On the M-theory Interpretation of Orientifold Planes

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Abstract

We obtain an M–theory interpretation of different IIA orientifold planes by compactifying them on a circle and use a chain of dualities to get a new IIA limit of these objects using this circle as the eleventh dimension. Using the combination of the two IIA description, we give an interpretation for all orientifold four-planes in M-theory, including a mechanism for freezing M5-branes at singularities.

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I. INTRODUCTION

In the past year, M-theory has emerged as useful method for understanding the non-perturbative dynamics of four dimensional field theories [1] (for a review and more references, see Ref. [2]). At low energy, higher loop effects of IIA string theory can be understood in terms of 11-dimensional supergravity. A configuration of NS5-branes, D4-branes, and D6-branes in IIA can intersect along a common world-volume to produce a variety of possible four dimensional gauge theories with SU(n) type gauge symmetries. A non-perturbative description of these theories’ vacua exists in terms of a single M-theory five-brane wrapping a holomorphic two-cycle in a background geometry determined by the D6-branes. The moduli space of this curve yields the exact moduli space of the four dimensional field theory under investigation. One of the natural extensions of this work was to introduce orientifold planes into the IIA picture to get orthogonal and symplectic groups (see Ref. [3]. This leads to the natural question: what do IIA orientifold planes become in the M-theory limit?

A complete list of possible orientifold O4-planes was recently given in the work of Hori [4], along with a natural M-theory interpretation for most of them. One type of symplectic O4 plane remained a puzzle, as it seemed to consist of M5-branes mysteriously “frozen” at a singularity in a manner reminiscent of Refs. [5,6]. In this paper, we will provide additional information for the interpretation of O4 planes in terms of M-theory by changing the direction along which we reduce M-theory to IIA string theory. This can be done by starting with a IIA background containing the O4 plane of interest compactified along one of the dimensions of its worldvolume. Performing a chain of T-S-T dualities along this dimension, we perform the so-called “9-11 flip”, i.e. we exchange the circle along the worldvolume with the M-circle. This yields a different IIA description of the same M-theory background. In analogy with the coordinatization of manifolds, we can think of the two IIA backgrounds as charts which make up an atlas for the description of the M-theory background. That is, by putting our “charts” together, we can reconstruct the full M-theory interpretation for each separate type of O4-plane. In particular, we will be able to uncover...
how the mysterious “freezing” process operates with $O_4$ planes.

This paper will be organized as follows. We will first review the T-S-T chain of dualities necessary for our analysis, and demonstrate how this corresponds to a simple exchange of the circles along the $X^9$ and $X^{10}$ directions in the M-theory background. We will next cover the $O_4$ planes which yield orthogonal groups as they can be entirely generated by the background M-geometry. We will then add non-dynamical five-branes to the mix, providing us with the elements necessary to construct $O_4$ planes yielding symplectic groups. We will conclude with some remarks on what this analysis teaches us about M-theory.

II. THE 9-11 FLIP

In this section we will trace the effects of a chain of T-S-T dualities on a IIA compactification. Consider IIA string theory compactified on a circle, $S^1$, along the $X^9$ direction, with radius $R$. We now know that this is in fact M-theory compactified on $R^{8,1} \times S^1 \times \bar{S}^1$, where the radius $\bar{R}$ controls the string coupling of IIA. We have:

\[ g_{\text{IIA}} = \bar{R} M_S \]
\[ R_9 = R \]

After we perform a T-duality along the $X_9$ direction, we get a IIB background with:

\[ g_{\text{IIB}} = g_{\text{IIA}} \frac{M_S}{R} = \frac{\bar{R}}{R} \]
\[ R_9 = \tilde{R} = \frac{1}{RM_S^2} = \frac{1}{M_5^2 \bar{R}} \]

Now, if we perform an S-duality transformation, we get a new IIB background. We will label this the IIB’ background. It has:

\[ g_{\text{IIB'}} = R \text{ over } \bar{R} \]
\[ R_9 = \tilde{R} = \frac{1}{M_5^3 \bar{R}} \]

Note that the string length has now been rescaled.
Our final T-duality takes back to a IIA background with different data:

\[ g_{\text{IIA}} = R M' S \]
\[ R_9 = \frac{1}{M'^2 \bar{R}} = \bar{R} \]

The role of the parameters \( R \) and \( \bar{R} \) have now been exchanged. This corresponds to exchanging what was the \( X^9 \) circle, \( S^1 \), with the M-circle, \( \bar{S}^1 \) (see Refs. [7,8]). We will use the 9-11 flip to trace the descent of objects in M-theory within both the IIA and \( \text{IIA} \) descriptions.

