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21 cm signal from the PMFs (a draft prepared as a part of sec. 3 "constraining new physics from heating")

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I am more than happy if you could include the sentences below in section 3. Please trim and polish up the draft. Thank you very much!

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3. Constraining new physics from heating

3.1 21 cm signal from the PMFs

Primordial magnetic fields (PMFs) has been intensively investigated in the literature as possible seeds for large scale magnetic fields observed in galaxies and clusters of galaxies (for a recent review, see [1]). Magnetic fields in galaxies in high redshifts [2] and in void regions [3, 4, 5] can well be the pieces of evidence that the seed fields are of primordial origin. The primordial magnetic fields may be created in the very early universe, e.g., at the epoch of inflation, cosmological phase transition, and cosmological recombination. The Planck collaboration recently places limits on the PMFs as $B_{\lambda=1\mathrm{Mpc}} < 3.4$ nG and $n_B < 0$ from the temperature anisotropies on large and small angular scales [6].

The CMB brightness temperature fluctuations produced by the neutral hydrogen 21-cm line (21 cm) would offer a new probe of the primordial magnetic fields (PMFs) created in the early universe. For the 21 cm observation, aside from the early structure formation effect by the Lorentz force from the PMFs, one of the important effects is the dissipation process of the PMFs that increases the baryon temperature. The dissipation occurs mainly through the ambipolar diffusion due to the velocity difference between neutral hydrogen (which is the dominant component in the dark ages) and ionized particles (whose trajectory is bent by the Lorentz force). The effect of the dissipation is rather significant. The gas temperature can reach 1000 K or even 10^4 K at $z = 30$ if the magnetic fields have the strength of $B_\lambda \sim 3$ nG [7, 8, 9, 10].

This dissipation will give rise to a unique signature of the PMFs on the 21 cm observation. Because the spin temperature is closely coupled to the gas temperature at high redshift ($z > 30$), the 21 cm signal would come as 'emission' if the energy dissipation is efficient. In Fig. 1 the global HI signal with several magnetic field strengths are shown. For cases with sufficient magnetic fields, say $B \gtrsim 0.03$ nG, the signal is always emission against CMB while in the standard ΛCDM model the signal would be absorption for the frequency range of $f_\nu \lesssim 80$ MHz (corresponding to the signal from redshift $z \gtrsim 20$).

We show the angular power spectrum of the 21 cm brightness temperature including the PMFs in Fig. 2 [11]. Here we do not account for any (standard) heating effects (i.e., UV, X, and Lα background emissions) to isolate and clarify the effects from the PMFs. On large scales which may be relevant to SKA observations, there are two distinct contributions. One is from the standard (adiabatic) density fluctuations enhanced by the heating from the PMFs, and the other is from the PMF induced density fluctuations dominant on smaller scales [8, 9]. We can see from the figure that $B = 1$ nG magnetic fields are marginally within reach for a statistical detection of the power spectrum. Stacking observing channels in principle will add more statistical power.

The angular correlation function in real space including the effects from the PMFs is also studied in [12]. The function exhibits a distinct feature because the PMFs induce early structure formation and the small scale halos form more compared to the case in the standard ΛCDM model The signal from primordial magnetic fields shows oscillatory feature contrary to that in the standard ΛCDM since the matter power spectrum induced by the PMFs is blue and most of halos are formed at the scale close to the magnetic Jeans' length. It has been argued that 5 sigma detection of the 0.5 nG magnetic fields will be possible with less than one week integration of SKA observation [12].

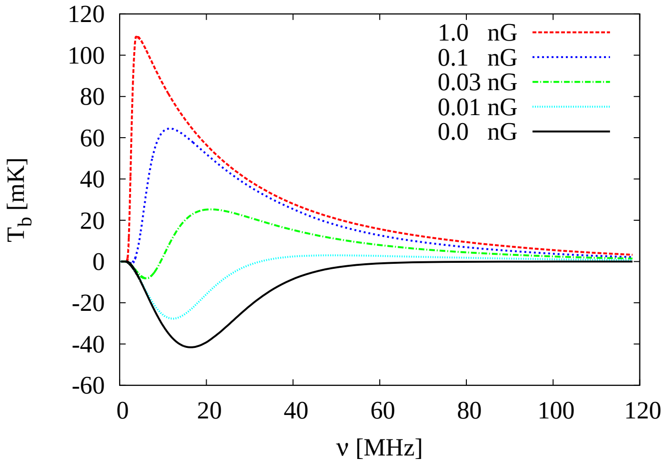

Figure 1: The global 21 cm signal with magnetic field strength $B = 1$ 0.1, 0.03, and 0.01 nG (colored lines from top to bottom). The solid line corresponds to the model without primordial magnetic fields. Note that any other heating source than magnetic fields is neglected in the figure.

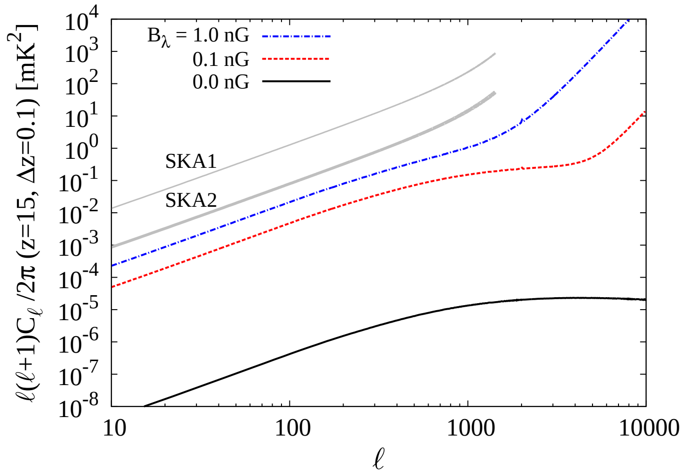

Figure 2: Angular power spectra for PMF strengths: $B = 0,\ 0.1,\ 1.0$ nG at $z = 15$. The bottom curve shows the power spectrum from the standard density perturbations for fully neutral medium without any heating and reionization processes. The red and blue curves correspond to the cases with heating by the PMFs with $B = 0.1$ nG and $B = 1.0$ nG, respectively. The heating induces deviations of the spin temperature from the CMB temperature and the signal is enhanced. The noise curves for SKA1 and SKA2 are also shown as indicated. By courtesy of M. Shiraishi & H. Tashiro.

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