D3-branes at angle in a linear dilaton pp-wave background

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Abstract

We present a class of low energy type IIB supergravity solutions of two D3-branes rotated by an angle $\alpha \in SU(2)$ in a linear dilaton pp-wave background. The D-branes bound state configurations is found to preserve 1/16 of the total type IIB supersymmetries. We also present a class of D1-D5 solution by applying T-duality on $D3 \perp D3$ configuration.
1 Introduction

The study of string theory in time dependent background is one of the most interesting and challenging subjects till date. Until now, it has not been fully explored. Due to their applications in solving puzzles of early universe cosmology, physicists have taken much interest in finding time dependent supersymmetric solutions of supergravities in ten and eleven dimensional space time [1, 2, 3, 4, 5]. In this connection, it has been proposed that a null linear dilaton background could play a toy model in solving the puzzles of early universe cosmology [6]. This background preserves 1/2 of the space-time supersymmetry, thereby, giving some hope of studying string theory in supersymmetric time dependent background. It has been shown that the space-like singularity can be resolved by proposing a kind of matrix string theory. At early time, the theory is strongly coupled, and hence the matrix degrees of freedom describe the correct physics. At late times, however, the theory can be seen as a free theory. The AdS/CFT duality has also been examined in time dependent background with linear dilaton. It has been shown that the dual field theory can be realized with a time dependent Yang-Mills coupling constant [8].

The study of D-branes is very useful in various developments of string theory. As it explains nonperturbative phenomena, it is very important to explore them further. In this context, supersymmetric D-brane solutions has been discussed in light-like linear dilaton

†see [7] for discussions on various issues in null dilaton background
background in literature \cite{8, 9, 10, 11, 12, 13, 14}. Motivated by the recent development in time dependent supersymmetric background and its necessity to explain cosmology, we present a class of time dependent linear dilaton pp-wave background solutions with various flux for two D3-branes rotated by an angle $\alpha \in SU(2)$ and its supersymmetric variation. In the present case, the harmonic function depends both on tranverse coordinates and on the light cone time like coordinate ($x^+$). Supergravity solutions for D-branes at angle has been constructed in various backgrounds earlier \cite{12, 13, 14, 15, 16, 17, 18, 19}.

The outline of this paper is as follows. In section-2 we present the classical supergravity solutions for various configurations of D3-branes. First we construct the type IIB supergravity solutions for a single rotated D3-brane in a time dependent linear dilaton pp-wave background. Then we present solutions for two orthogonally intersecting D3-branes and applying T-dualities, we find solutions for intersecting D1-D5 branes orthogonal to each other. Then we generalize it for two D3-branes rotated by an arbitrary angle $\alpha \in SU(2)$ to each other. In section-3, we study the supersymmetric properties of the D3-branes at angle by solving the dilatino and gravitino variations explicitly. We find, it preserves 1/16 of the total type IIB supersymmetries. In section-4, we conclude with some remarks.

## 2 D-brane Solutions

In this section we present classical solutions of D3-branes oriented along each other in the following linear dilaton pp-wave background supplemented by the Neveu-Schwarz - Neveu-Schwarz(NS-NS) flux:

\[
\begin{align*}
    ds^2 &= -2dx^+dx^- - \mu^2(x^+) \sum_{i=1}^{4} x_i^2 (dx^+)^2 + \sum_{a=5}^{8} (dy^a)^2 + \sum_{i=1}^{4} (dx^i)^2, \\
    e^{2\phi} &= e^{-2f(x^+)}; \quad H_{+12} = H_{+34} = 2\mu(x^+).
\end{align*}
\] (1)

### 2.1 Single rotated D3-brane

We would now like to write down the classical solutions for a single D3-brane rotated by a certain angle $\alpha \in SU(2)$ in the above linear dilaton pp wave background. The classical
solutions for the D3-brane lying along $x^+, x^-, x^6 & x^8$ directions in given by the following form of metric ($g_{\mu\nu}$), dilaton ($\phi$), R-R fields ($F_{\mu\nu\rho\sigma}$) and the NS-NS field ($H_{\mu\nu\rho}$):

$$ds^2 = \frac{1}{\sqrt{1 + \tilde{X}_1}} \left( 2dx^+dx^- - \mu^2(x^+) \sum_{i=1}^{4} x_i^2 (dx^+_i)^2 \right)$$

$$+ \left[ 1 + \tilde{X}_1 \cos^2 \alpha \right] ((dx^5)^2 + (dx^7)^2) + \left[ 1 + \tilde{X}_1 \sin^2 \alpha \right] ((dx^6)^2 + (dx^8)^2)$$