III. ORIENTIFOLD FOUR-PLANES WITH ORTHOGONAL GROUPS

The first class of objects that will interest us are orientifold four-planes associated with orthogonal gauge groups, i.e. \( D4 \)-branes which overlap the plane will carry orthogonal groups. We will align these such that they fill the \( X^0 ... X^3 \) and \( X^9 \) directions. There are two types of \( O4 \) planes associated with orthogonal gauge groups. The first is the standard \( O4^- \) plane constructed via the quotient \( \mathbb{R}^{1,9}/\{1, \Omega R_{45678}\} \), where \( \Omega \) acts with the orthogonal projection and \( R_{45678} \) reflects the \( X^4...8 \) directions. T-dualizing Type I theory implies that such planes have \( -\frac{1}{2} \) the charge of a \( D4 \)-brane in the bulk. \( N \) \( D4 \)-branes from the bulk which sit on this type of plane will carry an \( SO(2N) \) gauge group. The second type of \( O4 \) plane with an orthogonal \( \Omega \) projection is the \( O4^0 \) plane, which consists of taking the \( O4^- \) plane we just described and placing a stuck half \( D4 \)-brane on it (a half \( D4 \)-brane comes from just one \( D4 \)-brane in the covering space, while bulk \( D4 \)-branes come from 2). We change the \( O4 \) subscript to 0 to indicate that this configuration carries no net \( D4 \)-brane charge. The stuck half \( D4 \)-brane adds no new low-energy degrees of freedom to the \( O4 \) plane, but now a stack of \( N \) \( D4 \)-branes from the bulk sitting on top of the \( O4^0 \) plane will carry an \( SO(2N+1) \) gauge group. Our goal for this section will be to uncover evidence for the nature of the \( O4^- \) and \( O4^0 \) plane in M-theory using the 9-11 flip.
A. The O4⁻ plane

The O4⁻ plane is probably the best understood of O4 orientifold planes in M-theory. We know from Witten’s analysis in Ref. [9] (see also Ref. [10]) that the fixed 5-plane in \( \mathbb{R}^{1,10}/\mathbb{Z}_2 \), where \( \mathbb{Z}_2 \) reflects the \( X^{4-8} \) directions and flips the parity of the 3-form, carries \(-\frac{1}{2}\) the charge of an M5-brane. Thus this object can naturally be identified with the O4⁻ plane. If we compactify the \( X^9 \) and \( X^{10} \) directions on circles \( S^1 \) and \( \bar{S}^1 \) respectively, we should see no difference between the O4⁻ plane in the IIA background (where \( \bar{S}^1 \) is the M-circle) and its dual in the IIA background.

The first step in the T-S-T transformation for the O4⁻ plane, summarized in Fig. 1, is the T-duality along the \( X^9 \) direction (circle \( S^1 \)). The \( X^9 \) direction now has two O3⁻ planes, one at \( X^9 = 0 \) and one at \( X^9 = \pi \hat{R} \). This is a standard result (see for example Ref. [13]),
but is also clear from charge conservation. The $O4^-$ plane has D4-brane charge $-\frac{1}{2}$, so we expect the T-dual system to have D3-brane charge $-\frac{1}{4}$. Since the $O3^-$ planes have D3-brane charge $-\frac{1}{4}$, everything adds up. Furthermore, as explained in Ref. [11], $O3^-$ planes are $O3$ planes with zero NS-NS and RR two form fluxes through the $\mathbb{RP}^2$ in the $\mathbb{RP}^5$ surrounding their respective locations in $X^{4,..9}$. We will label them $(0,0)$ planes. Under S-duality $(0,0)$ planes remain $(0,0)$ planes (see Refs. [11,12]). This ensures that upon further T-duality we now return to an $O4^-$ plane in the IIA background. As expected, there is no change under the 9-11 flip.

