Gravitational Waves in Quintessential Inflation

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Abstract

Quintessential inflation explains both inflation and present accelerated expansion. In this model these two accelerated expansion is driven by a single scalar field. We construct a model based on an exponential potential. We consider two kinds of reheating process. One is the ordinary reheating in quintessential inflation, using gravitational particle creation. The other is the instant preheating which is much more effective. We calculate the relic gravitational waves produced during inflation in our model. We find that the spectrum of the gravitational waves is quite sensitive to the reheating process. Conversely, the detection or non-detection of primordial gravitational waves at ∼100MHz would have profound implications for the inflationary cosmology.

1. Introduction

Recent observations of super novae Ia suggest that our universe undergoes accelerated expansion at the present [6, 7]. It is considered that this expansion is caused by dark energy dominating the universe in energy density. Quintessence is a candidate for dark energy. This is a scalar field which slowly rolls down its potential. The energy of its potential is small and hardly change at present. But its potential energy has contribution to our universe as dark energy and brings accelerated expansion. This mechanism of expansion is similar to the idea of inflation.

Peebles and Vilenkin suggested that quintessence is identified with inflaton [5]. Both inflation and present accelerated expansion are caused by a single scalar field in this model. They called this inflation model quintessential inflation. But the potential they used is combination of chaotic inflation and quintessence potential. This potential is a toy model. In this paper we construct a smooth potential based on an exponential potential. We consider reheating process by instant preheating [3] as well as by gravitational particle production previously considered in [5].

Inflation produces primordial density perturbations and gravitational waves.

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The detection of the gravitational waves will be the evidence for inflation, although current detectors will not be able to detect them. It is known that the amplitude of gravitational waves is enhanced in quintessential inflation [5]. So, the possibility of detection of the gravitational waves is expected more than in other inflation model. We calculate the spectrum of gravitational waves in our model. We discuss the possibility of the detection and the difference of spectrum strength in our model.

2. Quintessential inflation model

We adopt as the potential form of the scalar field ϕ

$$V(\phi) = V_0 \exp(-\lambda(\phi)\phi/M_{\rm pl}), \tag{1}$$

$$\lambda(\phi) = (\tanh(\phi/M_{\rm pl}) + A)\left(\frac{(\phi/M_{\rm pl})^2 + u^2}{(\phi/M_{\rm pl})^2 + v^2}\right), \tag{2}$$

where A, u and v are constants and $M_{\rm pl} = 1/\sqrt{8\pi G} = 2 \times 10^{18}$ GeV. We assume $A = 1.1$, and arrange $u,\ v$ to fix $\Omega_\phi = 0.7$ at the present.

In quintessential inflation there is the scalar field's kinetic energy dominating era. In this era the scale factor is $a \propto t^{1/3}$ and the reheating process occur. We consider two kinds of reheating process. One is the reheating by gravitational particle production [5], and the other is instant preheating [3].

The reheating by gravitational particle production occur as follows [5]. The particle creation is caused by the expansion of the universe, and the created particles thermalize among the fermions and gauge bosons. The created energy density from it is $\rho = RH_{\rm end}^4(a/a_{\rm end})^{-4}$, where $R \sim 10^{-2}N_s$ and N_s is the number of scalar fields. The created particles thermalize when the rate of the interaction with gauge bosons is comparable to the expansion rate. The kinetic energy density is proportional to a^{-6}, and the radiation energy density is proportional to a^{-4}. Therefore kinetic energy density is equal to the energy density of radiation and the radiation dominant era begins. At this beginning the temperature is $T_r \sim R^{3/4}V_0M_{\rm pl}^{-3} \sim R^{3/4} \times 10^6$ GeV. This temperature is enough for the big bang nucleosynthesis.

Instant preheating was suggested for the potential with no oscillation [3]. The mechanism is similar to preheating by parametric resonance. They introduce the interaction lagrangian, $L_{int} = -\frac{1}{2}g^2\phi^2\chi^2 - \frac{1}{2}\psi\bar{\psi}\chi$. The energy of the field ϕ is transferred into the energy of the fermion ψ through the scalar field χ. The fermion ψ is decay immediately, so we can assume the energy density of the fermion ψ as that of radiation. This reheating is more efficient than the reheating by gravitational particle production.