$$+ 2\tilde{X}_1 \cos \alpha \sin \alpha (dx^7dx^8 - dx^5dx^6) + \sqrt{1 + \tilde{X}_1} \sum_{i=1}^{4} (dx_i)^2,$$

$$H_{+12} = H_{+34} = 2\mu(x^+),$$

$$F^{(5)}_{++68} = -e^{2f} \frac{\partial_i \tilde{X}_1}{(1 + \tilde{X}_1)^2} \cos^2 \alpha,$$

$$F^{(5)}_{++57} = e^{2f} \frac{\partial_i \tilde{X}_1}{(1 + \tilde{X}_1)^2} \sin^2 \alpha,$$

$$F^{(5)}_{++-67} = -e^{2f} \frac{\partial_i \tilde{X}_1}{(1 + \tilde{X}_1)^2} \cos \alpha \sin \alpha,$$

$$e^{2\Phi} = e^{-2f(x^+)}, \quad \tilde{X}_1(r) = \frac{1}{2} e^{-f(x^+)} \left( \frac{\ell}{|\vec{r} - \vec{r}_1|} \right)^2,$$

where $(1 + \tilde{X}_1)$ is the harmonic function in the transverse space of the D3-brane. Here the metric functions depend on both transverse space coordinates and a light-cone coordinate $x^+$. In order to explain the procedure for getting the above solutions from a D3-brane in a linear dilaton background, we start with the single unrotated D3-brane lying along $x^+, x^-, x^6$ and $x^8$ directions. By applying a rotation between $(x^5 - x^6)$ and $(x^7 - x^8)$ planes, with the rotation angle $(\alpha, \beta) = (0, \alpha)$ as described by [16], we get the configuration where the D3-brane is now oriented by an angle $\alpha \in SU(2)$ with respect to the original plane. For $\alpha = 0$, we get back the D3-brane solutions as given in [8] and for $f(x^+) = 0$, we get a tilted D3-brane solutions in pp wave background. The above solutions [2] gives the generalization of the time independent tilted D-brane solutions to that of a time dependent one, with a linear dilaton pp-wave background. We have verified that the solutions [2] solves all the type IIB field equations.
2.2 Orthogonal Intersection of Two D3-branes

Now we present the classical solutions of a system of two D3-branes lying relatively perpendicular to each other in a time dependent linear dilaton pp-wave background. The supergravity solutions of such system is given by

\[
ds^2 = (1 + \tilde{X}_1)^{-\frac{1}{2}}(1 + \tilde{X}_2)^{-\frac{1}{2}} \left[ 2 dx^+ dx^- - \mu^2(x^+) \sum_{i=1}^{4} x_i^2 (dx^i)^2 \right] + (1 + \tilde{X}_1)^{-\frac{1}{2}}(1 + \tilde{X}_2)^{-\frac{1}{2}} \left[ (dx^5)^2 + (dx^7)^2 \right] + (1 + \tilde{X}_1)^{-\frac{1}{2}}(1 + \tilde{X}_2)^{-\frac{1}{2}} \left[ (dx^6)^2 + (dx^8)^2 \right] + \sum_{i=1}^{4} (dx^i)^2,
\]

\[
H_{+12} = H_{+34} = 2\mu(x^+),
\]

\[
F_{+68i}^{(5)} = e^{2f} \frac{\partial_i \tilde{X}_2}{(1 + \tilde{X}_2)^2},
\]

\[
F_{+57i}^{(5)} = -e^{2f} \frac{\partial_i \tilde{X}_1}{(1 + \tilde{X}_1)^2}, \quad e^{2\Phi} = e^{-2f(x^+)}, \quad \tilde{X}_{1,2}(r) = \frac{1}{2} e^{-f(x^+)} \left( \frac{\ell_{1,2}}{|\vec{r} - \vec{r}_{1,2}|} \right)^2.
\]

Here, the dilaton is linear in light cone time coordinate \( x^+ \). In this case, we start from two D3-branes parallel to each other and are lying along \( x^+, x^-, x^6 \) and \( x^8 \) directions. Now, applying SU(2) rotation to the branes at an angle \( \pi/2 \) along \( (x^5 - x^6) \) and \( (x^7 - x^8) \) directions as described earlier. Now, one of the branes will lie along \( x^+, x^-, x^5 \) and \( x^7 \) directions and the other will lie along \( x^+, x^-, x^6 \) and \( x^8 \). At the same time, the branes are delocalized along \( (x^6 - x^8) \) and \( (x^5 - x^7) \) planes respectively. We have checked that the solutions given equation (3) also solves all type IIB field equations.

