Effects of isocurvature fluctuations on cosmic microwave background

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abstract

The cosmic microwave background (CMB) anisotropy is a powerful tool to test cosmological scenarios since it depends on the thermal history of the universe, in addition, it originates to fluctuations in the early universe. Origin of the CMB anisotropy attributes to two types of fluctuations, "adiabatic fluctuation" and "isocurvature fluctuation." In the standard scenario of cosmology, origin of the CMB anisotropy is assumed to be quantum fluctuation of the inflaton field during inflation. In this case, since the inflaton decays into radiation, quantum fluctuation of inflaton field is inherited into that of radiation. Hence it becomes that the dominant component fluctuates initially. This kind of primordial fluctuation is called "adiabatic fluctuation," which has been well investigated. On the other hand, from the viewpoint of particle physics, there can exist other fields besides the inflaton field such as the axion field and the Affleck-Dine (AD) fields. In this case, fluctuation of a subdominant component can be an origin of the anisotropy, which is called "isocurvature fluctuation." Thus, in cosmological scenarios with exotic fields, the CMB anisotropy originates to mixture of adiabatic and isocurvature fluctuation, which induces non-standard signal on the CMB. Hence, if we observe the CMB anisotropy, we can test cosmological scenarios with exotic fields. So far the cases where *uncorrelated* mixture of adiabatic and isocurvature fluctuations is generated are well studied by many authors. In general, however, adiabatic and isocurvature fluctuations can be *correlated*.

In this thesis, we discuss effects of cosmological moduli fields on the CMB. In superstring theory, it is well known that there are various flat directions parameterized by scalar fields which is often called as "moduli" fields. Since their potential is usually generated by effects of supersymmetry (SUSY) breaking, their masses are expected to be of the order of the gravitino mass. Although masses of the moduli fields can be as light as (or even lighter than) the electroweak scale, moduli fields do not affect collider experiments since their interactions are suppressed by inverse powers of the gravitational scale. Cosmologically, however, they may cause serious problems. Since the primordial amplitude of the modulus field ϕ may be displaced from the minimum of the potential, ϕ may dominate the energy density of the universe. If the mass of the moduli fields $m_\phi \lesssim O(10\mathrm{TeV})$, reheating temperature of the universe becomes lower than $\sim$ 1MeV. With such a low reheating temperature, the success of the big bang nucleosynthesis (BBN) is spoiled. For lighter moduli fields $m_\phi \lesssim O(100\mathrm{MeV})$, they survive until today and overclose the universe. One solution to these difficulties is to push up the mass of the moduli fields. Indeed the reheating temperature can be higher than 1MeV if $m_\phi \gtrsim O(10\mathrm{TeV})$. In this case, the BBN occurs after the decay of the modulus field.

Although the thermal history after the BBN is mostly the same as the standard one, cosmology before the modulus decay is completely different. Importantly, fluctuations of moduli fields affect the CMB. Thus, by observing the CMB anisotropy, we can test this scenario. With the cosmological moduli fields, *correlated* mixture of adiabatic and isocurvature fluctuations may be generated. In calculating the CMB angular power spectrum C_l, we have to specify the origin of cold dark matter (CDM) and baryon. Here we assume that CDM is generated by the decay of ϕ. In this case, after the decay of the modulus field, there is no entropy between CDM and radiation. On the contrary we consider two possibilities of generating baryon asymmetry: (i) the other field (here we assume it as the Affleck-Dine field) generates the baryon or (ii) the baryon is (somehow) generated at the time of (or after) the decay of ϕ. First, let us discuss the case (i). In this case, fluctuation in the modulus field generates isocurvature fluctuation between baryon and radiation, which is *correlated* with adiabatic fluctuation. If we assume that the fluctuation in the AD field is negligible, the total CMB angular power spectrum C_l is given by the sum of contributions from perturbations in the inflaton field $C_l^{(\mathrm{adi})}$ which is given by the conventional adiabatic one and that in the modulus field $C_l^{(\delta\phi)}$ which is from *correlated* mixture of adiabatic and isocurvature fluctuations; $C_l = C_l^{(\mathrm{adi})} + R^2 C_l^{(\delta\phi)}|_{R=1}$, where R parameterizes relative size of contribution from $C_l^{(\delta\phi)}$ to $C_l^{(\mathrm{adi})}$.

In the left panel of Fig. 1, we plotted the CMB angular power spectrum with cosmological moduli fields $C_l^{(\delta\phi)}$, purely adiabatic case $C_l^{(\mathrm{adi})}$ and purely baryonic isocurvature case $C_l^{(\mathrm{uncorr})}$. From the figure, we can see that $C_l^{(\delta\phi)}$ at higher multipoles is enhanced relative to that of lower ones. In the right panel of Fig. 1, we plotted the total C_l with several values of R. As increasing the value of R, the total C_l at higher multipoles is enhanced relative to lower ones. Such an enhancement can be an evidence of the cosmological moduli fields, and may be observed in on-going and future experiments. Even with the existing data, we can constrain parameters of R which is one of the main result of this thesis. We also studied the case where fluctuation in the AD field is not negligible.