![Diagram](image)

**FIG. 2.** 9-11 flip for the $O4^0$ plane
B. The $O4^0$ plane

At this point, we might expect a similarly simple scenario for the $O4^0$ plane. The naive expectation would be to quotient M-theory on

$$\mathbb{R}^{1,8} \times S^1 \times \bar{S}^1$$

with an $M5$-brane at the origin using the $\mathbb{Z}_2$ that gave us $O4^-$ plane. In Ref. [4], Hori showed that this simple scenario cannot be correct due to flux quantization rules. There is a topological obstruction to having a single $M5$-brane at the $\mathbb{Z}_2$ fixed plane. It was suggested that, as an alternative, the $O4^0$ plane might correspond to M-theory on

$$\mathbb{R}^{1,4} \times (\mathbb{R}^5 \times S^1) / \mathbb{Z}_2$$

where $\mathbb{Z}_2$ reflects all five directions of $\mathbb{R}^5$ but acts as a translation by $\pi \bar{R}$ on $\bar{S}^1$. This Möbius bundle is everywhere smooth, so doesn’t generate any $M5$-brane charge. Upon reduction along $\bar{S}^1$ to IIA, the translation action along $S^1$ implies that in the $O4^0$ background, $\Omega R_{56789}$ also flips the sign of the $U(1)_{RR}$ gauge field [4].

So far, the Möbius bundle makes an interesting proposal, yet there is no obvious stringy reason why the presence of a half $D4$-brane on top of an $O4^-$ plane should necessarily correlate with $\Omega R_{56789}$ acting non-trivially on the $U(1)_{RR}$ gauge bundle. We will use the 9-11 flip to see that this effect must be there (see Fig. 2). The non-trivial nature of the $U(1)_{RR}$ gauge field first becomes obvious when we perform the first T-duality of the 9-11 flip.

Consider a curve, $\hat{C}$ in the $O4^0$ covering space (with the $X^9$ direction now compactified as the circle $S^1$) going from a point to its mirror image point under the transformation $\Omega R_{56789}$. After we gauge this transformation, we have a closed curve, $C$ in the $O4^0$ background with

1Because the $U(1)_{RR}$ gauge field comes from Kaluza-Klein reduction on $S^1$, a translation by $R\theta$ along $S^1$ acts like multiplication by the phase $\exp(i\theta)$ on the $U(1)_{RR}$ gauge bundle.
the property that as we go once around, string states flip their orientation (due to $\Omega$) and the $U(1)_{RR}$ bundle flips sign. Thus we have:

$$e^{iI} \equiv e^{i \int \mathcal{A}_{\mu}^{RR} dx_{\mu}} = -1 \quad (3.3)$$

How does this property manifest itself after T-duality? After T-duality the gauge field integral, $I$, above becomes the integral of $B_{\mu\nu}^{RR}$ along the surface $\hat{C} \times \tilde{S}^1$ in $(\mathbb{R}^5 \times \tilde{S}^1)/\mathbb{Z}_2$. We expect this integral, $I$, to equal $\pi$.

From stringy considerations, we know that after T-duality the $O4^0$ plane, made up of an $O4^-$ plane and a stuck half D4-brane, will turn into an $O3^-$ plane at $X^9 = 0$ with a stuck half D3-brane along with a plain $O3^-$ plane at $X^9 = \pi \tilde{R}$ (the half D3-brane can also be positioned at $X^9 = \pi \tilde{R}$ with a judicious choice of Wilson lines). The $O3^-$ plane has D3-brane charge $-\frac{1}{4}$, so placing a half D3-brane on it gives a total charge of $+\frac{1}{4}$. This bound system has total $RR$ two-form flux $\pi$ through any $\mathbb{R}P^2$ inside the $\mathbb{R}P^5$ surrounding it in $X^{4\ldots9}$ (see Ref. [1]). We will refer to it as an $O3^+$ plane of type $(0,1)$. $I$ will now be the total flux (mod $2\pi$) from the $O3^-$ $(0,0)$ plane and the $O3^+$ $(0,1)$ plane, which clearly adds up to $\pi$. Thus we seem to have identified the correct originating M-theory configuration for describing the $O4^0$ plane.