It is interesting to get more intersecting D-brane solutions from the (3) by applying T-dualities along any of its longitudinal and transverse direction. For example, we can get orthogonal D1-D5 branes by applying T-dualities along \( x^6 \) and \( x^8 \) directions [20, 21]. The supergravity solutions for orthogonally intersecting D1-D5 branes in time dependent linear dilaton pp-wave background is given by:

\[
ds^2 = (1 + \tilde{X}_1)^{-\frac{1}{2}}(1 + \tilde{X}_2)^{-\frac{1}{2}} \left[ 2 dx^+ dx^- - \mu^2(x^+) \sum_{i=1}^{4} x_i^2 (dx^i)^2 \right]
\]
\[ + (1 + \tilde{X}_1)^{-\frac{1}{2}}(1 + \tilde{X}_2)^{\frac{1}{2}} \left[ (dx^5)^2 + (dx^6)^2 + (dx^7)^2 + (dx^8)^2 \right] \]

\[ + (1 + \tilde{X}_1)^{\frac{1}{2}}(1 + \tilde{X}_2)^{\frac{1}{2}} \sum_{i=1}^{4} (dx^i)^2, \]

\[ H_{+12} = H_{+34} = 2\mu(x^+), \]

\[ F^{(3)}_{+i} = e^{2f} \frac{\partial_i X_2}{(1 + X_2)^2}, \]

\[ F^{(7)}_{+5678i} = -e^{2f} \frac{\partial_i X_1}{(1 + X_1)^2}, \]

\[ e^{2\Phi} = e^{-2f(x^+)} \left\{ \frac{1 + \tilde{X}_2}{1 + X_1} \right\}. \]

(4)

In the equation (4), for \( \tilde{X}_1 = 0 \), we get solution for D1-brane lying along \( x^+ \) and \( x^- \) directions and for \( \tilde{X}_2 = 0 \), we get solutions for D5-brane lying along \( x^+, x^-, x^5, x^6, x^7 \) and \( x^8 \) directions.

2.3 Two D3-branes at angle

Now, we generalize the above solutions for two D3-branes rotating by an angle \( \alpha \in SU(2) \). It has been discussed in literature that SU(2) rotation of D-brane preserves certain supersymmetries [15]. Now, we present the low energy classical supergravity solutions of a system of two D3-branes oriented by an angle \( \alpha \in SU(2) \) with respect to each other. The supergravity solutions of such a system in linear null dilaton pp-wave background with NS-NS and R-R fluxes is given by:

\[ ds^2 = \frac{1}{\sqrt{1 + X}} \left( 2dx^+ dx^- - \mu^2(x^+) \sum_{i=1}^{4} x_i^2 (dx^+)^2 \right. \]

\[ + (1 + \tilde{X}_2)[(dx^5)^2 + (dx^7)^2] + (dx^6)^2 + (dx^8)^2 \]

\[ + \tilde{X}_1 \left[ (\cos \alpha dx^5 - \sin \alpha dx^6)^2 + (\cos \alpha dx^7 + \sin \alpha dx^8)^2 \right] \] \[ + \sqrt{1 + \tilde{X} \sum_{i=1}^{4} (dx^i)^2}, \]
\[ H_{+12} = H_{+34} = 2\mu(x^+), \]
\[ F^{(5)}_{+68i} = e^{2f}\partial_t \left\{ \tilde{X}_2 + \tilde{X}_1 \cos^2 \alpha + \tilde{X}_1 \tilde{X}_2 \sin^2 \alpha \right\}, \]
\[ F^{(5)}_{+58i} = -F^{(5)}_{+67i} = e^{2f}\partial_t \left\{ \frac{\tilde{X}_1 \cos \alpha \sin \alpha}{(1 + \tilde{X})} \right\}, \]
\[ F^{(5)}_{+57i} = -e^{2f}\partial_t \left\{ \frac{(\tilde{X}_1 + \tilde{X}_1 \tilde{X}_2) \sin^2 \alpha}{(1 + \tilde{X})} \right\}, \]
\[ e^{2\Phi} = e^{-2f(x^+)}. \] (5)

and \( \tilde{X} \) is given by
\[ \tilde{X} = \tilde{X}_1 + \tilde{X}_2 + \tilde{X}_1 \tilde{X}_2 \sin^2 \alpha. \] (6)

