Published by Institute of Physics Publishing for SISSA/ISAS
Received: *October 9, 2003*
Accepted: *November 27, 2003*

Note on D-brane effective action in the linear dilaton background

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Abstract: In this short note we will study effective action for unstable D-brane in the linear dilaton background. We will solve the equation of motion for large T and we will calculate the stress energy tensor. Then we compare our results with the calculations performed using exact conformal field theory description of the open string worldsheet theory.

Keywords: Bosonic Strings, D-branes, Tachyon Condensation.

Contents

1. Introduction

The study of time-dependent open string tachyons [1]–[7] was very intensive in recent two years and also leads to the discovery of new dualities and reinterpretation some old ones, especially relation between two dimensional string theories and matrix models [8]–[35].

In the same way recent works on dynamics of unstable D-branes in string theory has led to an effective action for the open string tachyon T and massless open string modes A_μ (the gauge field on the D-brane) and Y^I (the scalar field parametriziing the location of the D-brane in the transverse directions) [36]–[44]. This action has the form[1]

$$\begin{aligned} S &= \int d^{p+1}x\mathcal{L} \\ \mathcal{L} &= -\tau_p V(T)\sqrt{-\det \mathbf{A}}\,, \\ \mathbf{A}_{\mu\nu} &= \eta_{\mu\nu} + \partial_\mu T\partial_\nu T + \delta_{IJ}\partial_\mu Y^I \partial_\nu Y^J + F_{\mu\nu}\,, \end{aligned} \tag{1.1}$$

where τ_p is Dp-brane tension and $V(T)$ is tachyon potential that for large T is expected to behave as

$$V(T) \sim e^{-\alpha T/2}\,, \tag{1.2}$$

with $\alpha = 1$ for a bosonic string and $\alpha = \sqrt{2}$ for the non-BPS D-brane in superstring. The action (1.1) is known to reproduce some aspects of open string dynamics. For example, if we choose the tachyon potential as [14]

$$V(T) = \frac{1}{\cosh\frac{\alpha T}{2}}\,, \tag{1.3}$$

one finds from (1.1) the correct stress energy tensor $T_{\mu\nu}$ in homogeneous tachyon condensation. For the case of an unstable D-brane in type-II string theory we can also construct a codimension one BPS D-brane as a solitonic solution of (1.1).

[1] We use the conventions $\alpha' = 1$, $\eta_{\mu\nu} = (-1, +1, \ldots, +1)$.

Thanks to these results one can believe that the action (1.1) captures some class of phenomena of classical open string theory. Following [43] we can consider the action (1.1) as generalisation of the DBI action describing the gauge field A_μ and scalars Y^I on D-brane. The DBI action is valid in the full open string theory in situations when $F_{\mu\nu}$ and $\partial_\mu Y^I$ are arbitrary but slowly varying.

Since the success of the action (1.1) in the description of the tachyon condensation in the flat spacetime is very intriguing it seems to be natural to consider this action in a more general closed string background. Recently the exact conformal field theory (CFT) analysis of the time-dependent tachyon condensation in the linear dilaton background was performed in [17]. We mean that would be interesting to look at this problem also from the effective action point of view. The starting point of our calculation is the presumption that the action (1.1) gives good description of the effective field theory dynamics of unstable D-brane in the linear dilaton background $\Phi = V_\mu x^\mu$ in the situation when the tachyon field T is large. Then the equation of motion implies an asymptotic behaviour of the tachyon as $T \sim \beta t$ where β is constant which depends on time component V_0 of the spacelike vector V_μ. It turns out however that the dependence of β on V_μ is not as the same as the exact CFT relation $\beta(\beta - V_0) = 1$ [17]. We also find that the asymptotic behaviour of the stress energy tensor derived from (1.1) is completely different from the exact calculation given in [17]. More precisely, we will find that the stress energy tensor diverges at far future. These results imply that the effective action description of the tachyon condensation in the linear background is much more complicated than in case of the constant string coupling.