Continuing along the sequence of dualities which make up the 9-11 flip, we can gather further evidence for our M-theory picture of the $O4^0$ plane. After S-duality, the $(0,0)$ and $(0,1)$ $O3$ planes transform into $(0,0)$ and $(1,0)$ $O3$ planes respectively [2][3]. T-dualizing this new configuration might appear to be difficult, as we are dealing with two different type of $O3$ planes. Fortunately, a very similar type situation, featuring an $O8^+$ and an $O8^-$ plane was analyzed in Ref. [3]. There we start with two $O8$ planes describing the IIA background $\mathbb{R}^{1,8} \times \tilde{S}^1/\mathbb{Z}_2$ where $\tilde{S}^1$ is a circle of radius $\tilde{R}$. After T-duality along $\tilde{S}^1$, a new type I theory with no vector structure was found with radius $\frac{1}{2\tilde{R}}$. In this theory, however, only even windings are allowed in the cylinder amplitude, and only odd windings are allowed in the Klein bottle amplitude. A simpler way to understand this new theory is to think of it as the gauging of the IIB theory on $\mathbb{R}^{1,8} \times S^1$, $S^1$ with radius $\tilde{R} = \frac{1}{R}$, by the operation
$\Omega Z_2$ where $Z_2$ acts as a translation by $\pi \tilde{R}$.

It is now simple to extend the situation with $O8$ planes of opposite charges to the similar case of the $(0, 0)$ and $(1, 0)$ $O3$ planes. After T-dualizing the $X^9$ direction, we now get $IIA$ on

$$R^{1,3} \times (R^5 \times \tilde{S}^1)/(\Omega R_{5678} \tilde{Z}_2).$$

(3.4)

The second factor describes a Möbius bundle. It has no fixed planes (and therefore no orientifold planes) and is everywhere smooth. It does, however, possess a circle along $X^9$ of minimal length, $\tilde{R}/2$ at $X^5 = ... = X^8 = 0$ which will become important in the next section. This $IIA$ compactification is exactly what we expect if we started from Eq.3.2 with one of the directions of $R^{1,4}$ on compactified and then used this $S^1$ as the M-circle. We can thus be confident that we now have the correct interpretation of the $O4^0$ plane in M-theory.

IV. ORIENTIFOLD FOUR-PLANES WITH SYMPLECTIC GROUPS

The second class of $O4$ planes we must consider for a complete treatment are the $O4^+$ (they have $D4$-brane charge $+\frac{1}{2}$) which give symplectic groups when we place $D4$-branes on them. In Ref. [4], it was pointed out that there exists in fact two type of $O4^+$ planes, differentiated by there action on the IIA $U(1)_{RR}$ gauge bundle. As was the case with the $O4^0$ plane, we can allow $\Omega R_{5678}$ to also act with a phase $\pm 1$ on this gauge bundle. If we define the same $A_{\mu}^{RR}$ integral, $I$, as in the previous section, it can take values 0 or $\pi$ modulo $2\pi$.

A. The $O4^+$ plane with $I = 0$

After T-duality, $I$ will be the total measure of the $RR$ two-form fluxes from the $O3^+$ planes at $X^9 = 0$ and $X^9 = \pi \tilde{R}$. Both of these planes must give $USp(2N)$ type gauge groups. This means that an $O4^+$ plane with $I = \pi$ transforms into a $(1, 0)$ and a $(1, 1)$ $O3$ plane, while an $O4^+$ plane with $I = 0$ can transform into a pair of $(1, 0)$ $O3$ planes or into
a pair of $(1, 1)$ $O_3$ planes. The ambiguity in the $I = 0$ case might seem confusing at first, until one realizes that the two possibilities are related by the $SL(2, \mathbb{Z})$ transformation which takes $\tau$ to $\tau + 1$. This implies that they correspond different values for the axion scalar. We will assume, for now, that the $O_4^+$ transforms into a pair $(1, 0)$ $O_3$ planes, and the transformation into $(1, 1)$ planes involves some non-trivial conditions on the $U(1)_{RR}$ gauge field along the $X^9$ direction.

