Published by Institute of Physics Publishing for SISSA/ISAS
Received: *May 26, 2002*
Accepted: *July 8, 2002*

Tachyon matter in boundary string field theory

Shigeki Sugimoto

CIT/USC Center for Theoretical Physics, University of Southern California, Los Angeles CA90089-2535, USA
E-mail: sugimoto@citusc.usc.edu

Seiji Terashima

Institute for Theoretical Physics, University of Amsterdam Valckenierstraat 65, 1018 XE, Amsterdam, The Netherlands
E-mail: sterashi@science.uva.nl

Abstract: We analyse the classical decay process of unstable D-branes in superstring theory using the boundary string field theory (BSFT) action. We show that the solutions of the equations of motion for the tachyon field asymptotically approach to $T = x^0$ and the pressure rapidly falls off at late time producing the tachyon matter irrespective of the initial condition. We also consider the cosmological evolution driven by the rolling tachyon using the BSFT action as an effective action.

Keywords: Superstrings and Heterotic Strings, D-branes, Tachyon Condensation, String Field Theory.

Dedicated to the memory of Sung-Kil Yang

JHEP07(2002)025

Contents

1. Introduction

Recently, classical time dependent solutions in string theory describing the decay process of an unstable D-brane was constructed [1, 2]. The decay of an unstable D-brane is caused by the tachyon field on the brane which is rolling down toward the minimum of the potential. In particular, it was shown in [2] that the rolling of tachyon makes the unstable D-brane toward the tachyon matter which is pressureless gas with nonzero energy density. These solutions are described by boundary states of the unstable D-brane including boundary perturbation associated with the rolling tachyon. In [3, 2], it was also shown that the effective action proposed by [4, 5, 6] with a specific tachyon potential reproduces the following two properties of the tachyon matter: 1) absence of plane wave solutions, and 2) exponential fall off of the pressure. However, since this action with the potential has not been derived from any off-shell string theory, the validity of the analysis based on this action is not clear.

On the other hand, the action of boundary string field theory (BSFT) for bosonic string theory [7] successfully describes some dynamics of the tachyon [8, 9]. In the superstring case, the BSFT actions were obtained for non-BPS D-branes [10, 11, 12] and D-brane-anti D-brane pairs [13, 14]. These actions exactly describe lower dimensional D-branes as solitons and are expected to satisfy the first property above because of their forms of tachyon potentials. Moreover, we know the coupling of massless closed string modes, including the RR-fields [13, 14], to the fields in the unstable D-brane in BSFT. Therefore it is both reasonable and interesting to consider the rolling of the tachyon in BSFT.

In this paper, we analyse the classical decay process of the unstable D-brane using the BSFT action. More precisely, we will use the usual BSFT action which is obtained by neglecting $\partial\partial T$ and higher derivatives. This action is exact as long as we use the linear tachyon profile $T = v + \sum u_\mu x^\mu$.[1]

[1] In this paper, we only consider the superstring.

At first sight, one might think that the rolling tachyon will hit the singularity within finite time, since the geodesic distance between the points $T = 0$ and $T = \infty$ in the space of tachyon field T is finite [9]. However, as we will show in the following section, the time dependent solutions of the action approach $T \sim \pm x^0$ asymptotically and keep rolling forever. The solution with the asymptotic behavior such that $T \sim x^0$ as $x^0 \to \pm\infty$ can be thought of as the space-like brane considered in [15].

We will also show that the pressure of the system will rapidly converge to zero while the energy density is conserved. Hence the system will become the tachyon matter which is consistent with the Sen's result.

Unfortunately, since our solution is slightly away from the linear profile, where the BSFT action is reliable, some of our results may receive corrections. We will discuss this issue in section 4.

One of the interesting subject for the rolling tachyon of unstable D-brane systems is the relevance in cosmology [16]–[23]. We will also consider the system coupled with gravity, and examine cosmological evolution using the BSFT action.

The rest of the paper is organized as follows. In section 2, we analyse the BSFT action for a non-BPS D-brane, and obtain the asymptotic solution of the rolling tachyon. We show that the system will become the tachyon matter in the large time limit. In section 3, we couple the system to gravity and examine the cosmological evolution. Section 4 is devoted to conclusion and discussion.