Here, \( \tilde{X}_{1,2} \) is same as defined in equation (3). To start with, two D3-branes parallel to each other and lying along \( x^+, x^-, x^6 \) and \( x^8 \) directions. Now, by applying rotation of an angle \( \alpha \in SU(2) \), like discussed in case of perpendicular case, one will get the solutions as given in equation (5). We have verified that the above solutions given in (5) solves all type IIB field equations. If we put \( \alpha = \pi/2 \), we will return to the equation (3) and for \( \tilde{X}_2 = 0 \) one will get back the equation (4). The solutions given in equation (5) reduces to that of [18] for \( f = 0 \). Hence, the solutions given by us is a more generalized one in a class of time dependent pp-wave background with a linear dilaton.

### 3 Supersymmetry Analysis

It has already been discussed in the literature [15] that a system of D-branes oriented at certain angle \( \alpha \in SU(N) \) subgroup of rotations, with respect to each other, preserve certain amount of unbroken supersymmetries. We would like to analyze the fate of the supersymmetry in a linear dilaton background through a particular example discussed in this paper by solving the type IIB supersymmetry variations explicitly. The supersymmetry variation of dilatino and gravitino fields of type IIB supergravity in ten dimension, in string frame, is given by [22, 23]:
\[ \delta \lambda_\pm = \frac{1}{2} (\Gamma^\mu \partial_\mu \Phi \mp \frac{1}{12} \Gamma^{\mu\rho\sigma} H_{\mu\rho\sigma}) \epsilon_\pm + \frac{1}{2} e^\Phi (\pm \Gamma^M F^{(1)}_M + \frac{1}{12} \Gamma^{\mu\rho\sigma} F^{(3)}_{\mu\rho\sigma}) \epsilon_{\mp}, \] (7)
\[ \delta \Psi^{\pm}_\mu = \left[ \partial_\mu + \frac{1}{4} (w_{\mu\hat{a}\hat{b}} \mp \frac{1}{2} H_{\mu\hat{a}\hat{b}}) \Gamma^{\hat{a}\hat{b}} \right] \epsilon_\pm \]
where we have used $\mu, \nu, \rho, \lambda$ to describe the ten dimensional space-time indices, and hat’s represent the corresponding tangent space indices. Solving the above two equations for the solutions describing the system of two D3-branes as given in equation (5), we get several conditions on the spinors. First the vanishing dilatino variation gives:

$$\Gamma^\pm \epsilon_\pm = 0,$$  \hspace{1cm} (9)

and

$$\left(1 - \Gamma^{1234}\right) \epsilon_\pm = 0.$$  \hspace{1cm} (10)

Gravitino variations gives the following conditions on the spinors:

$$\delta \psi^\pm = \partial_\mu \epsilon_\pm + \left[\frac{1}{8}(1 + \tilde{X})^{-1}\partial_\mu \tilde{X} + \frac{1}{8}(1 + \tilde{X})^{-\frac{1}{2}}\partial^-i \partial_\mu \tilde{X}\right] \epsilon_\pm$$

$$\mp \frac{1}{2} \frac{\mu}{\sqrt{1 + X}} (\Gamma^{i2} + \Gamma^{34}) \epsilon_\pm$$

$$\mp \frac{e^{f/2}}{8} \Gamma^{i+\delta i} \left[(1 + \tilde{X}_1 \sin^2 \alpha)^2 \partial_i \tilde{X}_2 + \cos^2 \alpha \partial_i \tilde{X}_1 \right] \Gamma^+ \epsilon_+$$

$$\mp \frac{e^{f/2}}{8} \Gamma^{i+\delta i} \left[\frac{1}{(1 + X)^{5/2}}(1 + \tilde{X}_1 \sin^2 \alpha)\right] (\tilde{X}_1^2 \cos^2 \alpha \sin^2 \alpha \partial_i \tilde{X}_2 + (1 + \tilde{X}_2)^2 \sin^2 \alpha \partial_i \tilde{X}_1)$$

$$- (\tilde{X}_1^2 \cos^2 \alpha \sin^2 \alpha \partial_i \tilde{X}_2 + (1 + \tilde{X}_2)^2 \sin^2 \alpha \partial_i \tilde{X}_1)$$

$$+ \frac{1}{(1 + X)^{5/2}}(2 \tilde{X}_1^2 \cos^2 \alpha \sin^2 \alpha \partial_i \tilde{X}_2 + 2 \tilde{X}_1^3 \cos^2 \alpha \sin^4 \alpha \partial_i \tilde{X}_1)$$