The organisation of this paper is as follows. In the next section (2) we review how to get the solution of the tachyon equation of motion on unstable D-brane when T is large and when the dilaton field is constant. Then we extend this analysis to the case of the linear dilaton background. In order to understand better of the problem of the tachyon condensation in the linear dilaton background we will study in section (3) D-brane effective action proposed in [43]. We will show that even if this action correctly describes the mass of the tachyon fluctuation around the unstable vacuum $T = 0$ in case of the constant dilation its description of the tachyon dynamics in the linear dilaton background is more involved. In particular, we will show that on-shell condition for tachyon fluctuations around unstable vacuum $T = 0$ is different from the exact one. In conclusion (4) we outline our results and also suggest other problems that deserve further study.

2. D-brane effective action

In this section we will study the process of the tachyon condensation on unstable D-brane in the bosonic theory when the closed string background is nontrivial. As we claimed in the introduction the main point of our interest is the Dp-brane effective action

$$\begin{aligned} S &= -\tau_p \int d^{p+1}x e^{-\Phi} V(T)\sqrt{-\det \mathbf{A}} = -\tau_p \int d^{p+1}x e^{-\Phi}\sqrt{-g}V(T)\sqrt{\mathbf{B}}\,, \\ \mathbf{A} &\equiv \eta_{\mu\nu} + \partial_\mu T \partial_\nu T\,, \quad g = \det \quad \eta = -1\,, \\ -\det \mathbf{A} &\equiv -g\mathbf{B} = (1 + \eta^{\mu\nu}\partial_\mu T\partial_\nu T)\,, \end{aligned} \tag{2.1}$$

where we restrict ourselves to the dynamics of the tachyon T only. In this place it is important to stress that the action (2.1) was not obtained from the first principles, it is only consistent with the time evolution of the stress energy tensor of various classical solutions in string theory in late times [4]. In the same way the form of the potential was derived by requiring that during the rolling tachyon process the pressure associated with this configuration falls off as e^{-t}.

Before we proceed to the study of the tachyon dynamics in the linear dilaton background we firstly review the rolling tachyon solution in case of the constant Φ. For the time-dependent tachyon $T(t)$ the equation of motion that arises from (2.1) has the form

$$e^{-\Phi}V'(T)\sqrt{\mathbf{B}}+\frac{d}{dt}\left(\frac{e^{-\Phi}\dot{T}}{\sqrt{\mathbf{B}}}\right)=0\,. \tag{2.2}$$

Since for large T the expected behaviour of V is $V=e^{-\alpha T/2}$ it is natural to consider following asymptotic form of T

$$\dot{T}=1-K^2e^{-\alpha t}\,,\qquad \dot{T}^2=1-2K^2e^{-\alpha t}\Rightarrow\sqrt{\mathbf{B}}=\sqrt{2}Ke^{-\alpha t/2}\,. \tag{2.3}$$

It is easy to see that the ansatz (2.3) solves the equation of motion (2.2)

$$-\frac{\alpha}{2}e^{-\alpha T/2}\sqrt{2}Ke^{-\alpha t/2}+\frac{d}{dt}\left(\frac{e^{-\alpha t/2}\dot{T}}{\sqrt{2}Ke^{-\alpha t/2}}\right)=0\Rightarrow$$
$$-\frac{\alpha K}{\sqrt{2}}e^{-\alpha t}+\frac{d}{dt}\frac{(1-K^2e^{-\alpha t})}{\sqrt{2}K}=-\frac{\alpha K}{\sqrt{2}}e^{-\alpha t}+\frac{\alpha K}{\sqrt{2}}e^{-\alpha t}=0\,. \tag{2.4}$$