2. Tachyon matter in BSFT

In this paper we consider the non-BPS Dp-brane in type II string theory. The effective theory of non-BPS Dp-brane is described by the BSFT action [10]

$$S = -\tilde{T}_p \int d^{p+1}x\, e^{-\frac{T^2}{4}} \mathcal{F}\left(\frac{\alpha'}{2}\eta_{\mu\nu}\partial_\mu T \partial_\nu T\right), \tag{2.1}$$

where

$$\mathcal{F}(z) = z\frac{4^z}{2}\frac{\Gamma(z)^2}{\Gamma(2z)} = \frac{\sqrt{\pi}\Gamma(z+1)}{\Gamma(z+1/2)} \tag{2.2}$$

and $\tilde{T}_p$ is the tension of the non-BPS Dp-brane. Here we only consider the tachyon field and set the other fields to zero for simplicity. This action is considered to be exact if we set $T = v + \sum u_\mu x^\mu$, where v and u_μ are constants. Using the expansion

$$\mathcal{F}(z) = 1 + 2\log 2\, z + \mathcal{O}(z^2)\,, \tag{2.3}$$

we can read the potential and kinetic term for the tachyon

$$S = -\tilde{T}_p \int d^{p+1}x\, e^{-\frac{T^2}{4}} \left(1 + \log 2\, \alpha' \partial_\mu T \partial^\mu T + \mathcal{O}\left((\partial_\mu T \partial^\mu T)^2\right)\right). \tag{2.4}$$

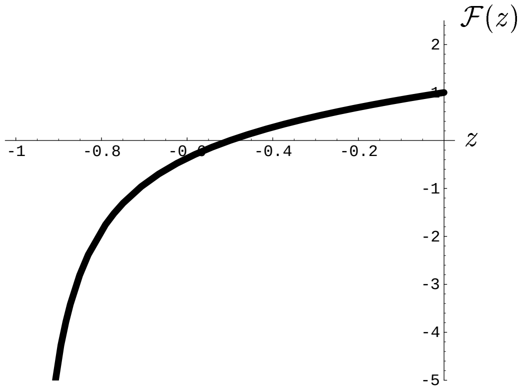

Figure 1: The behavior of the function $\mathcal{F}(z)$ defined in (2.2).

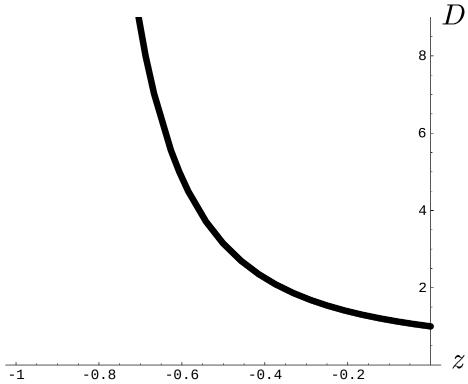

Figure 2: The behavior of the function $D(z)$ defined in (2.7).

Next, we compute the hamiltonian as in [3]. In this paper, we focus on the time dependence of the tachyon field, and mainly assume $\partial_i T = 0$ for $i = 1, \ldots, p$. Then the momentum conjugate to T is

$$\Pi = \frac{\delta S}{\delta \dot{T}} = \tilde{T}_p \, e^{-\frac{T^2}{4}} \alpha' \dot{T} \mathcal{F}'(z) \,, \tag{2.5}$$

where $\dot{T}$ stands for time derivative of T and $z = -\frac{\alpha'}{2}\dot{T}^2$. The hamiltonian density is

$$\mathcal{H} = T_{00} = \tilde{T}_p \, e^{-\frac{T^2}{4}} D(z) \,, \tag{2.6}$$

where

$$D(z) = \mathcal{F}(z) - 2z\mathcal{F}'(z) = -\mathcal{F}(z) \left(1 + 2\log 4\, z + 4z(\psi(z) - \psi(2z))\right) . \tag{2.7}$$

where $\psi(z)$ is the poly-gamma function defined as

$$\psi(z) \equiv \frac{d}{dz} \log \Gamma(z) = \frac{\Gamma'(z)}{\Gamma(z)} \,. \tag{2.8}$$

The behavior of the functions $D(z)$ and $\mathcal{F}(z)$ for $-1 < z \leq 0$ is depicted in figure 1 and figure 2.

