論文内容の要旨

論文題目

The effect of primordial magnetic field on the early universe
(初期宇宙における磁場の影響)

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Magnetic field plays a very important role in many astronomical phenomena at various scales of the universe. Before recombination epoch for the photon last scattering (PLS) by the electron, because photons and electrons interact with each other through Thomson scattering, the primordial magnetic field (PMF) affects the photon dynamics. Thus the radiation of cosmic microwave background (CMB) is influenced by the PMF through electron-photon dynamics. In addition, because the energy density, pressure, and tension of the PMF affect gravitational collapse of the plasma, the fluctuation of matter density, which is an origin of the large scale structures (LSS), should be influenced by the PMF. Therefore, precise observations of the CMB anisotropies can place a stringent constraint on the PMF parameters. Several theoretical models of the origin and amplification mechanism of the PMF in the scale of galaxy cluster have recently been proposed and studied intensively in a number of papers. However, there is not satisfactory understanding of the origin and evolution of the PMF yet. Especially, there still remains missing link between the PMF and the observed magnetic field in galaxy clusters.

In order to compare the CMB anisotropy induced by the PMF with observations precisely, we need to perform numerical calculations of the fully linearized MHD equations along with a realistic recombination history of the universe. In particular, we need to develop a numerical method to predict the theoretical spectrum for intermediate angular scales, in which the previous analytic approximation becomes inappropriate. The approximate PMF power spectrum adopted in the previous works applies only to and around the PMF power spectral index $n_B = -1$. In this thesis we take an assumption that the PMF is expressed as $B \propto B_\lambda k^{n_B}$, where B_λ is the strength and n_B is the power spectral index of the PMF. This approximation is useful for studying PMF effect around $n_B = -1$. However, it is dangerous to use such approximation for wider range of n_B values because the origin of PMF is still open to debate and becuse the PMF parameters including n are not well constrained. Therefore we need to calculate the PMF power spectrum more generally for all available n_B values more generally. In this thesis we developed the new method to estimate PMF power spectrum without approximations.

Using our new formula, we can numerically investigate the effects of stochastic PMF on the fluctuation of the matter density and CMB with high accuracy. We found that the PMF is one of the most important cosmological physical processes on a "middle" cosmological scale. In this thesis we denote that the middle cosmological scale means less than the Silk damping scale which corresponds to relatively larger mutilpoles $1000 \leq l$ in the CMB power spectrum. For such scale there is a potential discrepancy between the best-fit cosmological model and the CMB anisotropy data from the Wilkinson Microwave Anisotropy Probe (WMAP), the Arcminute Cosmology Bolometer Array Receiver(ACBAR), and the Cosmic Background Imager (CBI) in the liner perturbation theory. We found that the PMF is one of the most predominant physical processes for resolving such a discrepancy.

We confirmed numerically without approximation that the excess power in the CMB at higher l was able to be explained by the existence of PMF. Also, we confirmed that the vector mode effect of the PMF dominates the TT mode of CMB fluctuation from the PMF. A likelihood analysis utilizing the WMAP, ACBAR and CBI data with the Markov Chain Monte Carlo(MCMC) method was applied for the first time to constrain the upper limit on the strength of the PMF, which turned out to be

$$|B_\lambda| < 7.7nG \quad .$$

We also considered three conditions on the generation and evolution of the cosmological PMF: 1) the constraint on the PMF from the CMB (our result); 2) the lower limit of the PMF from the magnetic field of galaxy clusters; and 3) the constraint on the PMF from gravity waves. Combining these three conditions, we found the following concordance region for the PMF parameters;

$$1 \text{ nG} < |B_\lambda| < 4.7 \text{ nG} \quad , \quad -3.0 < n < -2.4 \quad .$$

We will be able to constrain the PMF more accurately when we combine our study and future data of observed CMB anisotropies and polarizations for higher multipoles l via the *Planck Surveyor.*

We also investigated the effect of the PMF on the energy density fields by numerically studying the stochastic PMF that depends on scales, and we quantitatively discussed the effect of the PMF on the seeds of LSS in the early universe. We considered not only the magnetic field tension but also the increases of pressure and energy density perturbations from the field. Furthermore, by considering the correlation between the PMF and the fluctuation of the matter density, and taking the mathematically exact stochastic PMF power spectrum, we obtained reasonable and accurate evolutions of baryon, cold dark matter (CDM), photon, and therefore the LSS, too. We showed that the PMF can play very different roles in the evolution of density perturbations according to the correlation between the PMF and the primordial density fluctuations. After decoupling, CDM is also influenced indirectly by the PMF through gravitational interaction. We have estimated the effects numerically and found that the amplitude ratio between the density spectra with and without PMF, $|P(k)/P_0(k)|$ at $k > 0.2$ Mpc^{-1}, lies between 75% and 130% at present for the range of PMF parameters n_B = -2.001 and -1.0, 0.5 nG $< |B_\lambda| <$ 1.0 nG, and $-1 < s < 1$, where s is the correlation parameter between the PMF and the primordial density fluctuations.

It is reported that the magnetic field around $|B_\lambda| \sim$ nG at large scales (λ =1Mpc) provides a new interpretation for the excess of CMB anisotropies at smaller angular scales for the reason below. If the PMF had such strength it is very likely, as shown in the present thesis, that the PMF has affected the formations of LSS. Yoshida, Sugiyama and Hernquist (2003) suggested that in order to avoid false coupling of the baryon and CDM at small scales, it is preferable to use independent transfer functions for the baryon and CDM. The PMF could be another source of this difference in the transfer function for baryon and CDM. The LSS with the PMF should have evolved differently from that without the PMF, since the density perturbations in the early universe have evolved to the LSS at present epoch. We have shown that the perturbations of baryon and the CDM energy density follow very different evolutions in the presence of the PMF. The evolution of large scale structure should become more complicated and interesting with the PMF being taken into consideration.