We must stress that the tachyon grows at far future as $T\sim\beta t$,$\beta=1$. On the other hand in the CFT description of the rolling tachyon the parameter β is presented in the exponential of the marginal operator $T\sim e^{\beta X^0}$,$\beta=1$ which is inserted on the boundary of the worldsheet. We then mean that it is reasonable to ask the question whether there is similar relation between the asymptotic form of tachyon field in the effective theory description $T\sim\beta t$ and the parameter β' in the worldsheet boundary interaction term $T\sim e^{\beta' t}$ when the string is embedded in the linear dilaton background

$$\Phi=V_\mu x^\mu\,,\qquad V_\mu V^\mu=\frac{(26-D)}{6}>0\,. \tag{2.5}$$

More precisely, the CFT description of the tachyon condensation on unstable D-brane in the linear dilaton background is as follows [17]. Tachyon condensates can be in the form $\exp\left(\beta' X^0\right)$ with $\beta'>0$. The conformal dimension of worldsheet boundary interaction operator is $\triangle=\beta(\beta'-V_0)$. Requiring that the boundary interaction is marginal implies that $\triangle=1$ and hence we obtain

$$V_0=\beta'-\frac{1}{\beta'}\,. \tag{2.6}$$

The question is whether we can find similar relation between V_0 and the parameter β in the effective theory description if we propose following form of T at far future

$$\dot{T}=\beta-Ke^{-\gamma t}\,,\qquad \dot{T}^2=\beta^2-2K\beta e^{-\gamma t}\,,\qquad \sqrt{\mathbf{B}}=\sqrt{1-\beta^2}+\frac{K^2\beta}{\sqrt{1-\beta^2}}e^{-\gamma t}\,. \tag{2.7}$$

We presume that $\gamma > 0$ so that the exponential term vanishes for large t. We also demand that $\beta \neq 1$ in order $\sqrt{1-\beta^2}$ to be finite. Then the equation of motion is

$$-\frac{\alpha}{2}e^{-\Phi-\alpha\beta t/2}\sqrt{1-\beta^2}+\frac{d}{dt}\left(\frac{e^{-\Phi-\alpha\beta t/2}\beta}{\sqrt{1-\beta^2}}\right)=0 \Rightarrow$$
$$\Rightarrow -\frac{\alpha}{2}(1-\beta^2)-V_0\beta-\frac{\alpha\beta^2}{2}=0 \Rightarrow \alpha=-2V_0\beta\,. \tag{2.8}$$

Since the system rolls to the stable vacuum at $T=\infty$ we must have $\beta > 0$ and hence (2.8) implies $V_0 < 0$. In other words the tachyon condensation when the tachyon reaches its stable minimum at $T=\infty$ is only possible when the string coupling constant vanishes at far future. Since we are interested in the dynamics of unstable D-brane in bosonic theory we have $\alpha = 1$ and then from (2.8) we get

$$V_0 = -\frac{1}{2\beta}\,. \tag{2.9}$$

This result is clearly different from the exact CFT relation (2.6). We mean that this is the first indication that the effective field theory description of the tachyon condensation in the linear dilaton background does not completely reproduce results obtained through CFT analysis. Further support for this claim follows from the study of the asymptotic behaviour of the stress energy tensor $T_{\mu\nu}$ defined as

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S}{\delta g^{\mu\nu}}\,. \tag{2.10}$$

From (2.1) and using $\frac{\delta\sqrt{-g}}{\delta g^{\mu\nu}} = -\frac{1}{2}\sqrt{-g}g_{\mu\nu}$ we obtain

$$\begin{aligned}
T_{\mu\nu} &= -\eta_{\mu\nu}e^{-\Phi}V(T)\sqrt{\mathbf{B}}+\frac{e^{-\Phi}V(T)\partial_\mu T\partial_\nu T}{\sqrt{\mathbf{B}}}\,,\\
T_{00} &= \frac{e^{-\Phi}V(T)(1+\eta^{ij}\partial_i T\partial_j T)}{\sqrt{\mathbf{B}}}\,,\\
T_{ij} &= -\delta_{ij}\frac{e^{-\Phi}V(T)}{\sqrt{\mathbf{B}}}(1-\partial_0 T\partial_0 T)\,.
\end{aligned} \tag{2.11}$$

