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Exotic Branes and Nongeometric Backgrounds

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When string or M theory is compactified to lower dimensions, the U-duality symmetry predicts so-called exotic branes whose higher-dimensional origin cannot be explained by the standard string or M-theory branes. We argue that exotic branes can be understood in higher dimensions as nongeometric backgrounds or U folds, and that they are important for the physics of systems which originally contain no exotic charges, since the supertube effect generically produces such exotic charges. We discuss the implications of exotic backgrounds for black hole microstate (non-)geometries.

Introduction.—String theory includes various extended objects as collective excitations, such as D-branes. The U-duality symmetry [1] which maps these objects into one another has played a pivotal role in the development of string theory and provided crucial insights into its nonperturbative behavior. When string or M theory is compactified to lower dimensions, the U-duality group gets enhanced, relating objects that were not related in higher dimensions. For example, M theory compactified on $T^2$ has a discrete U-duality group known as $E_{6(6)}(Z)$ [1].

In the lower $(d = 11 - k)$ dimensional theory, if we start from a codimension-two object obtained by partially wrapping a known 11D object and act by $U$ duality on it, we start to produce objects whose higher-dimensional origin is unknown; they are called exotic branes [2]. In type II language, some of them have a tension proportional to $g_s^{-3}$ or $g_s^{-4}$. For example, in type II string compactified on $T^2$, consider an NS5-brane extending along six of the eight remaining noncompact directions, not wrapping the internal $T^2$. If we perform a $T$ duality along both $T^2$ directions, we obtain an exotic brane called $S_2^2$. We will see later that this is a nongeometric background known as a $T$ fold [3]; as we go around the exotic brane, the internal $T^2$ is nontrivially fibered and does not come back to itself, but rather to a $T$-dual version.

One may think that such codimension-two objects are problematic due to logarithmic divergences [4], and that we do not need them if we are concerned with the physics of nonexotic states. However, this is not true because of the supertube effect [5]—the spontaneous polarization phenomenon that occurs when we bring a particular combination of charges together. A basic example is

$$D0 + F1(1) \rightarrow D2(1\psi)$$

in which D0-branes and fundamental strings along $x^1$ polarize into a D2-brane extending along $x^1$ and a closed curve in the transverse directions parametrized by $\psi$. Note that the D2 charge did not exist in the original configuration. Since the D2 is along a closed curve, there is no net D2 charge, but only a D2 dipole charge. The microscopic entropy of the D0-F1 system can be recovered by counting the possible $\psi$ curves that the system can polarize into [6].

Even if we start with a configuration of nonexotic charges, the supertube effect can produce exotic charges. Because the exotic charges thus produced are dipole charges, there is no net exotic charge at infinity and the problem of log divergences does not arise. This implies that exotic states are relevant even for the physics of systems which do not originally contain exotic charges.

This is especially interesting in the context of black hole physics where one typically considers a configuration of multiple (nonexotic) charges. We will argue later that the supertube effect and exotic charges are relevant for the understanding of the physics of such black holes.

Exotic states and their higher-dimensional origin.—If we compactify M theory on $T^8$ or type IIA/B string theory on $T^7$ down to 3D, we obtain $\mathcal{N} = 16$ supergravity [7] with 128 scalars (note that gauge fields can be dualized into scalars in 3D). This theory has $E_{8(8)}$ as the U-duality group which is broken to the discrete subgroup $E_{8(8)}(Z)$ in string theory [1]. This $E_{8(8)}(Z)$ is generated by $S$ and $T$ dualities along the internal torus. For example, in type IIB, a $D7$-brane wrapped on the $T^1$ yields a point particle in three dimensions. Acting with $S$ and $T$ dualities, we can obtain all other states in the “particle multiplet” of the $U$-duality group as explained in [2].

In Table I, we list the states in the particle multiplet, including the exotic ones. The notation for nonexotic states is standard; e.g., $P$ denotes a gravitational wave and KKM denotes a Kaluza-Klein monopole. For type II exotic states, we follow [2] and denote them by how their mass depends on the $T^3$ radii. The mass $M$ of $b_n^{d,c}$ depends linearly on $b$ radii and quadratically on $c$ radii. For $b_n^{d,c}$, $M$ also depends cubically on $d$ radii. Moreover, $M$ is proportional to $g_s^{-n}$. For example, the mass of $S_2^2$ depends on the radii $R_i$, $i = 3,\ldots,9$ of $T^7$ as $M = R_3 \cdots R_7(R_8 R_9)^2/g_s^2 R_1^2$. We often display how the state “wraps” the internal $T^1$ as $S_2^2(34567,89)$. In this notation, the KK monopole is denoted by $S_1$. In M theory, we use a similar notation except that we drop the subscript $n$. Using the transformation rules...
for the radii $R_i$ and $g_s$ under $S$ and $T$ dualities, we can read off how those states transform into one another [2].

