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Cosmology with rolling tachyon

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Abstract. We examine the possibility of rolling tachyon to play the dual role of inflaton at early epochs and dark matter at late times. We argue that enough inflation can be generated with the rolling tachyon either by invoking the large number of branes or brane world assisted inflation. However, reheating is problematic in this model.

1. Introduction

Cosmological inflation has become an integral part of the standard model of the universe. Apart from being capable of removing the shortcomings of the standard cosmology, it gives important clues for structure formation in the universe. The inflationary paradigm seems to have gained a fairly good amount of support from the recent observations on microwave background radiation. On the other hand there have been difficulties in obtaining accelerated expansion from fundamental theories such as M/string theory. Recently, Sen [1–3] has shown that the decay of an unstable D-brane produces pressure-less gas with finite energy density that resembles classical dust. Gibbons has emphasized the cosmological implications of tachyonic condensate rolling towards its ground state [4] (see [5,6] for further details). Rolling tachyon matter associated with unstable D-branes has an interesting equation of state which smoothly interpolates between -1 and 0. The tachyonic matter, therefore, might provide an explanation for inflation at the early epochs and could contribute to some new form of dark matter at late times [7] (see also [8–11] on the related theme and [12] for an alternative approach to rolling tachyon cosmology). We shall review here the cosmological prospects of rolling tachyon with exponential potential.

2. Cosmology with rolling tachyon

It was recently shown by Sen that the dynamics of string tachyons in the background of an unstable D-brane can be described by an effective field theory with Born–Infeld-type action [3]

$$S = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{R}{16\pi G} - V(\phi)\sqrt{1 + g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi}\right), \tag{1}$$

where ϕ is the tachyon field minimally coupled to gravity. In a specially flat FRW cosmology the stress tensor acquires the diagonal form $T^\alpha_\beta = \mathrm{diag}(-\rho, p, p, p)$ where the pressure and energy density are given by

$$\rho = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \tag{2}$$

$$p = -V(\phi)\sqrt{1 - \dot{\phi}^2}. \tag{3}$$

The Friedmann equation takes the form

$$H^2 = \frac{1}{3M_p^2}\rho \equiv \frac{1}{3M_p^2}\frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}. \tag{4}$$

The equation of motion of the tachyon field which follows from (1) is

$$\frac{\ddot{\phi}}{1 - \dot{\phi}^2} + 3H\dot{\phi} + \frac{V_{,\phi}}{V(\phi)} = 0. \tag{5}$$

The conservation equation equivalent to (5) has the usual form

$$\frac{\dot{\rho}_\phi}{\rho_\phi} + 3H(1 + \omega) = 0,$$

where $\omega \equiv (p_\phi/\rho_\phi) = \dot{\phi}^2 - 1$ is the equation of state for the tachyon field. Thus a universe dominated by tachyon field would go under accelerated expansion as long as $\dot{\phi}^2 < (2/3)$ which is very different from the condition of inflation for non-tachyonic field, $\dot{\phi}^2 < V(\phi)$. This is related to the fact that field potential falls out of the equation of state in case of the tachyon field. It should also be noted that evolution equation for tachyon field contains the logarithmic derivative of the potential.

2.1 *Dynamics of tachyonic inflation in FRW cosmology*

The tachyon potential $V(\phi) \to 0$ as $\phi \to \infty$ but its exact form is not known at present [13]. Sen has argued that the qualitative dynamics of string theory tachyons can be described by (1) with exponential potential [3]. Padmanabhan went further to suggest that one can construct a phenomenological runaway potential with the tachyonic equation of state capable of leading to a desired cosmology [14] (see also [15] on the similar theme). In what follows, we shall consider (1) with the exponential potential in purely phenomenological context without claiming any identification of ϕ with the string tachyon field. Indeed, there are problems with inflation in case the origin of ϕ is traced in string theory [16] and we will come back to this point later. The field equations (4) and (5) for tachyonic matter with the exponential potential

$$V(\phi) = V_0 \mathrm{e}^{-\alpha\phi} \tag{6}$$

can be solved exactly in the slow roll limit. The integration of these equations leads to [17]

$$\dot{\phi}_{\mathrm{end}} = \sqrt{\frac{2}{3}}, \quad \phi_{\mathrm{end}} = -\frac{1}{\alpha} \ln\left(\frac{\alpha^2}{6\beta^2}\right), \quad V_{\mathrm{end}} = \frac{\alpha^2 M_p^2}{2}, \tag{7}$$

where $\beta = \sqrt{V_0/3M_p^2}$. Equation (7) is consistent with the expression of the slow roll parameter