We would like to consider a solution of the equations of motion which represent the tachyon rolling down to the bottom of the potential. So, we require $T^2 \to \infty$ at $x^0 \sim \infty$. Then, (2.6) implies that $D(z)$ should become infinity in the limit $x^0 \to \infty$, since the hamiltonian $H = \int dx^p \mathcal{H}$ is conserved. Therefore, it is important to examine the singularity of $D(z)$ to know the asymptotic behavior of the solution.

Now, we summarize some properties of $\Gamma(z)$. It is holomorphic except $z = -n$ with $n = 0, 1, \ldots$, and has a pole $\Gamma(z) \sim \frac{(-1)^n}{n!} \frac{1}{z+n}$ near $z = -n$. And $1/\Gamma(z)$ is holomorphic in $|z| < \infty$. The poly-gamma function $\psi(z)$ has singularities $\psi(z) \sim \frac{-1}{z+n}$ at $z = -n$ with $n = 0, 1, \ldots$ Using these properties, it is easy to see that $\mathcal{F}(z)$ and $D(z)$ behaves as

$$\mathcal{F}(z) \sim -n4^{-n} \frac{(2n)!}{(n!)^2} \frac{1}{z+n}\,, \tag{2.9}$$

$$D(z) \sim \frac{2n^2}{4^n} \frac{(2n)!}{(n!)^2} \frac{1}{(z+n)^2}\,, \tag{2.10}$$

near $z = -n$ where $n = 1, 2, \ldots$[2]

The fact that $D(z)$ has singularities for finite z is crucial for our consideration. Indeed, if $D(z)$ had no singularities except $z = \infty$, the tachyon might become infinite within finite time. Actually, we can show that it does occur for the effective action of the Minahan-Zwiebach model [24] which has $\mathcal{F}(z) = 1 + 2\log 2\, z$, i.e.

$$S = -\tilde{T}_p \int d^{p+1}x e^{-\frac{T^2}{4}} \left(1 + \log 2\, \alpha' \partial_\mu T \partial^\mu T\right), \tag{2.11}$$

which is obtained by dropping $\mathcal{O}((\partial_\mu T \partial^\mu T)^2)$ terms in (2.4). In this case, $H = \tilde{T}_p\, e^{-\frac{T^2}{4}}(1 + \alpha' \log 2\, \dot{T}^2)$, which means

$$\dot{T} \sim \sqrt{\frac{H}{\tilde{T}_p} e^{\frac{T^2}{4}} - 1}\,.$$

Then we can see that

$$t = \int^T dT' \left(\frac{H}{\tilde{T}_p} e^{\frac{T'^2}{4}} - 1\right)^{-\frac{1}{2}} \sim \int^T dT' \sqrt{\frac{\tilde{T}_p}{H}} e^{-\frac{T'^2}{8}}$$

and then t is finite at $T \to \infty$.

Let us consider the behavior of $D(z)$ near $z = -1$, which is the nearest singularity from the origin $z = 0$. From (2.10), we know that the function $D(z)$ behaves as

$$D(z) \sim \frac{1}{(z+1)^2}\,, \tag{2.12}$$

near $z = -1$. As explained above, if we set the initial condition for z to be in $-1 < z \leq 0$, we expect the asymptotic behavior of the solution is $T \sim \pm x^0$ in the limit $x^0 \to \infty$ and $-\infty$ (we set $\alpha' = 2$ for notational simplicity).

[2]Note that $z = 0$ is a regular point for $\mathcal{F}(z)$ and $D(z)$, as we have already seen in (2.3).

Then, suppose that the asymptotic form of the solution at $x^0 \sim \infty$ is of the form

$$T = a + x^0 + \epsilon(x^0)\,, \tag{2.13}$$

where $\epsilon(x^0)$ is considered to be a small perturbation. The energy conservation condition implies

$$\dot{\epsilon}(x^0) \propto e^{-\frac{(x^0)^2}{8}}\,, \tag{2.14}$$

where $\dot{\epsilon}$ denotes the time derivative of ϵ. Then, the asymptotic behavior of the pressure can be computed as

$$\begin{aligned} P = \mathcal{L} &= -\tilde{T}_p\, e^{-\frac{T^2}{4}} \mathcal{F}(z) && (2.15)\\ &\propto e^{-\frac{(x^0)^2}{8}}\,. && (2.16) \end{aligned}$$

Therefore, this analysis also suggest that the system behaves as a pressureless gas for large time, which is consistent with the result in [2]. So, we conclude that the asymptotic solution (2.13) represents the tachyon matter in BSFT.

