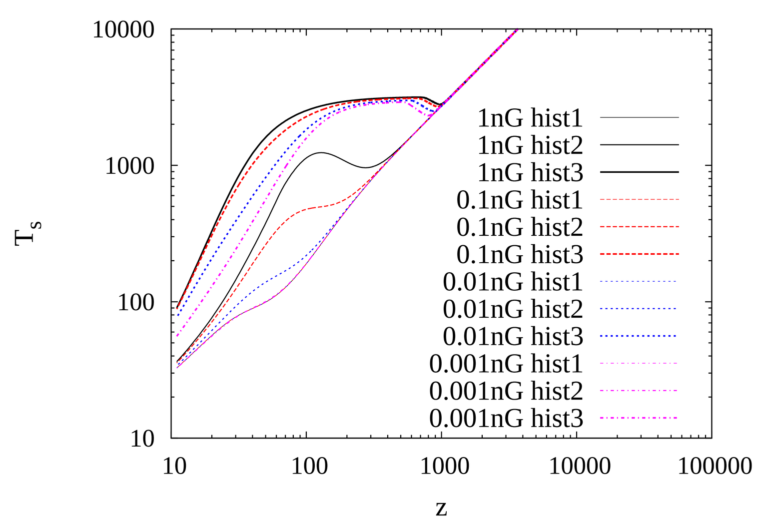

Figure 2: Same as Fig. 1, but for spin temperature.

Monte Carlo Simulation

We generate seed magnetic fields in k-space with 512^3 grid whose power spectrum is parameterized by a power law with strength smoothed on $\lambda = 1$ Mpc (B_λ) and power-law spectral index (n_B) as

$$\left\langle B_{0i}(\mathbf{k})B_{0j}^*(\mathbf{p})\right\rangle = (2\pi)^3\frac{P_B(k)}{2}\left(\delta_{ij} - \hat{k}_i\hat{k}_j\right)\delta^{(3)}(\mathbf{k}-\mathbf{p})\,,$$
$$P_B(k) = \frac{(2\pi)^{n_B+5}B_\lambda^2}{\Gamma(\frac{n_B+3}{2})k_\lambda^{n_B+3}}k^{n_B}\,, \tag{5}$$

where $k_\lambda = 2\pi/\lambda$. We then calculate the thermal history at every pixel for a realization of $\Gamma(\mathbf{x})$, and estimate the power spectrum of 21cm signal.

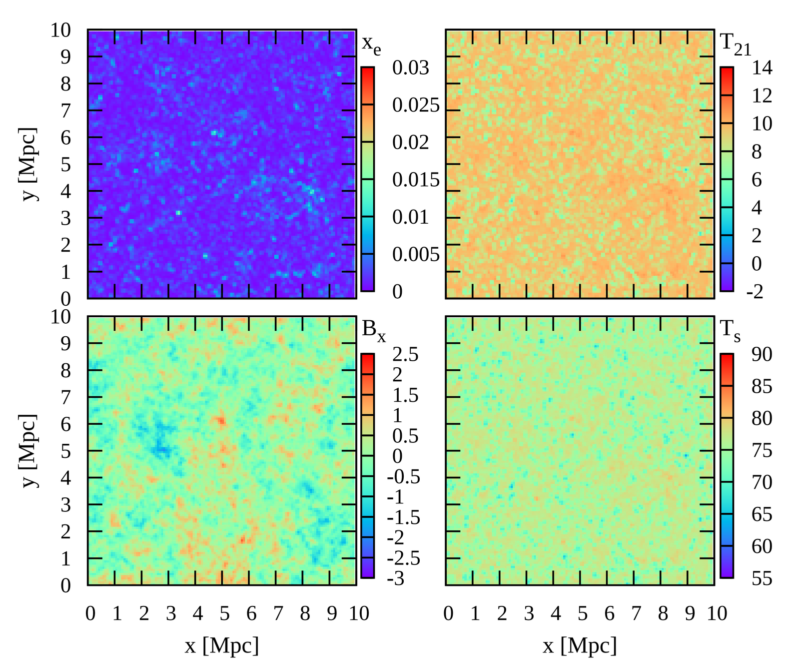

Figure 3: Realization of (the x-component of) primordial magnetic fields [nG] (bottom left) and corresponding ionization fraction (top left), spin temperature [K] (bottom center) and 21cm brightness temperature [mK] (top center), with parameters $B_\lambda = 1$ [nG] and $n_B = -2.9$. The heating is dominated by small scale structure. It can be seen that spin temperature and ionization fraction fluctuations are positively correlated.