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \frac{1}{V}. \tag{8}$$

The COBE normalized value for the amplitude of scalar density perturbations

$$\delta_H^2 \simeq \frac{1}{75\pi^2} \frac{V_{\mathrm{i}}^2}{\alpha^2 M_p^6} \simeq 4 \times 10^{-10}, \tag{9}$$

can be used to estimate V_{end} as well as α. Here V_{i} refers to the value of the potential at the commencement of inflation and is related to V_{end} as

$$V_{\mathrm{end}} = \frac{V_{\mathrm{i}}}{2N+1}. \tag{10}$$

Using eqs (9) and (10) with $\mathcal{N} = 60$ we obtain

$$V_{\mathrm{end}} \simeq 4 \times 10^{-11} M_p^4. \tag{11}$$

At the end of inflation, apart from the field energy density, a small amount of radiation is also present due to particles being produced quantum mechanically during inflation [18]

$$\rho_r = 0.01 \times g_p H_{\mathrm{end}}^4 \qquad (10 \le g_p \le 100) \tag{12}$$

which shows that the field energy density far exceeds the density in the radiation

$$\frac{\rho_r}{\rho_\phi} \simeq 0.01 \times g_p \frac{V_{\mathrm{end}}}{9M_p^4} \simeq 4 \times g_p \times 10^{-14}. \tag{13}$$

From (7) we find that $\alpha \simeq 10^{-5} M_p$ and there is no problem as long as we consider the tachyonic model of inflation in phenomenological context. However, it would be problematic if we trace the origin of field ϕ in string theory as there is no free parameter to tune. Indeed, α and V_0 can be expressed through string length scale and string coupling g_{s} as $\alpha = \alpha_0/l_{\mathrm{s}}$, $V_0 = v_0/(2\pi)^3 g_{\mathrm{s}} l_{\mathrm{s}}^4$ where v_0 and α_0

are dimensionless constants and V_0/v_0 is brane tension and α is the tachyon mass. Tuning α to $10^{-5}M_p$ leads to one of the two unacceptable situations: light mass of the tachyon or large value of string coupling g_s. This problem is quite independent of the form of tachyonic potential (see the paper of Fairbairn and Tytgat [7]). The situation can be remedied by invoking a large number of D-branes separated by distance much larger than l_s [18a]. The number of such branes in our case turns out to be of the order of 10^{10}. The other alternative could be the brane-assisted inflation. Indeed, the prospects of inflation in brane world scenario improve due to the presence of an additional quadratic density term in the Friedmann equation. Enough inflation can be generated in this case without tuning α (see the paper by Bento *et al* [7] and [17]). The non-brane world alternatives to tackle this problem are discussed by Yun–Song Piao and collaborators [7].

Regarding the late time behaviour, the phase space analysis of tachyon field with exponential potential was carried out in [17]. It was shown that dust-like solution is a late time attractor of the tachyonic system. Therefore the tachyon field, in principle, could become a candidate for dark matter.

Inspite of the very attractive features of the rolling tachyon condensate, the tachyonic inflation faces difficulties associated with reheating [16,17]. A homogeneous tachyon field evolves towards its ground state without oscillating about it and, therefore, the conventional reheating mechanism in tachyonic model does not work. Quantum mechanical particle production during inflation provides an alternative mechanism by means of which the universe could reheat. Unfortunately, this mechanism also does not seem to work: the small energy density of radiation created in this process red-shifts faster than the energy density of the tachyon field and therefore radiation domination in the tachyonic model of inflation never commences. However, the tachyon field could play the role of dark matter if the problem associated with caustics could be overcome [20].

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