$$- 2 \tilde{X}_1(1 + \tilde{X}_2) \cos^2 \alpha \sin^2 \alpha \partial_i \tilde{X}_2 \right] \Gamma^- \epsilon_-$$

$$\mp \frac{e^{f/2}}{8} \left\{ \frac{\Gamma^{i+\delta i} - \Gamma^{i+\delta i}}{(1 + X)^2(1 + X_1 \sin^2 \alpha)} \right\} \left[-\tilde{X}_1 \cos \alpha \sin \alpha \partial_i \tilde{X}_2 \right] \epsilon_-$$
\[ + (1 + \tilde{X}_2) \sin \alpha \cos \alpha \partial_i \tilde{X}_1 - \tilde{X}_1^2 \sin^3 \alpha \cos \alpha \partial_i \tilde{X}_1(1 + \tilde{X}_1 \sin^2 \alpha) \]
\[ + \tilde{X}_1 \cos \alpha \sin \alpha (1 + \tilde{X}_1 \sin^2 \alpha)^2 \partial_i \tilde{X}_2 \]
\[ + \tilde{X}_2 \cos^3 \alpha \sin \alpha \partial_i \tilde{X}_1 \bigg] \Gamma_i^\epsilon \epsilon_\mp = 0. \tag{11} \]

\[ \delta \psi_\pm \equiv \partial_\epsilon \epsilon_\pm = 0, \quad \delta \psi_a^\pm \equiv \partial_a \epsilon_\pm = 0 \quad (a = 5, 6, 7, 8). \]
\[ \delta \psi_i^\pm \equiv \partial_i \epsilon_\pm + \frac{1}{8(1 + \tilde{X})} \partial_i \tilde{X} \epsilon_\pm = 0. \tag{12} \]

While writing down the \( \delta \psi_i^\pm \) variation, we have made use of the conditions (9), and (10). Now, the variation \( \delta \psi_+^\pm \) in equation (11) is further solved by imposing the following conditions, including (9) and (10).

\[ (\Gamma_i^\delta - \Gamma_i^\delta) \epsilon_\mp = 0, \quad (\Gamma_i^\delta + \Gamma_i^\delta) \epsilon_\mp = 0, \]
\[ (\Gamma_i^\delta - \Gamma_i^\delta) \epsilon_\pm = 0, \tag{13} \]

and the usual D3-brane supersymmetry conditions of flat space:
\[ \Gamma_\gamma^\delta \epsilon_\pm = \epsilon_\pm, \quad \Gamma_\gamma^\delta \epsilon_\mp = \epsilon_\pm. \tag{14} \]

After imposing all these conditions (9), (10), (13) and (14), the equation (11) and equation (12) reduce to the following form:
\[ \partial_\epsilon \epsilon_\pm + \frac{1}{8(1 + \tilde{X})} \partial_\epsilon \tilde{X} \epsilon_\pm = 0, \]
\[ \partial_i \epsilon_\pm + \frac{1}{8(1 + \tilde{X})} \partial_i \tilde{X} \epsilon_\pm = 0. \tag{15} \]

The above two equations are clearly solved by the following spinor,
\[ \epsilon_\pm = (1 + \tilde{X})^{-1/8} \epsilon_0, \tag{16} \]
where $\epsilon_0$ is a constant spinor. Let’s now count the total number of independent conditions, we have taken for solving the dilatino and gravitino variations. First imposing (9), the dilatino variation (7) is satisfied completely, thereby breaking $1/2$ supersymmetry. Further to satisfy all the gravitino variations, we have made use of the conditions (13) and (14), in addition to (10), thereby breaking $1/8$ of the remaining supersymmetry, as these are only three independent conditions. Hence, the system of two D3-branes rotated by an angle $\alpha \in SU(2)$ in a linear dilaton time dependent pp-wave background preserves $1/16$ of total type IIB spacetime supersymmetries.

4 Conclusions

In this paper we have constructed the classical solution of two D3-branes rotated by an angle $\alpha \in SU(2)$ with respect to each other in a linear dilaton time dependent pp-wave background. The supersymmetry of this solution has been checked by solving the dilatino and gravitino variations, and we found, it preserves $1/16$ supersymmetries of type IIB string theory. The open string construction for various branes and their bound states can be done by following [24, 25] and choosing the boundary conditions appropriately. We wish to come back to this issue in future.

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