Result (Power Spectrum)

The power spectra are directly estimated from the simulations.

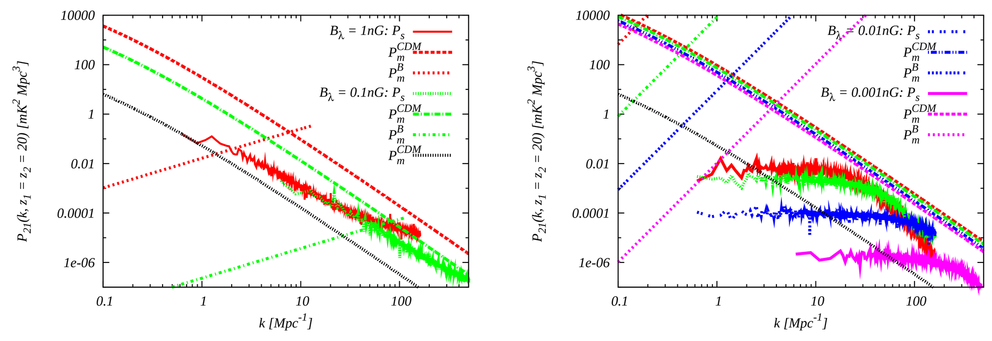

Figure 4: power spectra of 21cm signal at $z_{1,2} = 20$ for magnetic field strengths ranging from $B_\lambda = 0.001$ nG to 1 nG, with spectral index $n_B = -2.9$ and 0.0. See text below for details.

The power spectrum of 21 cm brightness temperature mainly has three parts. First is the temperature fluctuation term that is proportional to $\delta\left((\bar{T}_s - \bar{T}_\gamma)/\bar{T}_s\right)\bar{n}_{\rm HI}$ (and dented by P_s in Fig. 4), second is the density fluctuation term proportional to $(\bar{T}_s - \bar{T}_\gamma)/\bar{T}_s\delta n_{\rm HI}$ where $\delta n_{\rm HI}$ is the density fluctuations that originate from the standard adiabatic mode (denoted by $P_m^{\rm CDM}$), and third is the density fluctuations from the primordial magnetic fields (dented by $P_m^{\rm B}$). In Fig. 4, we separately plot these three contributions. We find that magnetic fields with nano Gauss levels significantly enhance the power over the wide range of scales through the density fluctuation term, because they realize that $(\bar{T}_s - \bar{T}_\gamma)/\bar{T}_s|_{\rm PMF} \sim 1 \gg (\bar{T}_s - \bar{T}_\gamma)/\bar{T}_s|_{\rm no\ PMF}$ and give larger density fluctuations especially on small scales. If we consider the case with $n_B = 0.0$, even weaker magnetic fields with strength as small as $B_\lambda = 10^{-3}$ nG can amplify the standard signal by three orders of magnitude (see the right panel in the figure). We also find that the temperature fluctuation term can give comparable contributions only at smallest scales for nearly scale invariant magnetic fields ($n_B = -2.9$; the left panel in the figure). The contributions, however, are always subdominant for magnetic fields with bluer spectrum, as shown in the right panel in Fig 4.

Summary

We consider the heat injection into IGM in high-redshift due to the ambipolar diffusion of primordial magnetic fields. Using simple Monte Carlo simulations we successfully estimate the 21cm power spectrum, and find that nG magnetic fields can significantly amplify the cosmological signal by up to three orders of magnitude at $z = 20$. The dominant contribution is coming from the homogeneous heating on top of density fluctuations of the standard adiabatic mode on large scales, and that generated from primordial magnetic fields on small scales.

References

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