Note, however, that there is a subtle difference between the two analyses. The pressure near the end of the rolling given in [2] using the boundary state is given by

$$P \sim -e^{-\alpha x^0} \tag{2.17}$$

which can also be reproduced by using the effective action of [4, 5, 6] if we take a specific form of the tachyon potential [3]. The sign of the pressure near the end of the evolution in our model is also different from Sen's one. Our analysis suggests that the pressure approaches zero from the positive side, while it is negative in [2]. There are several possible reasons for the discrepancy. First, the boundary state of [2] is different from the solution considered here. Then, the asymptotic form of pressure might be depend on the specific forms of the solutions. Second, the massive modes ignored in the analysis might change the asymptotic form since the difference between the solution and the linear profile could be affected by them. There is another possibility that the higher derivative term could change the asymptotic form.

In the above consideration, we only considered z which satisfies $-1 < z \leq 0$. We can also consider an asymptotic solution such that z approaches -1 from the $z < -1$ side.[3] This solution has a peculiar property. Since the function $D(z)$ increases when z approaches -1 from the $z < -1$ side, the tachyon slows down while it rolls down the potential. The situation is the same for the other singularities $z = -n$ $(n = 1, 2, \ldots)$ of the function $D(z)$, and there are asymptotic solutions approaching $z = -n$. In any cases the pressure converges to zero, and the system end up with the tachyon matter at late time.

[3] We thank J. Minahan for pointing out an error in the argument about this solution in the first version of the paper.

In principle, we can construct a full solution connecting its asymptotic behavior $T \sim \pm x^0$. There are basically two types of solutions distinguished by the sign of the asymptotic values of T, namely, time-like kink solutions, which approach $T \to x^0$ (or $T \to -x^0$) as $x^0 \to \pm\infty$. and bounce solutions $T \to |x^0|$ (or $T \to -|x^0|$) as $x^0 \to \pm\infty$. This can be seen from the equation of motion,

$$\frac{1}{2} T D(z) + 2\ddot{T} D'(z) = 0\,. \tag{2.18}$$

Note that the left hand side is proportional to $\dot{\mathcal{H}}\dot{T}^{-1}$, and hence it is equivalent to the energy conservation condition as long as $\dot{T} \neq 0$. Since we know $D(z) > 0$ and $D'(z) < 0$ from figure 2, (2.18) implies that T is accelerated toward the bottom of the the potential. Thus, once the tachyon starts rolling down the potential, it will never stop. Then, suppose that we set the initial condition, such that the tachyon rolls up the potential. Since $D(z) \geq 1$ and the equality holds only for $z = 0$, the energy conservation condition implies that the tachyon cannot stop if the energy density is bigger than the tension $\tilde{T}_p$ and get over the potential barrier, while it will stop at the point where $\tilde{T}_p\, e^{-T^2/4}$ is equal to the energy and turn back if the energy density is smaller than the tension $\tilde{T}_p$.

Note that both of these two types of solutions are localized in the time direction. The time-like kink solutions has "charge",[4] which is calculated from the Chern-Simons term for the non-BPS D-brane [13, 14], $S_{CS} = \tilde{T}_p \int \mathrm{Str}\, e^{2\pi\alpha' \mathcal{F}} \wedge C$, where $\mathcal{F}$ is the superconnection. Then, we can identify this type of solutions as the space-like branes considered in [15].

Note that this time-like kink solution cannot be obtained by simple Wick rotation of usual kink solution for the BSFT action. The kink solution is of the form $T = ux$ where u is a parameter and we have to take the limit $u \to \infty$ to minimize the action. The Wick rotation trick $u \to iu$ and $x \to ix^0$ implies a configuration with $z \sim -u^2 \to -\infty$. However, there is an upper bound for the speed of the rolling of the tachyon in the time-like kink solutions, which is not compatible with this limit.

3. Cosmological evolution using the BSFT action

Here, we sketch the cosmological evolution by the BSFT action (2.1) following [16]. Although it is difficult to make a precise analysis in the string field theory point of view, since the higher derivative terms are truncated in the action, it is still interesting to see the qualitative nature of the model and compare it with other models for the cosmological evolution driven by the rolling tachyon [16]. (See also [17]–[23].)