In the 3D theory, we would have 128 gauge fields if we could dualize all the scalars into gauge fields [2]. However, as we can see from Table I, there are as many as 240 charged particles [8], and this discrepancy (240 versus 128) in the 3D theory is not understood [2]. For $d = 4$, this issue does not arise because we obtain just as many charged particles as gauge fields [2]. Here, we argue that the higher-dimensional origin of exotic states consists of nongeometric backgrounds or $U$ folds [3,9].

The argument is simple. For example, consider a $D7$-brane wrapping $T^7$, which is (magnetically) coupled to the RR 0-form $C^0$. From the 3D viewpoint, the $D7$-brane is a point particle and, as we go around it, the 3D scalar $\phi = C^0$ shifts as $\phi \to \phi + 1$. Namely, in 3D, the “charge” of the point particle is nothing but the monodromy of the scalar $\phi$ around it. This symmetry of shifting $\phi$ by one gets combined with other dualities such as $S$ and $T$ dualities to form the $U$-duality group $G(\mathbb{Z}) = E_{8(8)}(\mathbb{Z})$, and the scalar $\phi$ gets combined with other scalars into a matrix $M$ parametrizing the moduli space $\mathcal{M} = SO(16) \backslash E_{8(8)}(\mathbb{R})/E_{8(8)}(\mathbb{Z})$. $U$ duality means that we can more generally consider a 3D particle around which $M$ jumps by a general $U$-duality transformation. Thus, the charge of a 3D particle is defined by the $U$-duality monodromy around it. This can be regarded as a non-Abelian generalization of the usual notion of $U(1)$ charges for which the monodromy is an additive shift. Clearly, the number of different charges thus generalized is not in general equal to that of gauge fields, which resolves the above puzzle.

If we lift such a monodromy to 10D/11D, we obtain a configuration in which the internal space is nontrivially fibered as we go around the particle and glued together by a $U$-duality transformation. So, exotic states correspond in 10D/11D to nongeometric backgrounds, or “$U$ folds” [3]. To our knowledge, the interpretation of exotic states as $U$ folds has not appeared in the literature. Note that this construction differs from the more familiar $U$ folds in the context of string compactifications [9], where $U$ duality is nontrivially fibered over a noncontractible circle in the internal manifold, not over a contractible circle in the noncompact directions.

Let us discuss how to classify “charges” defined by the monodromies around them. First, assume the existence of a charge with monodromy $q$. Namely, as we go around the particle in three dimensions, the moduli matrix $M$ undergoes the monodromy transformation $M \to Mq$, $q \in G(\mathbb{Z})$. If we go to another $U$ duality frame by a $U$-duality transformation $U \in G(\mathbb{Z})$, then this becomes $\tilde{M} \to \tilde{M}q$ with $\tilde{M} = MU$, $\tilde{q} = U^{-1}qU$. So, in the dual frame, there exists a charge with monodromy $\tilde{q}$. Namely, in 3D, the “charge” of the point particle is nothing but the monodromy of the scalar $\phi$ around it. This symmetry of shifting $\phi$ by one gets combined with other dualities such as $S$ and $T$ dualities to form the $U$-duality group $G(\mathbb{Z}) = E_{8(8)}(\mathbb{Z})$, and the scalar $\phi$ gets combined with other scalars into a matrix $M$ parametrizing the moduli space $\mathcal{M} = SO(16) \backslash E_{8(8)}(\mathbb{R})/E_{8(8)}(\mathbb{Z})$. $U$ duality means that we can more generally consider a 3D particle around which $M$ jumps by a general $U$-duality transformation. Thus, the charge of a 3D particle is defined by the $U$-duality monodromy around it. This can be regarded as a non-Abelian generalization of the usual notion of $U(1)$ charges for which the monodromy is an additive shift. Clearly, the number of different charges thus generalized is not in general equal to that of gauge fields, which resolves the above puzzle.