Next we discuss the case (ii). In this case, there is no entropy between baryon and radiation, so the cosmic fluctuations are same as the conventional adiabatic case once the modulus field decays. Thus, when $C_l^{(\mathrm{adi})} \ll C_l^{(\delta\phi)}$ is realized, the resultant CMB angular power spectrum may be like that from adiabatic perturbation. This fact relax constraints on models of inflation.

We also investigated effects of quintessence fields on the CMB anisotropy. Recent cosmological observations suggest that there exists a dark energy which must be added to the matter density in order to reach the critical density. Although the cosmological constant is usually assumed as the dark energy, in the past years, a slowly evolving scalar field, dubbed as "quintessence," has been proposed as the dark energy. Since the quintessence is a scalar field, it fluctuates. This fluctuation affects the CMB anisotropy. We discuss effects of the quintessence fields on CMB focusing on effects of their isocurvature fluctuation. The models of quintessence are classified into two types; the cosine type and tracker type. We study effects of isocurvature fluctuation in both types of model. We found that, for the cosine type model, the CMB angular power spectrum at low multipoles is significantly affected in some cases. For the tracker type quintessence models, we showed that effects of isocurvature fluctuation depend on the initial amplitude of the quintessence fields. In such models, different from the cosine type case, the CMB angular power spectrum at higher multipoles can be enhanced in some cases. In both types of quintessence case, effects of isocurvature fluctuation may be detectable in on-going and future experiments.

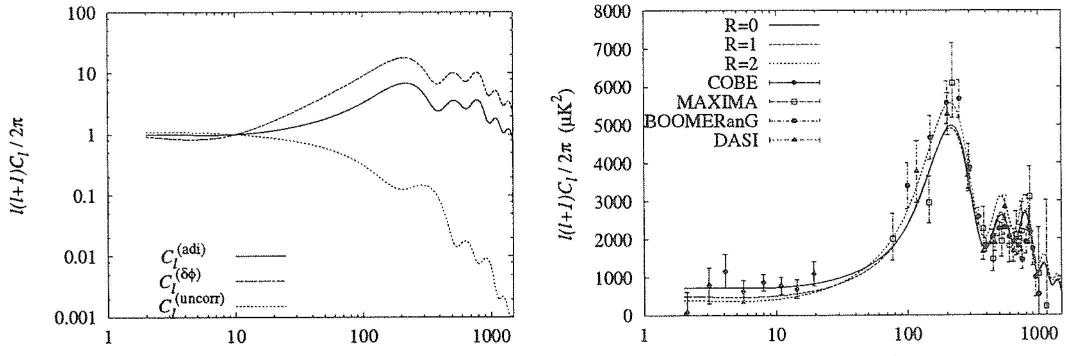

Fig. 1: *Left:* The CMB angular power spectrum $C_l^{(\delta\phi)}$, $C_l^{(\mathrm{adi})}$ and $C_l^{(\mathrm{uncorr})}$. Here we used the normalization $[l(l+1)C_l/2\pi]_{l=10} = 1$.
Right: The CMB angular power spectrum C_l with several values of R. The overall normalization of C_l is determined to be best fitted to the observational data. In these figures, the cosmological parameters are taken to be $h = 0.65$, $\Omega_b h^2 = 0.019$, $\Omega_m = 0.4, \Omega_\Lambda = 0.6$, and scale-invariance is assumed for the initial power spectrum.

論文審査の結果の要旨

宇宙背景放射の揺らぎは，宇宙初期に関する様々な情報を与えるという点において大変興味深い研究対象である。ただしこれまでの宇宙背景放射の揺らぎの理論計算は，ほとんどが断熱的揺らぎと標準的な宇宙模型とを仮定したものであった。しかし様々な素粒子模型に基づく宇宙模型を構築した場合，それらの仮定は必ずしも適当とは言えず，従って非標準的な場合の宇宙背景放射の性質を理解しておくことは素粒子論の立場からも重要である。

高橋智は以上の観点から，モジュライ場やクインテッセンス場というスカラー場を導入した宇宙模型における宇宙背景放射の研究を行った。特に高橋はそれぞれのシナリオにおいてスカラー場の揺らぎから等曲率揺らぎが生じることに着目し，その宇宙背景放射への影響について議論した。

超弦理論に現れるモジュライ場が一時期宇宙を支配し，その崩壊によって現在観測されている宇宙背景放射が生成される場合，インフレーション中に生じたモジュライ場の揺らぎは宇宙背景放射の揺らぎに受け継がれる。高橋提出の論文においては，この過程が詳しく調べられており，そのようなシナリオでは断熱的揺らぎと等曲率揺らぎとが相関を持って生じる可能性があることが示されている。さらに高橋は，その結果によってこれまで知られていたインフレーション模型に対する宇宙背景放射からの制限が大きな変更を受け得ることを示すとともに，宇宙背景放射にこの模型に特徴的な揺らぎが現れうることも指摘している。また，同論文では，宇宙の「暗黒エネルギー」としてクインテッセンス場を導入した場合，大きな角度スケールの宇宙背景放射の揺らぎが標準的な宇宙模型を仮定した場合に比べて大きくなり得ることも示されている。以上の結果は，将来宇宙背景放射の精密観測を用いて宇宙初期の物理を理解する上で重要な役割を果たすものである。

以上から，高橋智が自立した研究活動を行うのに必要な研究能力と学識を持っていることは明らかであり，高橋智提出の論文は，博士（理学）の学位論文として合格と認める。