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Is string theory a theory of strings?

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Recently a great deal of evidence has been found indicating that type IIA string theory compactified on $K3$ is equivalent to heterotic string theory compactified on T^4. Under the transformation which relates the two theories, the roles of fundamental and solitonic string solutions are interchanged. In this letter we show that there exists a solitonic membrane solution of the heterotic string theory which becomes a singular solution of the type IIA theory, and should therefore be interpreted as a fundamental membrane in the latter theory. We speculate upon the implications that the complete type IIA theory is a theory of membranes, as well as strings.

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Beyond the first quantized framework of the Polyakov path integral [1], our knowledge of string theory is sorely lacking. Determining a more fundamental formulation of the theory will be an essential step in fully addressing nonperturbative issues, such as supersymmetry breaking and selection of the vacuum. Recently there has been rapid progress into understanding the strong coupling dynamics of certain supersymmetric string theories [2]. These advances should provide new insights into the correct fundamental framework which must underly string theory. We take one step in this direction by presenting evidence that type IIA superstrings are only one component of a larger theory which also contains fundamental membranes.

The recent developments seem to indicate that the strong coupling physics of certain superstring theories may be reformulated as the weak coupling physics of "dual" string theories [2,3,4] and *vice versa*. One interesting example is the duality in six dimensions between heterotic strings compactified on a four-torus T^4, and type IIA superstrings compactified on a particular four-manifold known as $K3$. In fact, the duality relies on the much stronger conjecture that these two string are completely equivalent. Some of the evidence supporting this conjecture is: (i) both theories have the same supersymmetric multiplets of massless states [4,2]; (ii) the moduli space of the possible vacua is identical in both theories [5]; (iii) the low energy effective actions can be identified with a strong-to-weak coupling duality mapping of the massless fields [2]; (iv) there is one-loop consistency via certain anomaly constraints [6].

One further result which supports the equivalence is that the heterotic string can be identified as a soliton within the type IIA string theory, and conversely, the type IIA string can be identified as a soliton in heterotic string theory[1] [7]. Thus under the duality transformation, the roles of the fundamental and solitonic strings are interchanged. This interchange is a stringy version of the role reversal between magnetic monopoles and electric charges arising in the strong-to-weak coupling duality of gauge field theories conjectured in [8], and recently confirmed in the context of supersymmetric field theory [9].

In general, the low energy string theories contain a rich array of solutions corresponding to extended objects, so-called p-branes for p-dimensional bodies (see [10] and references therein). It is now apparent that these objects play an important role in the non-perturbative physics of the string theories [11]. One is then prompted to ask how

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[1] This second identification is made only at the level of external field configurations, in the first of the references in [7].

these solutions behave under the strong/weak coupling duality transformations discussed above. There will be three distinct possibilities: (i) the p-brane could be a singular field configuration in both of the dual string theories, which would justify discarding these configurations as unphysical, (ii) the p-brane could be nonsingular in both theories, in which case it would be treated as a soliton in both contexts, and finally (iii) the p-brane could be nonsingular in one theory but singular in the dual theory. In the latter case, since it appears as a soliton in one theory, one would not be able to omit it from the spectrum. However the fact that the p-brane solution is singular in the dual theory suggests that it represents the external fields around a fundamental source[2] – *i.e.,* the dual theory should contain fundamental p-branes!

An immediate question is how the singular or nonsingular nature of these objects is to be determined[3]. The result can be phrased in terms of examining the p-brane with a certain test-probe, *i.e.,* determining the behavior of a small test object as it approaches the core of the p-brane. The choice of the test-probe would depend on which fundamental theory underlies the original brane solution (see [13,10]). For example, in a heterotic string theory, the natural test-probe to examine any p-brane solution would be a fundamental heterotic string. This amounts to measuring possible curvature singularities with the metric which couples to the world-volume of the fundamental objects in the theory, *i.e.,* the metric which appears in the sigma-model describing these fundamental objects. Applied to the case of the six-dimensional string/string duality, this means that the heterotic string appears singular in the heterotic string sigma-model metric, but is nonsingular in the type IIA superstring metric [7].