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Supergravity description of exotic states.—To demonstrate the above idea, let us present the supergravity metric

| Type IIA | $P(7)$, $F1(7)$, $D0(1)$, $D2(21)$, $D4(35)$, $D6(7)$, $NS5(21)$, $KKM(42)$, $S3(21)$, $O2(1)$, $O2(35)$, $S3(7)$, $041^6(7)$, $15^7(7)$ |
| Type IIB | $P(7)$, $F1(7)$, $D1(7)$, $D3(35)$, $D5(21)$, $D7(4)$, $NS5(21)$, $KKM(42)$, $S3(21)$, $15^7(7)$, $33(35)$, $53^7(21)$, $73(1)$, $041^6(7)$, $15^7(7)$ |
| $M$ theory | $P(8)$, $M2(28)$, $M5(56)$, $KKM(56)$, $53(56)$, $23(28)$, $041^7(8)$ |
for $S^2$ as an example. This can be obtained by $T$ duality of the KK monopole metric transverse to its worldvolume. The KK monopole $(5_2(56789,4))$ metric is

$$ds^2 = dx_{56789}^2 + Hdx_{123}^2 + H^{-1}(dx^4 + \omega)^2, \quad e^{2\Phi} = 1,$$

$$d\omega = \ast_3 dH, \quad H = 1 + \sum_p H_p, \quad H_p = R_4/\langle 2|\tilde{x} - \tilde{x}_p \rangle,$$

where $\tilde{x}_p$ are the positions of the centers in $\mathbb{R}^3_{123}$. Now compactify $x^3$, which is the same as arraying centers at intervals of $2\pi R_3$ along $x^3$. So,

$$H = 1 + \sum_{n \in \mathbb{Z}} R_4/\langle 2(r^2 + (x^3 - 2\pi R_3 n)^2)^{1/2} \rangle = 1 + \sigma \log([\Lambda + \sqrt{r^2 + \Lambda^2}]/r), \quad (3)$$

where $\sigma = R_4/2\pi R_3$ and we took a cylindrical coordinate system $dx_{123}^2 = dr^2 + r^2 d\theta^2 + (dx^3)^2$. We approximated the sum by an integral and introduced a cutoff $\Lambda$ to make it convergent (see [11,12]). $H$ in (3) diverges as we send $\Lambda \to \infty$, but this can be formally shifted away by introducing a "renormalization scale" $\mu$ and writing

$$H(r) = h + \sigma \log(\mu/r) = \omega = -\sigma \theta dx^3, \quad (4)$$

where $h$ is a "bare" quantity which diverges in the $\Lambda \to \infty$ limit. The log divergence of $H$ implies that such an infinitely long codimension-two object is ill-defined by itself. In physically sensible configurations, this must be regularized either by taking a suitable superposition of codimension-two objects [4] or, as we will do later, by considering instead a configuration which is of higher codimension at long distance.

Now let us do a $T$ duality along $x^3$. By the standard Buscher rule, we obtain the metric for $S^2(56789,34)$:

$$ds^2 = H(dr^2 + r^2 d\theta^2) + H K^{-1} dx_{34}^2 + dx_{56789}^2,$$

$$B_{34}^2 = -K^{-1} \theta \sigma, \quad e^{2\Phi} = HK^{-1}, \quad K = H^2 + \sigma^2 \theta^2. \quad (5)$$

In terms of the radii in this frame, $\sigma = R_3 R_4/2\pi \alpha'$. Similar metrics of exotic states have been written down (e.g., [12] considered 61), but they do not appear to have been discussed in the context of $U$ folds. As can be seen from (5), as we go around $r = 0$ from $\theta = 0$ to $2\pi$, the size of the $3+4$ torus does not come back to itself:

$$\theta = 0: \quad G_{33} = G_{44} = H^{-1},$$

$$\theta = 2\pi: \quad G_{33} = G_{44} = H/[H^2 + (2\pi \sigma)^2]. \quad (6)$$

This can be understood as a $T$ fold. If we package the 3-4 part of the metric and $B$ field in a $4 \times 4$ matrix [13]

$$M = \left( \begin{array}{cc} G^{-1} & G^{-1} B \\ -BG^{-1} & G - BG^{-1} B \end{array} \right) \quad (12)$$

then the $SO(2,2; \mathbb{R})$ $T$-duality transformation matrix $\Omega$ satisfying $\Omega' \eta \Omega = \eta,$

$$\eta = \left( \begin{array}{cc} 0 & I_2 \\ I_2 & 0 \end{array} \right)$$

acts on $M$ as $M \to M' = \Omega^* M \Omega$. It is easy to see that the matrix

$$\Omega = \left( \begin{array}{cc} I_2 & 0 \\ 0 & 2\pi \sigma \end{array} \right)$$

relates the $\theta = 0, 2\pi$ configurations in (6). Namely, $S^2$ is a nongeometric $T$ fold with the monodromy $\Omega$.