To continue the 9-11 flip for the $O4^+$ case, we next perform an S-duality (see Fig.3). The two $(1, 0)$ $O3^+$ planes now become $(0, 1)$ $O3^+$ planes. We can think of these two planes as each consisting of an $O3^-$ plane with a stuck half $D3$-brane. The final T-duality thus yields

FIG. 3. 9-11 flip for the $O4^+$ plane with trivial $U(1)_{RR}$ bundle
an $O4^-$ plane with one full $D4$-brane on top of it. This $D4$-brane, which normally would be free to move of the $O4^-$ plane, has a special $O(2)$ Wilson line along the $X^9$ direction off the form:

$$
\begin{pmatrix}
0 & 1 \\
1 & 0
\end{pmatrix}
$$

(4.1) modulo a gauge transformation. This implies that open string endpoints on this $D4$-brane live on a double cover. Since open strings quantize the oscillations and zero modes of the $D4$-brane, we know that the $D4$-brane is wrapped twice around the circle $\bar{S}^1$.

The interesting feature here is that the orientifold projection prevents the doubly wrapped $D4$-brane from becoming two singly wrapped $D4$-branes. Before the orientifold projection, the gauge group on the $D4$-brane (which is overlapping with its image) is $U(2)$. In that gauge group, the Wilson line in Eq.4.1 is continuously connected to the identity, so there is the possibility of separating the $D4$-brane into two $D4$-branes with $U(1)$ gauge groups. While the orientifold projection is possible once the $D4$-branes are separated (they need only be placed at mirror image positions), it does turn $U(2)$ into $O(2)$. The Wilson line in Eq.4.1 is then disconnected from the identity, and the separation process is no longer possible.

Putting together our information from the IIA and IIA backgrounds and decompactifying $S^1$, we see that the $O4^+$ plane with the trivial $U(1)_{RR}$ gauge bundle can be thought of as M-theory on

$$
\mathbb{R}^{1,4} \times \mathbb{R}^5/\mathbb{Z}_2 \times \bar{S}^1
$$

(4.2) with an $M5$-brane along $\mathbb{R}^{1,4}$ and doubly wrapped around $\bar{S}^1$. Because the $M5$-brane is doubly wrapped, we expect that it will have low-energy excitations with mass of order $\frac{1}{2R}$. We can see this excitation in the IIA picture of the $O4^+$ plane as the half $D0$-brane stuck on the orientifold plane. It will have half the mass of a regular $D0$-brane:

$$
\frac{1}{2} \frac{M_S}{g_{\text{IH}}} = \frac{1}{2R}.
$$

(4.3)
The half $D0$-brane should also couple to the $U(1)_R R$ gauge field.

Finally, if we return to the $O4^+$ plane with $I = 0$ wrapped again on the circle $S^1$, we still need to explain what is necessary for T-dualizing to a configuration with two $(1, 1) O3^+$ plane. This IIB configuration is S-dual to itself. This means that the original $O4^+$ plane must correspond to an M-theory background like the one in Eq.4.2, only where the $M5$-brane wraps both $S^1$ and $\tilde{S}^1$. The IIB configuration with two $(1, 1) O3$ planes is also related to one with two $(1, 0) O3$ planes by the $SL(2, \mathbb{Z})$ transformation which takes the coupling $\tau$ to $\tau + 1$. In IIA variables, this means that the $U(1)_{RR}$ gauge field along $X^9$ becomes $\frac{1}{R}$. This means that $D0$ branes states will be multiplied by a phase $e^{i2\pi}$ as they go around $S^1$. Since the half $D0$-brane states have half the charge, they will see a phase $e^{i\pi}$ as they go around. These states effectively live on a circle of twice the radius $R$, demonstrating how in the M-theory picture we have an $M5$-brane which is doubly wrapped on both $S^1$ and $\tilde{S}^1$.