Hence for solution (2.7) components of the stress energy tensor at far future are equal to

$$\begin{aligned}
T_{00} &= \frac{e^{\left(\frac{1-4V_0^2}{4V_0}\right)t}}{\sqrt{1-\beta^2}}\,,\\
T_{ij} &= -\delta_{ij}e^{\left(\frac{1-4V_0^2}{V_0}\right)t}\sqrt{1-\beta^2}\,.
\end{aligned} \tag{2.12}$$

From the requirement that the stress energy tensor should be real and finite we get the condition $\beta^2 < 1$ which using (2.9) also implies

$$V_0 > -\frac{1}{2}\,. \tag{2.13}$$

From (2.12) we also see that for $-1/2 < V_0 < 0$ all components of the stress energy tensor diverge at far future. This behaviour is completely different from the exact CFT description given in [17] where it was shown that zero component of the stress energy tensor T_{00} does not depend on time at far future while the spatial components T_{ij} vanish. We mean that these results show that the effective action (1.1) description of the tachyon condensation in the linear dilaton background is slightly problematic. On the other hand it is possible that our proposed ansatz (2.7) is too naive and more complicated form of the tachyon at far future could give better results. In any case we see that the effective action description of the tachyon condensation in the linear dilaton background is much more complicated than in case of constant Φ. More comments about this result will be given in conclusion.

In the next section we will study the tachyon condensation in the linear dilaton background using an effective action that was proposed [43].

3. Other form of the D-brane effective action

We begin this section with the brief review how the D-brane effective action in bosonic string theory was derived in [43]. We start with the D-brane effective action proposed in [14]

$$S = -\tau_p \int e^{-\Phi} \frac{1}{\cosh \frac{\tilde{T}}{2}} \sqrt{1 + \eta^{\mu\nu}\partial_\mu \tilde{T} \partial_\nu \tilde{T}}\,. \tag{3.1}$$

Using the following field redefinition [43]

$$T = \sinh^2 \frac{\tilde{T}}{2}\,, \qquad \dot{T} = \dot{\tilde{T}} \cosh \frac{\tilde{T}}{2} \sinh \frac{\tilde{T}}{2} \tag{3.2}$$

we obtain an action in the form

$$S = -\tau_p \int e^{-\Phi} \frac{1}{1+T} \sqrt{1 + T + \frac{\eta^{\mu\nu}\partial_\mu T \partial_\nu T}{T}}\,. \tag{3.3}$$

We must say few words about the action (3.3). The main point is that the lagrangian in (3.1) is analytic in $\tilde{T}$ while the lagrangian in (3.3) is non-analytic in terms of T. This result has important consequence and we mean that this is the reason why the effective action (3.3) deserves to be studied separately. In particular, it was shown that the action (3.1) does not give the correct mass of the tachyon fluctuations around the unstable minimum $\hat{T} = 0$. As was explained in [43] this disagreement can be understood to be due to the non-analytic relation (3.2) between the open string tachyon T and the field $\tilde{T}$ that appears in (3.1). Taking the map into account we can show that (3.3) correctly describes on-shell physics of the tachyon fluctuations around the unstable minimum $T = 0$. More precisely, let us expand (3.3) around unstable minimum of the potential $T = 0$ when we presume that $T, \frac{\eta^{\mu\nu}\partial_\mu T \partial_\nu T}{T}$ are small

$$S = -\tau_p \int e^{-\Phi} \left(\frac{\eta^{\mu\nu}\partial_\mu T \partial_\nu T}{2T} - \frac{T}{2} \right). \tag{3.4}$$

Then the equation of motion that arises from (3.4) is

$$-\frac{e^{-\Phi}}{2}-\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\mu T\partial_\nu T}{2T^2}-\partial_\mu\left(\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\nu T}{T}\right)=0\,. \tag{3.5}$$