We consider the BSFT action (2.1) in 4 dimension, turning on the minimal coupling to gravity, with the usual Einstein-Hilbert action. We assume that the tachyon only depends on time and the metric is the Robertson-Walker metric

$$ds^2 = -dt^2 + a(t)\left(\frac{dr^2}{1-Kr^2} + r^2 d\Omega_2^2\right). \tag{3.1}$$

[4] This "charge" is not the usual conserved charge. It is defined as the integral of the RR-field over a large sphere surrounding the finite time region of the non-BPS D-brane in the ten dimensional space-time [15].

JHEP07(2002)025

The equations of motion are

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}\,, \tag{3.2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)\,, \tag{3.3}$$

where ρ and P are the energy density and pressure given in (2.6) and (2.15), respectively.

$$\rho = \tilde{T}_p\, e^{-\frac{T^2}{4}} D(z)\,, \tag{3.4}$$

$$P = -\tilde{T}_p e^{-\frac{T^2}{4}} \mathcal{F}(z)\,, \tag{3.5}$$

where $z = -\dot{T}^2$.

From (3.2), we can immediately see that $\dot{a}$ is always positive for $K \leq 0$ cases, describing the expanding universe, since the function $D(z)$ is positive the weak energy condition $\rho > 0$ is satisfied.

The equations of motion also imply

$$\dot{\rho} = -3\frac{\dot{a}}{a}(\rho + P)\,, \tag{3.6}$$

which is equivalent to the conservation equation for the energy momentum tensor. Inserting (3.4) and (3.5), this equation can be rewritten as

$$\frac{1}{2}TD(z) + 2\ddot{T}D'(z) = 3\frac{\dot{a}}{a}(D(z) - \mathcal{F}(z))\dot{T}^{-1}\,. \tag{3.7}$$

Suppose that we set the initial condition $T(\bar{t}) > 0$ and $\dot{T}(\bar{t}) = 0$ at $x^0 = \bar{t}$. We can easily see that the right hand side converges to zero in the limit $\dot{T} \to 0$. Then, $D(0) = 1$ and $D'(0) = -F'(0) \sim -2\log 2 < 0$ imply $\ddot{T} > 0$ which shows that the tachyon starts rolling down the potential. This argument also implies that the tachyon will not stop rolling once it starts, as we observed in the previous section for the model without gravity.

The ratio of the pressure and the energy density is given by

$$\omega = \frac{P}{\rho} = \frac{1}{1 + 2\log 4\, z + 4z(\psi(z) - \psi(2z))}\,, \tag{3.8}$$

which has maximum near $z \sim -0.7$ with $\omega(-0.7) \sim 0.1$ and $\omega(0) = -1$, $\omega(-1) = 0$ as depicted in figure 3.

Hence, the dominant energy condition $|\omega| \leq 1$ is satisfied. However the strong energy condition

$$\rho + 3P \geq 0\,, \tag{3.9}$$

does not hold for $|z| \leq 0.278\ldots$ As we can see from the equation (3.3), this implies the acceleration of the scale factor in the initial stage with small $|z|$.

In summary, the qualitative behavior of the model is roughly the same as that given in [16]. It would be interesting to examine further to see if it can be considered as a realistic model of inflation or dark matter. (See [17]–[23])

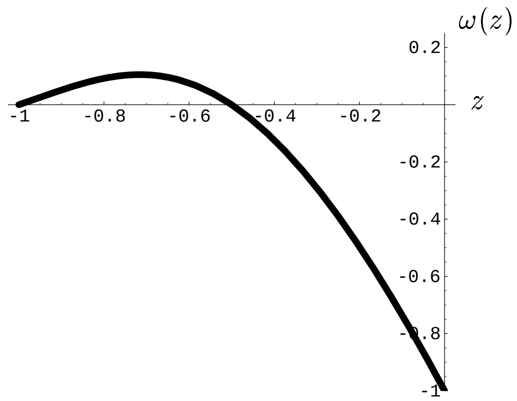

Figure 3: The behavior of the function $\omega(z)$ defined in (3.8).

4. Conclusion and discussion

In this paper, we have analysed the classical decay process of unstable D-branes in superstring theory using the BSFT action. We have shown that the solutions of the equations of motion for the tachyon field asymptotically approach to $T = \pm x^0$ producing the tachyon matter. We also considered the cosmological evolution driven by the rolling tachyon using the BSFT action.