In this letter as a first step we construct a certain membrane soliton solution for $D = 6$ heterotic string theory. We choose this solution to be spacetime supersymmetric, and show that it is nonsingular to all orders in the α' expansion. However, the membrane solution is singular for type IIA string test-probes. Hence it falls into class (iii), wherefore we are led to conclude that the full type IIA theory includes fundamental membranes, as well as strings. Finally, we discuss the possible implications of this result.

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[2] In case (i), one could also consider the possibility that the p-brane is fundamental in both of the theories.

[3] Ref. [12] recently presented a complementary discussion of singular solutions which stresses the importance of the source terms. It also conjectures that in the presence of such sources the singularities may actually be smoothed out with certain field redefinitions.

We begin by considering the heterotic string theory arising from toroidal compactification down to six dimensions. For a generic point in the moduli space, the low energy effective theory is $N = 2$ supergravity coupled to twenty abelian vector multiplets. Thus the bosonic fields include the metric, the dilaton, the antisymmetric Kalb-Ramond field, 24 abelian gauge fields, and 80 scalar moduli fields. Given these fields, it is straightforward to list the objects which arise naturally as solutions in the low energy theory. For example, in six dimensions the three-form field strength of the Kalb-Ramond two-form couples naturally as the "electric" or "magnetic" field around a one-brane, or string. In fact these correspond to the two string solutions discussed above, *i.e.,* the fundamental heterotic string with the electric Kalb-Ramond charge, and its dual solitonic string, with the magnetic three-form charge. Point-like or zero-brane solutions also appear, with conventional electric charges from the $U(1)$ two-form field strengths. In particular, singular point-like objects arise as the extremal limits of electrically charged black holes [14]. In this case, the dual objects are two-branes or membranes with magnetic $U(1)$ charge. To complete the list, one could also consider three-branes which carry a "magnetic" charge from the periodic moduli scalars, and "minus-one"-branes or instantons carrying scalar electric charge. We will restrict our attention, though, to a class of solitonic membranes.

For the solutions which we wish to consider, it is consistent to truncate the low energy action as follows:

$$S_{het} = \int d^6x\,\sqrt{-G}\,e^{-2\Phi}\left(R + 4(\partial\Phi)^2 - \frac{1}{4}F^2\right), \tag{1}$$

where $F = dA$ is the field strength for one of the $U(1)$ gauge fields, Φ is the six-dimensional dilaton and the metric is that which couples to the heterotic string sigma-model. For this action, one finds the following solution which represents a magnetically charged membrane

$$\begin{aligned} ds^2 &= -dt^2 + dx_1^2 + dx_2^2 + \left(1 + \frac{Q}{y}\right)^2 \left(dy^2 + y^2 d\Omega_2^2\right), \\ e^{2\Phi} &= 1 + \frac{Q}{y}, \\ F_{\theta\varphi} &= \sqrt{2}Q\sin\theta. \end{aligned} \tag{2}$$

Here (y, θ, φ) are polar coordinates on the (x_3, x_4, x_5) subspace, and $d\Omega_2^2$ is the line element on the unit two-sphere. Our solution may be more familiar as the magnetically-charged extreme dilaton black hole from four dimensions [15,16], raised to six dimensions by adding the flat x_1, x_2 directions, which are tangent to the membrane.

While the metric in (2) may appear singular at the core of the membrane, this is a coordinate artifact. In fact, the solution develops an infinitely long throat with a constant radius as $y \to 0$, as is most easily recognized with the coordinate transformation $\rho/Q = \log(y/Q)$. Then the fields near the core become

$$\begin{aligned} ds^2 &\simeq -dt^2 + dx_1^2 + dx_2^2 + d\rho^2 + Q^2\, d\Omega_2^2, \\ \Phi &\simeq -\rho/2Q, \\ F_{\theta\varphi} &= \sqrt{2} Q \sin\theta, \end{aligned} \tag{3}$$

The above description of the throat geometry is made using the heterotic string sigma-model metric, and hence this membrane is completely nonsingular for the heterotic string test-probes.