Although the mass of such a codimension-two object is not strictly well-defined, we can still compute it by the following ad hoc procedure. The Einstein metric in 3D is given by $ds^2 = -dt^2 + Hdx_{123}^2$. If $\gamma_{ij}$ is the spatial metric for constant $t$ slices and $G_{ij}$ is the Einstein tensor, we can compute $\sqrt{\gamma} G_{ij}^0 = \frac{1}{2} \partial_i \log H$. So, the energy is

$$M = -\frac{1}{8\pi G_3} \int d^2x \sqrt{\gamma} G_{ij}^0 = -\frac{1}{16\pi G_3} \int dS \cdot \nabla \log H.$$

If we use (4) and assume that $H(r = \infty) = 1$, then

$$M = \frac{1}{16\pi G_3} \left[ \frac{2\pi \sigma}{H(r)} \right]_{r=\infty} = \frac{(R_3 R_4^2 R_5 \cdots R_9)}{g^2 S_0^2},$$

as expected of a $S^2(56789,34)$. Here, we used $16\pi G_3 = g^2 S_0^2/2 \cdots R_9$. Although the $S^2$ changes the asymptotics, setting $H(r = \infty) = 1$ effectively puts it in an asymptotically flat space and allows us to compute its mass.

Similarly, one can derive the metric for other exotic states appearing in Table I. The metric provides an approximate description, just as for ordinary branes, unless the tension of the exotic branes is proportional to $g_s^{-3}$ or $g_s^{-4}$ and the metric description breaks down.

Supertube effect and exotic states.—The above exotic $S^2$ brane appears in $d = 3$ dimensions, but exotic states are relevant to physics in $d \geq 4$ dimensions as well. By dualizing the basic supertube effect (1), we can derive the following spontaneous polarization:

$$D(456789) + D(4589) \to S^2(45678,39). \quad (8)$$

The configuration on the left can be thought of as a configuration in 4D, which puffs up into an extended configuration of an exotic dipole charge along a curve in $\mathbb{R}^3_{123}$. Such exotic dipole charges do not change the asymptotics of spacetime. Note that the original configuration of $D4$-branes is part of the standard $D0$–$D4$ configuration used for the black hole microstate counting in four dimensions [14]. So, to understand the physics of such black holes, it is unavoidable to consider exotic charges.

The supergravity solution for the configuration (8) can be obtained by dualizing the solution for the supertube [15] and is given by

$$ds^2 = -f_1^{1-2} f_2^{2-2} (dt - A)^2 + f_1^{1/2} f_2^{1/2} dx_{123}^2 + f_1^{1/2} f_2^{1/2} dx_{45}^2 + f_1^{-1/2} f_2^{1/2} dx_{67}^2 + f_1^{1/2} f_2^{1/2} h^{-1} dx_{89}^2,$$

$$e^{2\Phi} = f_1^{1/2} f_2^{1/2} h^{-1}, \quad B_{89}^{(2)} = \gamma h^{-1}, \quad C^{(5)} = -\gamma \rho + \sigma. \quad (14)$$
where \( h = f_1 f_2 + \gamma^2 \) and \( \rho, \sigma \) are 3-forms given by

\[
\rho = (f_2^{-1} \delta t - dt) \wedge dx^4 \wedge dx^5 + (f_1^{-1} \delta t - dt) \wedge dx^6 \wedge dx^7 \\
\sigma = (\beta_1 - \gamma dt) \wedge dx^4 \wedge dx^5 + (\beta_2 - \gamma dt) \wedge dx^6 \wedge dx^7
\]

with \( \delta t = dt - A \). The \( \psi \) curve in (8) is an arbitrary closed curve in \( \mathbb{R}^{1234} \), and \( f_{i=1,2} \) are harmonic functions sourced along the curve [15]; see, e.g., [16] for their explicit expressions. The 1-form \( \beta_i \) and scalar \( \gamma \) are related to \( f_i \), \( A \) by \( d\beta_i = *_i d f_i \), \( d\gamma = *_3 d A \). In particular, for a circular curve, they can be explicitly written down [15,16], including \( \gamma, \beta_i \) [10]. As one goes around the curve, \( \gamma \) undergoes a shift \( \gamma \rightarrow \gamma + q \) with \( q \) a constant proportional to the \( S_2^2 \) dipole charge. This gives rise to a monodromic structure in the metric and the \( B \) field, similar to the one in (5). Because the exotic \( S_2^2 \) charge in (8) is merely a dipole charge, the 4D supergravity microstates constructed thus far (see, e.g., [21,22]) do not seem enough to account for the entropy of the three-charge black hole [22] may be related to the nongeometric nature of exotic branes that have been overlooked.

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[8] References [2] suggest that there are 8 more states (7 in type II and 8 in \( M \)) theory in addition to the ones in Table I. It would be interesting to study how they can fit within the arguments of the current note.