We used the BSFT action obtained by dropping terms which include second or higher derivatives of the tachyon field. However, in the time dependent solution of the equations of motion for this effective action, the second or higher derivatives of the tachyon field is not precisely zero. Therefore, there could be some corrections for the analysis if we include the terms we dropped.

Let us make some comments about the possible corrections. First, recall that the BSFT action that we used can be trusted for the tachyon of the form $T = a + ux^0$. We showed that the tachyon approaches the linear profile $T \sim \pm x^0$ in the asymptotic region. This comes from the fact that the function $D(z)$ has a pole at $z = -1$. The function $D(z)$ could receive some corrections. However, we expect that even if we include these corrections, it still has a singularity for the tachyon configuration $T = a \pm x^0$. This is because the action (2.1) is exact for the linear profile and we know that the action has a singularity for this tachyon configuration. It is quite natural to expect that the singularity coincides for the action and the energy density. Therefore, we strongly believe that there are solutions which approach $T \sim \pm x^0$ in the limit $|x^0| \to \infty$ even if we include the corrections.

On the other hand, we cannot exclude the possibility that there are solutions which does not approach $T \sim \pm x^0$ when we include the higher derivative corrections.

The precise form of the solution for the tachyon field seems to be difficult to obtain in this approach. In addition to the complexity of the action, there are some more fundamental difficulties. If we include the higher derivative corrections, the massive modes can no longer be ignored [9]. The BSFT action including these modes has not been obtained because it corresponds to the non-renormalizable terms in the boundary interaction. Therefore, our solution cannot be trusted away from the asymptotic region. However, most of our qualitative arguments given in section 2 and section 3 only require the broad behavior of the functions $\mathcal{F}(z)$ and $D(z)$ and so we hope that these analyses successfully catch the essential features of the theory.

We have observed that the asymptotic behavior of the pressure is slightly different from that obtained in [2]. These ambiguities might be the origin of this discrepancy. In order to clarify these issues, it would be important to study the relations between the BSFT approach and the boundary state approach given in [1, 2].

In this paper we only turned on the tachyon field. The action including both the gauge field strength F and the tachyon for a non-BPS D-brane was obtained in a closed form [25] as

$$S = -\sqrt{2}T_9 \int d^{10}x e^{-\frac{1}{4}T^2} \sqrt{-\det(\eta_{\mu\nu} + F_{\mu\nu})}\mathcal{F}\left(\frac{1}{4\pi}\mathcal{G}^{\mu\nu}\partial_\mu T \partial_\nu T\right), \tag{4.1}$$

where

$$\mathcal{G}^{\mu\nu} \equiv \left(\frac{1}{1+F}\right)^{(\mu\nu)} . \tag{4.2}$$

We can also obtain the action including scalar fields, representing the transverse fluctuation of the D-brane, by T-dualizing the above action. It would be interesting to include the effect of the gauge field and scalar fields in the consideration of the rolling tachyon. See [26] for the related analysis. In particular, the time evolution of the system with the electric flux [27] is interesting to study.

As argued in [28, 29], all the Dp-branes can be constructed from infinitely many unstable D-particles, i.e. non-BPS D0-branes in type IIB theory or D0-brane - anti D0-brane pairs in type IIA theory. Therefore, it is possible to analyse the decay process of the non-BPS Dp-brane in terms of the unstable D-particles. Then, the tachyon matter produced by the decay of the non-BPS Dp-brane can be thought of as the pressureless gas consists of the decay products of the unstable D-particles. It might be interesting to consider the tachyon matter in this point of view.

Note added. After this work was completed, a related paper [30] appeared.

Acknowledgments

We would like to dedicate this article to the memory of Sung-Kil Yang from whom we learned a lot of things. We will not forget his warm encouragements.

S.T. would like to thank J. de Boer for helpful discussions and T. Takayanagi and J. Minahan for useful comments and discussions. S.S. is grateful to T. Okuda and K. Okuyama for useful discussions.

References

[1] A. Sen, *Rolling tachyon*, *J. High Energy Phys.* **04** (2002) 048 [hep-th/0203211].

[2] A. Sen, *Tachyon matter*, hep-th/0203265.

[3] A. Sen, *Field theory of tachyon matter*, hep-th/0204143.

[4] M.R. Garousi, *Tachyon couplings on non-BPS D-branes and Dirac-Born-Infeld action*, *Nucl. Phys.* **B 584** (2000) 284 [hep-th/0003122].