**B. The $O4^+$ plane with $I = \pi$**

The final $O4$ plane which we would like to consider is the $O4^+$ plane with $I = \pi$. In Ref. [4], it was proposed that in M-theory this object corresponds to the same background as the $O4^0$ plane, namely the one Eq.3.2, but with a single $M5-brane$ wrapped around $\tilde{S}^1$ at $X^4 = \ldots = X^8 = 0$. Because the $\tilde{S}^1/\mathbb{Z}_2$ circle fiber at the origin in $(\mathbb{R}^5 \times \tilde{S}^1)/\mathbb{Z}_2$ is the smallest in its topological class (any deformation of this circle will increase its overall length), the $M5$-brane can't move off. Its lowest energy excitation will have mass of order $\frac{1}{2\pi R}$. In the IIA background, this corresponds to the half $D0$-brane on the $O4^+$ plane. We will now use the 9-11 flip, as shown in Fig. 4, to verify that our picture for the $O4^+$ plane with $I = \pi$ is correct.

The first T-duality in the 9-11 flip gives us two $O3^+$ planes of type $(1, 0)$ and $(1, 1)$ respectively. The difference in $RR$ two-form fluxes allows us get $I = \pi$. After S-duality, there is no fixed point set in M-theory, so a single $M5$-brane is allowed in the covering space.
the $(1,0)$ $O3$ plane becomes a $(0,1)$ $O3$ plane, while it’s $(1,1)$ partner remains the same. T-duality now operates just as in the $O4^0$ case, except for two subtleties. First, the fact that we have a $(0,1)$ $O3$ plane instead of a $(0,0)$ one means that the T-dual $\mathbb{I}A$ background will contain a $D4$-brane. The second subtlety involves complications with possible non-trivial behavior for the $U(1)_{RR}$. The presence of a $(1,1)$ $O3$ plane opposite the $(0,1)$ $O3$ plane insures that there is no such troubling factor to deal with. Thus we see that the 9-11 flip gives us just the result we anticipated, namely a $\mathbb{I}A$ background just as in Eq. 3.4 with a $D4$-brane wrapped around the central circle of the Möbius fibration.

FIG. 4. 9-11 flip for the $O4^+$ plane with non-trivial $U(1)_{RR}$ bundle
V. CONCLUSIONS

To summarize, we have shown how $O4$ planes in IIA string theory arise from two very different types of configuration in M-theory. The first class of M-theory backgrounds consists of smooth Möbius bundles. They are smooth because we combine a reflection along five directions with a half-period shift on the M-circle. The naked background corresponds to an $O4^-$ plane with a stuck half $D4$-brane. We can also dress this background up with an $M5$-brane wrapped around the circle at the origin to get a special type of $O4^+$ plane. Both these object will have a non-trivial $U(1)_{RR}$ gauge bundle which swaps signs under orientation reversal.

The second class of $O4$ planes involves M-theory on a singular background, $\mathbb{R}^5/\mathbb{Z}_2 \times ...$. This background on it's own corresponds to an $O4^-$ orientifold plane. We can, however, wrap a single $M5$-brane at the origin around the M-circle, so long as it is doubly wrapped. In IIA, this object becomes an $O4^+$ plane with a trivial $U(1)_{RR}$ gauge bundle. For this second class of $O4$ planes, we have been able to learn something new about M-theory. Namely, not only does an $\mathbb{R}^5/\mathbb{Z}_2$ singularity carry $M5$-brane charge, but also a doubly wound $M5$-brane sitting at this singularity will be unable to “unwind” into two singly wrapped $M5$-branes.

Looking back, we can identify two main lessons that can be drawn from this analysis. First, the 9-11 flip is a useful method for understanding the M-theory origins of IIA objects. It can be used systematically to find these M-theory origins. If the M-theory configuration is already known, it can make a useful guide in understanding what happens under the various dualities that make up the 9-11 flip. Another interesting lesson we can draw from this analysis, is that while there are several type of $O4$ planes in M-theory, all but one depend on the M-circle compactification to make sense. Thus the full uncompactified M-theory has only one type of orientifold five-plane. It comes from the $\mathbb{R}^5/\mathbb{Z}_2$ quotient and carries $M5$-charge $-\frac{1}{2}$. If we look at M-theory on $AdS^7 \times S^4$, then their is a unique orientation reversing quotient we can take. The $(0,2)$ theory of the $2N$ $M5$-brane that this quotient is dual to can exhibit both $Sp$ or $SO$ types of gauge symmetries upon compactification.
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