We will be interested in considering these solutions in the strong coupling regime in which the dual type IIA string theory is weakly coupled. Thus we will seek supersymmetric membrane solutions saturating a BPS bound, for which the mass-charge relations are preserved against higher-order corrections in the strong coupling regime [17]. Therefore, while any of the 24 heterotic gauge fields could be used in the construction of the solution (2), we restrict our attention to those constructed with one of the four gauge fields contained in the supergravity multiplet. This provides a supersymmetric embedding of (2) in the full six-dimensional $N = 2$ theory in which half of the spacetime supersymmetries are preserved [18]. Again, the importance of this feature lies in the resultant absence of quantum corrections due to the existence of nonrenormalization theorems [17]. Choosing the gauge field from one of the vector supermultiplets results in a membrane which breaks all of the spacetime supersymmetries.

In the context of the ten-dimensional heterotic string theory, the supersymmetric choice of gauge fields corresponds to setting $G_{i\mu} = B_{i\mu} = A_\mu$, where G and B denote the ten-dimensional metric and Kalb-Ramond field, respectively, with $\mu = 0,1,2,3,4,5$, a spacetime index and $i = 6,7,8$ *or* 9 corresponding to *one* of the directions compactified on the four-torus. It is interesting to note that with this embedding the compact x_i direction combines with the spatial two-sphere to form a Hopf fibration of the three-sphere [19]. The ten-dimensional throat solution is then: a constant radius three-sphere supported by the parallelizing torsion of the Kalb-Ramond field, a linear dilaton background in the ρ direction, and five flat spatial directions and a trivial time direction. This corresponds precisely to the throat limit [20] of the ten-dimensional neutral fivebrane solution [21,20], and so reveals that our membrane is in fact a fivebrane "warped" around the toroidally compactified directions[4].

Despite their spacetime supersymmetry, one might expect that the membrane solutions are modified by corrections of higher order in the world-sheet α' expansion since we are working within heterotic string theory. These modifications could jeopardize the nonsingular nature of the membrane core, a property which is central to our discussion. However, in this case the throat of the membrane core is described on the heterotic string world-sheet by an exact conformal field theory [24]. In fact, this conformal field theory corresponds to precisely that which describes the throat of the symmetric five-brane [20], *i.e.,* a supersymmetric $SU(2)$ Wess-Zumino-Witten model together with a linear dilaton in the radial direction. Thus the throat solution (3) is essentially unchanged, and one is guaranteed that no singularities develop at the membrane core. Thus despite the appearance of α' corrections, we are assured that the membrane is a stable soliton of the heterotic string theory[5]. We also expect that the background Killing spinors are perturbatively corrected so that spacetime supersymmetry also survives the α' corrections. This is certainly the case in the throat region where the exact conformal field theory description applies.

Now consider transforming the membrane soliton to the type IIA string theory via the "duality" mapping indicated in [2]:

$$\Phi' = -\Phi, \qquad G'_{\mu\nu} = e^{-2\Phi} G_{\mu\nu}, \qquad A'_\mu = A_\mu. \tag{4}$$

Here the (un)primed fields are those arising in the type IIA (heterotic) string theory. In particular, $G'_{\mu\nu}$ is the metric which couples to the type IIA string sigma-model. The type IIA action is then given by

$$S_{IIA} = \int d^6x \sqrt{-G'} \left[e^{-2\Phi'} \left(R' + 4(\partial\Phi')^2 \right) - \frac{1}{4} F'^2 \right], \tag{5}$$

[4] The solution is a "warped" as opposed to "wrapped" fivebrane [22,3]. The latter dimensionally reduces to an $a = \sqrt{3}$ black hole/H-monopole [23] in $D = 4$ as opposed to the $a = 1$ solution we started with in this paper. In our "warped" solution one of the compact directions is tied up in the three-sphere surrounding the fivebrane in a topologically nontrivial way.

[5] Note that for vacua with enhanced gauge symmetry, the leading order solution (2) can be elevated to an exact solution by the addition of an $SU(2)$ Yang-Mills vector and scalar at order α' [25]. In the context of the ten-dimensional theory, these new fields correspond to the appearance of a non-abelian gauge field which cancels the gravitational part of the α' corrections.

and the solution becomes

$$\begin{aligned} ds'^2 &= \left(1+\frac{Q}{y}\right)^{-1}\left(-dt^2+dx_1^2+dx_2^2\right)+\left(1+\frac{Q}{y}\right)\left(dy^2+y^2d\Omega_2^2\right), \\ e^{2\Phi'} &= \left(1+\frac{Q}{y}\right)^{-1}, \\ F'_{\theta\varphi} &= \sqrt{2}Q\sin\theta. \end{aligned} \tag{6}$$