[5] E.A. Bergshoeff, M. de Roo, T.C. de Wit, E. Eyras and S. Panda, *T-duality and actions for non-BPS D-branes*, *J. High Energy Phys.* **05** (2000) 009 [hep-th/0003221].

[6] J. Kluson, *Proposal for non-BPS D-brane action*, *Phys. Rev.* **D 62** (2000) 126003 [hep-th/0004106].

[7] E. Witten, *On background independent open string field theory*, *Phys. Rev.* **D 46** (1992) 5467 [hep-th/9208027].

[8] A.A. Gerasimov and S.L. Shatashvili, *On exact tachyon potential in open string field theory*, *J. High Energy Phys.* **10** (2000) 034 [hep-th/0009103].

[9] D. Kutasov, M. Marino and G.W. Moore, *Some exact results on tachyon condensation in string field theory*, *J. High Energy Phys.* **10** (2000) 045 [hep-th/0009148].

[10] D. Kutasov, M. Marino and G.W. Moore, *Remarks on tachyon condensation in superstring field theory*, hep-th/0010108.

[11] M. Marino, *On the bv formulation of boundary superstring field theory*, *J. High Energy Phys.* **06** (2001) 059 [hep-th/0103089].

[12] V. Niarchos and N. Prezas, *Boundary superstring field theory*, *Nucl. Phys.* **B 619** (2001) 51 [hep-th/0103102].

[13] P. Kraus and F. Larsen, *Boundary string field theory of the $D\bar{D}$ system*, *Phys. Rev.* **D 63** (2001) 106004 [hep-th/0012198].

[14] T. Takayanagi, S. Terashima and T. Uesugi, *Brane-antibrane action from boundary string field theory*, *J. High Energy Phys.* **03** (2001) 019 [hep-th/0012210].

[15] M. Gutperle and A. Strominger, *Spacelike branes*, *J. High Energy Phys.* **04** (2002) 018 [hep-th/0202210].

[16] G.W. Gibbons, *Cosmological evolution of the rolling tachyon*, *Phys. Lett.* **B 537** (2002) 1 [hep-th/0204008].

[17] S. Mukohyama, *Brane cosmology driven by the rolling tachyon*, *Phys. Rev.* **D 66** (2002) 024009 [hep-th/0204084].

[18] M. Fairbairn and M.H.G. Tytgat, *Inflation from a tachyon fluid?*, hep-th/0204070.

[19] A. FEinstein, *Power-law inflation from the rolling tachyon*, hep-th/0204140.

[20] A. Frolov, L. Kofman and A.A. Starobinsky, *Prospects and problems of tachyon matter cosmology*, hep-th/0204187.

[21] T. Padmanabhan, *Accelerated expansion of the universe driven by tachyonic matter*, *Phys. Rev.* **D 66** (2002) 021301 [hep-th/0204150].

[22] D. Choudhury, D. Ghoshal, D.P. Jatkar and S. Panda, *On the cosmological relevance of the tachyon*, hep-th/0204204.

[23] G. Shiu and I. Wasserman, *Cosmological constraints on tachyon matter*, hep-th/0205003.

JHEP07(2002)025

[24] J.A. Minahan and B. Zwiebach, *Effective tachyon dynamics in superstring theory*, *J. High Energy Phys.* **03** (2001) 038 [hep-th/0009246].

[25] S. Terashima and T. Uesugi, *On the supersymmetry of non-BPS D-brane*, *J. High Energy Phys.* **05** (2001) 054 [hep-th/0104176].

[26] K. Hashimoto, *Dynamical decay of brane-antibrane and dielectric brane*, hep-th/0204203.

[27] G.W. Gibbons, K. Hori and P. Yi, *String fluid from unstable D-branes*, *Nucl. Phys.* **B 596** (2001) 136 [hep-th/0009061].

[28] S. Terashima, *A construction of commutative D-branes from lower dimensional non-BPS D-branes*, *J. High Energy Phys.* **05** (2001) 059 [hep-th/0101087].

[29] T. Asakawa, S. Sugimoto and S. Terashima, *D-branes, matrix theory and K-homology*, *J. High Energy Phys.* **03** (2002) 034 [hep-th/0108085].

[30] J.A. Minahan, *Rolling the tachyon in super BSFT*, *J. High Energy Phys.* **07** (2002) 030 [hep-th/0205098].