3. Spectrum of gravitational waves

In each reheating process, we arrange $u,\ v$ to fix $\Omega_\phi = 0.7$ at the present. We can get the scale factors at the beginning of each epoch. By using these values, we can obtain the energy density spectrum of gravitational waves. In transverse traceless gauge gravitational waves are written,

$$h_{\mu\nu} = \sum_{\lambda=(+,\times)} \int \frac{dk^3}{(2\pi)^{3/2}} \epsilon_{\mu\nu}{}^{\lambda} u_k(\tau) e^{i\mathbf{k}\cdot\mathbf{x}}, \tag{3}$$

where $\epsilon_{\mu\nu}$ is the polarization tensor and gravitational waves have two degree of freedom in polarization. The Einstein equations give an equation for u_k,

$$u_k{}'' + 2(a'/a)u_k{}' + k^2\, u_k = 0. \tag{4}$$

where the prime denotes the derivative with respect to the conformal time. From this equation we get the energy density of gravitational waves by using the Bogoliubov coefficients method [1, 2]. Fig. 1 is the spectrum of gravitational waves for two reheating processes. $h_0^2\Omega_{\rm gw}$ is the density parameter defined as $h_0^2\Omega_{\rm gw}(f) = (h_0^2/\rho_c)(d\rho_{\rm gw}/d\log f)$, where $\rho_{\rm gw}$ is the energy density of gravitational waves and ρ_c is the present critical energy density.

The spectrum of gravitational waves has the same shape as that of ordinary inflation at the lower frequency bands. However, due to the presence of the kination the shape can be different at the higher bands. The energy density spectrum of gravitational waves which enter into the horizon during kination is proportional to f. Therefore the gravitational waves at high frequency is amplified much more than that in ordinary inflation models. The duration of the kination depends on the efficiency of reheating, and the longer duration of the kination results in larger amplitude. But the energy density of the gravitational waves is constrained by the success of the big bang nucleosynthesis (It is called BBN bound), $h_0^2\Omega_{\rm gw} = 5 \times 10^{-6}$ [4]. Therefore the efficiency of the reheating by gravitational particle production is restricted at the left panel in Fig. 1.

Instant preheating is more efficient than gravitational reheating so that the enhancement of the spectrum of the gravitational waves entering into horizon during kination is restricted to higher frequency. When g and h are low value the decay of the field χ is delayed. Because the energy density ρ_χ is proportional to a^{-3}, the energy density of the field χ dominates the kinetic energy density of the field ϕ, depending on these values. The universes is dominated by non-relativistic particles. In the spectrum of the gravitational waves the imprint is left distinctly.

4. Conclusion

We investigate the possibility of the quintessential inflation by exponential potential. We consider two kinds of reheating process: gravitational particle

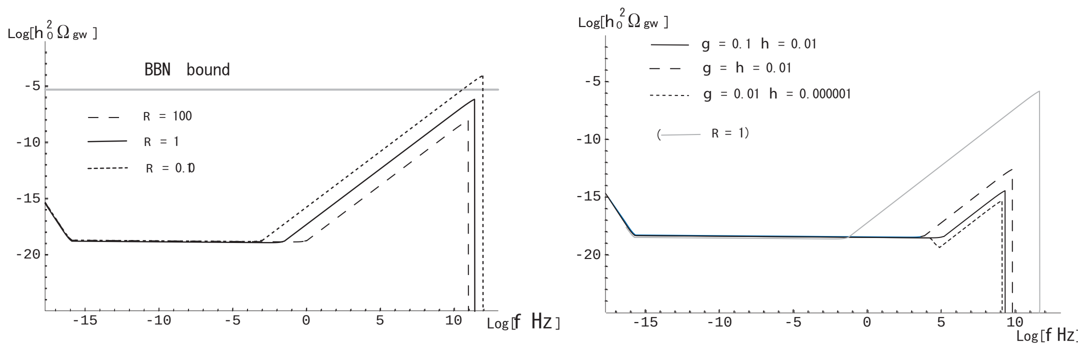

Fig. 1. The spectrum of gravitational waves. The left panel is in the case of the reheating by gravitational particle production. The right one is in the case of instant preheating. For comparison, we also plot the result of gravitational reheating with $R = 1$.

production and instant preheating. In both reheating processes the present accelerated expanding could be explained by the scalar field by which inflation was occurred in the past. We calculate the spectrum of gravitational waves produced during inflation. In our model the spectrum of the gravitational waves at the higher band is amplified more than that in ordinary inflation. We find that the spectrum is sensitive to reheating process and can be enhanced at $\sim$ 100MHz. Therefore by the observation at these bands we may be able to obtain information regarding the physics of early universe.

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