In this frame the leading order solution becomes singular, requiring sources to support it at the core. First, the core, *i.e.,* $y=0$, is a finite proper distance away, and the curvature diverges there, *e.g.,* the Ricci scalar goes as $R\sim 1/(Qy)$. Thus from the point of view of type IIA string test probes, the membrane appears singular. Essentially with (4), we have made a singular conformal transformation of the original metric which implicitly adds an extra "point-at-infinity" closing off the end of the throat. To consistently solve the new equations of motion for (5), we must now include a source at this end-point, *i.e.,* $y=0$. Hence in the type IIA theory, the membrane must be interpreted as fundamental.

In summary, we began by constructing a nonsingular supersymmetric solution in the heterotic string theory, which represents a magnetically charged membrane. Because of the nonsingular nature of the solution, it appears that these field configurations must be included in defining the heterotic string theory. Mapped to the type IIA theory via (4), these solutions require a source so become singular suggesting that they should be interpreted as fundamental membranes within the type IIA theory[6].

It would be of interest to determine the world-volume action describing their dynamics of these membranes. The construction of this action would require an examination of the zero-modes for these solutions [22]. Since the membranes only break half of the spacetime supersymmetries, we know that the world-volume action will be supersymmetric. However, a simple counting of bosonic translational and fermionic supersymmetric degrees of freedom [26,10] indicates that these membranes will not have a conventional κ-symmetric world-volume action [27]. One can also consider the description of these membranes in the context

[6] It may be that the duality transformation (4) is incomplete, and that it is corrected at higher orders in the heterotic string loop or α' expansions. One might speculate then that these corrections could smooth out the singular membrane core without a source term in the type IIA theory, which would then remain a theory of only fundamental strings by returning us to case (ii) above. If this scenario was realized, it would ruin the exchange of fundamental and solitonic strings between these two theories, as well. In any event, we find this an unlikely possibility.

of the ten-dimensional type IIA theory where they become six-branes. We were guided by supersymmetry to choose the gauge field as one of the four vectors in the supergravity multiplet. From the point of view of the ten-dimensional type IIA theory, three of these fields are associated with three-form potentials which are anti-self-dual harmonic forms on the internal $K3$ space, while the last is a linear combination of the fundamental vector and the dual of the spacetime three-form potential[7]. The membranes corresponding to the first three fields are then "up-lifted" to anisotropic six-branes with magnetic four-form charge – note that the antiselfdual form on K3 are not localized [28]. The last membrane is raised to an anisotropic six-brane carrying both conventional magnetic charge, and electric four-form charge. Again these branes in the ten-dimensional theory will not have a conventional Green-Schwarz world-volume action [26,10]. Determining the correct world-volume action would also provide an important consistency check for our analysis. Given this action, one could verify that the membrane solutions are also singular for the membrane's sigma-model metric, *i.e.,* from the point of view of membrane test-probes – note that given the previous discussion, we know this metric is *not* that determined by the usual scaling arguments [10]. Similarly the fundamental type IIA string solution should be singular from the membrane viewpoint. Both of these results are necessary for a consistent interpretation of the membranes as fundamental objects.

Given that not much is known about the quantization of p-branes for $p \geq 2$, we may still consider various scenarios by which these fundamental membranes (and possibly other objects) would be incorporated in the type IIA theory. The complete type IIA theory might be described by one of (at least) three alternatives:

An egalitarian theory of branes:– In this the simplest alternative, the full type IIA theory is a theory which contains (at least) two distinct fundamental objects, strings and membranes. First quantization would be separately applied for each brane with its distinct world-volume action. A second step would be to incorporate interactions between the different branes in this first quantized framework. Presumably in this theory, the

[7] In passing we add the following observations: Within the heterotic string theory, the four vectors are indistinguishable being interchanged by a discrete $O(20,4;\mathbf{Z})$ transformation. This permutation symmetry is obvious from the point of view of their embedding in the ten-dimensional heterotic string theory. The type IIA theory inherits this permutation symmetry since the equivalence of the two string theories dictates that $O(20,4;\mathbf{Z})$ remains an exact symmetry. However in the latter case, $O(20,4;\mathbf{Z})$ is permuting fields which know about the K3 space with others that do not.

membranes would not contribute to the massless spectrum at a generic point in the (known) vacuum moduli space, since the latter spectrum is fully accounted for by type IIA strings. In this case, the membranes would play no role in the low energy physics, but would be important for a consistent definition of the theory at the level of massive modes and through nonperturbative effects [11]. Such a egalitarian description the type IIA theory was advocated in [29], where in fact on the basis of U-duality the democracy was extended to all p-branes appearing in the low energy theory.