For constant Φ it is easy to see that the plane wave ansatz

$$T=e^{ik_\mu x^\mu} \tag{3.6}$$

is solution of the equation of motion on the condition

$$-1+k_\mu\eta^{\mu\nu}k_\nu=0 \tag{3.7}$$

which is correct on shell condition for the tachyonic mode in bosonic theory. However for the linear dilaton background we obtain disagreement with the exact CFT condition. The origin of this result is the fact that for the plane wave ansatz (3.6) the third term in (3.5) is nonzero for linear dilaton background and hence the mass shell condition is

$$-1+k_\mu\eta^{\mu\nu}k_\nu+2iV_\mu\eta^{\mu\nu}k_\nu=0\,. \tag{3.8}$$

On the other hand the exact CFT result gives

$$-1+k_\mu\eta^{\mu\nu}k_\nu+iV_\mu\eta^{\mu\nu}k_\nu=0\,. \tag{3.9}$$

We suspect that some corrections to the effective actions that are proportional to the derivatives of Φ become important for description of the effective action in the linear dilaton background, since for constant Φ the effective action (3.3) is in very good agreement with the exact CFT description. However to find these additional terms in the effective action is very difficult task and it is behind the scope of this paper.

Next we would like to solve the equation of motion for the time-dependent tachyon solution in case of large T. If we denote $\mathbf{B}=1+T+\frac{\eta^{\mu\nu}\partial_\mu T\partial_\nu T}{T}$ then the equation of motion that arises from (3.3) has the form

$$-\frac{e^{-\Phi}}{(1+T)^2}\sqrt{\mathbf{B}}+\frac{e^{-\Phi}}{2(1+T)\sqrt{\mathbf{B}}}-\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\mu T\partial_\nu T}{2(1+T)T^2\sqrt{\mathbf{B}}}-\partial_\mu\left(\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\nu T}{(1+T)T\sqrt{\mathbf{B}}}\right)=0 \tag{3.10}$$

that for large T reduces to

$$-\frac{e^{-\Phi}}{T^2}\sqrt{\mathbf{B}}+\frac{e^{-\Phi}}{2T\sqrt{\mathbf{B}}}-\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\mu T\partial_\nu T}{2T^3\sqrt{\mathbf{B}}}-\partial_\mu\left(\frac{e^{-\Phi}\eta^{\mu\nu}\partial_\nu T}{T^2\sqrt{\mathbf{B}}}\right)=0\,, \tag{3.11}$$

where now $\mathbf{B}=\frac{T^2-\dot{T}^2}{T}$. For the ansatz

$$T=ke^{\beta t} \tag{3.12}$$

we get

$$\dot{T}=\beta T\,,\qquad \mathbf{B}=T(1-\beta^2)\,. \tag{3.13}$$

Inserting these expressions into (3.11) we finally obtain

$$-\frac{e^{-\Phi}\sqrt{1-\beta^2}}{T^{3/2}}+\frac{e^{-\Phi}}{2T^{3/2}\sqrt{1-\beta^2}}+\frac{e^{-\Phi}\beta^2}{2T^{3/2}\sqrt{1-\beta^2}}+\frac{d}{dt}\left(\frac{e^{-\Phi}\beta}{T^{3/2}\sqrt{1-\beta^2}}\right)=0\Rightarrow$$
$$\Rightarrow -1+3\beta^2-2\beta V_0-3\beta^2=0\Rightarrow\beta=-\frac{1}{2V_0}\,. \tag{3.14}$$

We see that we have got the same relation between β and V_0 as in (2.9). In the same way as in the previous section we can calculate from (3.3) the stress energy tensor that now is equal to

$$\begin{aligned}
T_{\mu\nu} &= -\frac{e^{-\Phi}\eta_{\mu\nu}\sqrt{\mathbf{B}}}{1+T}+\frac{e^{-\Phi}\partial_\mu T\partial_\nu T}{(1+T)T\sqrt{\mathbf{B}}}\,,\\
T_{00} &= \frac{e^{-\Phi}}{\sqrt{1+T-\frac{\dot{T}^2}{T}}}\,,\\
T_{ij} &= -\frac{\delta_{ij}e^{-\Phi}\sqrt{1+T-\frac{\dot{T}^2}{T}}}{1+T}\,.
\end{aligned} \tag{3.15}$$