A theory of only higher branes:– In this second scenario, the true type IIA theory would actually be a theory of only membranes (or some higher p-branes). The fundamental strings would then be "string-like" excitations of the membrane. A similar scenario has already been conjectured for the heterotic string. There, certain supersymmetric electrically charged extremal black holes appear as singular point-like objects, but may be identified with states in the fundamental string spectrum [30,14]. In order for this alternative to be consistent in the present case, the membranes must also be able to act as sources for the Kalb-Ramond fields that are associated with the fundamental type IIA string. This requirement could be confirmed by examining the zero-mode structure of these solutions. Further, a much more stringent constraint is that consistently quantizing the fundamental membranes must reproduce precisely the same massless spectrum as the type IIA string in this $K3$ context. A higher brane description of the type IIA theory was advocated in [31] with the suggestion that the correct fundamental theory was an eleven-dimensional supermembrane theory.

Something else:– On this alternative, of course, we have the least to say. However we note that past efforts at quantizing higher p-branes have met with no success. Further even if a free-first quantized theory was constructed, the introduction of interactions for higher p-branes would remain a significant challenge. These technical obstructions lend favor to the opinion that only one-branes or strings should be treated as fundamental. The present analysis, which indicates that the type IIA theory must incorporate fundamental membranes, may then be an indication that the correct fundamental description of the theory is simply not one based on the first quantization of extended objects.

We expect that other solitonic p-brane solutions arising in various string theories will also become fundamental in the dual strong coupling theories. Indeed, another example is the solitonic fivebrane in $SO(32)$ heterotic string theory, which seems to satisfy all of the necessary criteria of spacetime supersymmetry and no core singularity as well as becoming singular for the type I strings [32], which is conjectured to be the dual strong coupling theory in ten dimensions.

In these examples, it is the strong coupling heterotic string that is replaced by a weak coupling theory that includes fundamental p-branes. An interesting question is then if the heterotic string theory stands as a complete perturbative theory of only fundamental strings[8]. Clearly further investigations of p-branes and searches for new solutions are required to determine the existence of p-brane solitons in *e.g.,* the weakly coupled IIA theory which become fundamental in the context of heterotic strings.

However, combining the evidence connecting all of the critical superstring theories in diverse dimensions and coupling regimes [2], the non–perturbative results in which p-brane solitons and instantons are indispensable [11,33], and our present results indicating the inclusion of fundamental membranes in the type IIA theory, it is perhaps not premature to respond to the question "Is string theory a theory of strings?" with the intriguing answer: No!

Note Added:

After this paper was submitted for publication, we computed how the mass per unit area of the membrane solutions scale with the string coupling constants of each theory, and found the following result:

$$\mu \sim \frac{1}{(\alpha'_{het})^{3/2}\lambda^2_{het}} \sim \frac{1}{(\alpha'_{II})^{3/2}\lambda_{II}} \quad ,$$

where μ is the ADM mass per unit area while λ and α' are the coupling constants and inverse string tensions for the respective theories indicated by the subscript. (The compactification volume is measured in units of the corresponding α'.) The essential point to understanding the consistency of these results is recognizing that varying λ_{het} with fixed α'_{het} is not the same as varying λ_{II} with fixed α'_{II} – *i.e.,* $\alpha'_{het}\lambda_{het} = \alpha'_{II}\lambda_{II}$. (This result is also consistent with the D–brane picture presented in the recent paper of Polchinski and Witten[34].) Although from the mass scaling in the type IIA theory it may appear that the solution is solitonic instead of fundamental, we note that a source term is still required for the membrane to be a solution of the equations, suggesting that the theory still needs

[8] We note that a complementary analysis [29] seems to indicate that the answer is affirmative.

to be supplemented by a new membrane–like object. Further discussion of these results will appear in a later publication in which we will examine the membranes in more detail.

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