Then for the ansatz (3.12) we get

$$\begin{aligned}
T_{00} &= \frac{e^{\frac{1-4V_0^2}{4V_0}t}}{\sqrt{1-\beta^2}}\,,\\
T_{ij} &= -\delta_{ij}e^{\frac{1-4V_0^2}{4V_0}t}\sqrt{1-\beta^2}\,.
\end{aligned} \tag{3.16}$$

As we could expect the asymptotic form of the stress energy tensor is the same as in the previous section since non-analycity of the field redefinition (3.2) does not show for large T. In spite of this fact we mean that it was useful to perform the analysis of the effective D-brane action (3.3) in the linear dilaton background too. In particular, using the action (3.3) we were able to study the behaviour of the tachyon fluctuations around the unstable minimum $T=0$. We have shown that even in this region the effective action (3.3) does not correctly reproduces exact CFT on shell condition for the tachyonic fluctuations in the linear dilaton background. On the contrary the action (3.3) is very successful in the description of the tachyon dynamics on the world volume of unstable D-brane when the dilaton field is constant. We mean that this result again suggests that the effective field theory description of the unstable D-brane in the linear dilaton background is rather subtle and much more complicated than in case of constant dilaton.

4. Conclusion

In this paper we have considered the effective field theory description of an unstable D-brane in the linear dilaton background. We have asked the question whether the effective field theory description of the time-dependent process of the tachyon condensation in this background can reproduce exact CFT calculation performed in [17]. Since it is generally believed that the effective action (1.1) is valid for large tachyon T [4] we restrict ourselves to the study of the asymptotic behaviour of T at far future where the tachyon field approaches its stable minimum at $T = \infty$. We have begun with the action (1.1) which reproduces correctly the stress energy tensor for rolling tachyon solution [1, 4, 14, 41, 43] in case of the constant dilaton field. We have found solution of equation of motion for large T and we have calculated the stress energy tensor. According to our results the tachyon condensation on unstable D-brane in the bosonic theory can occurs in case when the string coupling constant vanishes at far future. This is different from the exact CFT description where the tachyon condensation occurs for any spacelike dilaton vector. Then we have calculated the stress energy tensor for the rolling tachyon solution and we have found that all its components diverge. On the other hand CFT analysis [17] showed that for $t \to \infty$, T_{00} is independent on time while T_{ij} decays to zero which was interpreted as an emergence of the tachyon dust at far future. As was argued there the fact, that despite the time dependence of the string coupling, the energy density becomes constant and the pressure goes to zero suggests that the tachyon dust is a gas of massive closed strings whose energy is not affected by a change in the dilaton the way the energy of a D-brane is. On the other hand in the effective field theory description all components of the stress energy tensor go to infinity and there is no interpretation of the remnant of the tachyon condensation as pressureless dust. We can explain the divergence of the stress energy tensor as a consequence of the fact that the stress energy tensor is proportional to $\sim g_s^{-1} = e^{-\Phi}$ and according to the effective field theory analysis the tachyon condensation can occur only in case when the string coupling constant vanishes at far future. We mean that in order to describe the tachyon condensation in the linear background using the D-brane effective action we should include terms that are proportional to the derivation of the dilaton and hence vanish when it is constant. There is also possibility that in order to correctly describe D-brane in the linear dilaton background we should include the coupling to the closed string tachyon into the D-brane effective action in order to restore well known "Liouville wall". In any case, we mean that the effective action description of the tachyon condensation is very interesting and reach subject in the string theory and there are many open problems that deserve further study.

Acknowledgments

This work was supported by the Czech Ministry of Education under Contract No. 14310006.

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