Brane Decay and an Initial Spacelike Singularity

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We present a novel string theory scenario where matter in a spacetime originates from a decaying brane at the origin of time. The decay could be considered as a big-bang-like event at $X^0 = 0$. The closed string interpretation is a time-dependent spacetime with a semi-infinite time direction, with the initial energy of the brane converted into energy flux from the origin. The open string interpretation can be viewed as a string theoretic nonsingular initial condition.

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Introduction.—Perhaps the most ambitious problem in cosmology is the question of the initial conditions of the Universe. In this Letter we present a completely new scenario: the decay of an unstable brane beginning from the origin of the spacetime. Various proposals for initial conditions have been formulated in different frameworks (see [1] for a recent discussion). The most famous is the no-boundary proposal, where an expanding universe emerges from an instanton in the Euclidean geometry, thus removing the boundary from the spacetime manifold [2]. Alternatively, it has been speculated that a preceding long pre-big-bang phase [3] ended in a big crunch, with the Universe reemerging into a big bang. It has been hoped that this so-called big bounce could be reliably described, once the true quantum gravitational effects would be properly understood, perhaps in the context of string theory. This proposal then motivated a variant [4] where the big bounce was attributed to a collision of branes moving in a higher dimensional space, either as a singular event or in repeated cycles. The associated spacetimes were modeled in string theory as Lorentzian boost orbifolds, but as of yet it is still an open question whether a detailed understanding of the associated stringy effects [5] could lend support to the bounce idea.

A related development is the anti–de Sitter/conformal field theory (AdS/CFT) duality, or more generally the open-closed duality of string theory. Based on models of stacks of stable D-branes, one can establish a duality between the open string theory on the brane and closed string theory in a higher dimensional "bulk" spacetime. In the bulk spacetime, the additional spacelike direction can be related to renormalization group flow in the lower dimensional effective field theory of open strings on the brane. The branes in question have a timelike world volume. It was hoped that one could develop analogous models by replacing the timelike branes with spacelike branes [6]; the open string physics on the brane would give rise to a time direction, so that the dual closed string interpretation would be string theory in a higher dimensional time-dependent spacetime.

Natural candidates for the spacelike branes are unstable D-branes or D-brane–anti-D-brane configurations. The decay of these brane configurations can be modeled in open string theory in different ways, e.g., as conformal field theory of the open string world sheet. In this case, the brane decay can be modeled by a rolling tachyonic background [7] introduced into the action as an exactly marginal boundary deformation. On the other hand, for the dual spacetime interpretation one needs to find time-dependent (S-brane) solutions of supergravity which are sourced by the associated unstable D-brane configuration. This program is hampered by several technical difficulties on both sides: it is difficult to construct generic exactly marginal tachyonic deformations, and few examples of S-brane spacetimes are known. Furthermore, string dynamics in such backgrounds is technically very involved, obscuring the problem of identifying interesting scaling limits for simplified dualities.

The prototype scenarios for brane decay come in two basic variants. In the first [7], the brane decay has a finite time origin, but the decay phase is preceded by a buildup phase, where the unstable brane is first created by a carefully fine-tuned closed string initial state. In fact, the whole creation-and-decay process is completely time reflection symmetric. In the second variant [8], the decay starts at past infinity and continues through all time until future infinity. The first variant has the virtue that the time scale of the decay is a tunable parameter and the decay has a finite origin. But this is achieved at the expense of a highly fine-tuned creation phase. Alternatively, a prescription for brane nucleation in an empty spacetime has been proposed in [9]. The second variant has the virtue of only having decay, but the downside is not having a finite initial time and no tunable time scale.

We now propose a new model where the brane decay starts from a finite time origin, has a tunable time scale for the decay, and no creation phase. This opens up exciting possibilities for scenarios where the unstable brane on one hand provides initial conditions which can be phrased in terms of open strings on the brane and on the other hand has a dual interpretation of a time-dependent spacetime with a finite origin of time. The details have some flavor of the no-boundary proposal in that they involve physics in the complex time plane, some flavor of the pre-big-bang idea, and some flavor of Lorentzian string orbifold models, the AdS/CFT duality and perhaps even holography. This Letter presents the main features of our model; a more detailed discussion will follow in [10]. Let us note for clarity that we do not claim to be addressing detailed questions of post-big-bang cosmology, such as inflation.

As this Letter was prepared, other new ideas about cosmological singularities were reported in [11].

The model.—We begin by recalling the basic pre-big-bang idea: to resolve the initial singularity to extend the past history of the Universe, as sketched in Fig. 1(a).

The concept of "time" breaks down at the big-bang singularity. In big crunch/big bang scenarios one hopes to continue time's arrow across, by a resolution mechanism [12]. However, one can ask if time's arrow could be taken to point in multiple directions from the big bang. We could imagine several universes being created, such as is suggested by Fig. 1(b). It might be that this allows for a different kind of resolution of the initial singularity. An additional ingredient which can be added to such considerations is CPT. One could postulate that the two universes are simply CPT reflections of one another. Then it would be possible to identify them under the CPT reflection. An analogous proposal has been made before in the elliptic interpretation of the de Sitter space [13].

Consider then the two main models for brane decay; for simplicity, we focus on D-branes in bosonic string theory. The first variant, mentioned above, is the full S-brane, associated in the boundary CFT of the open string world sheet with the spatially homogenous tachyonic deformation

$$T(X^0) = \lambda \cosh(X^0/\sqrt{\alpha'}), \tag{1}$$

where the parameter $0 \leq \lambda \leq \frac{1}{2}$ controls the lifetime of the brane: the brane exists for a finite time of the order

$$\Delta X^0 \approx 2 \ln[\sin(\pi\lambda)]. \tag{2}$$

The decay starts at $X^0 = 0$ and is preceded by a formation phase, where the brane forms out of a carefully fine-tuned initial closed string configuration, which can be mapped to the final state by time reversal. The situation is analogous to building a bomb by reversing its explosion. From the target space point of view, this appears unnatural. It is possible to isolate the decay phase by considering instead a deformation $T(X^0) = \lambda e^{X^0}$, corresponding to the second variant, the half-S-brane. Now the parameter λ has no physical meaning as it can be absorbed into a shift of the origin of the time coordinate.

The full S-brane in Lorentzian spacetime is related by a Wick rotation $X^0 \to iX$ to an infinite periodic array of smeared D-branes in Euclidean space. The tachyonic deformation becomes periodic $\lambda \int_{\partial\Sigma} \cos(X/\sqrt{\alpha'})$ and alters the boundary conditions at the end point of the open string. Increasing λ from initial value 0 to a final value $1/2$ smoothly deforms the open string boundary conditions from Neumann to Dirichlet, so that the open strings become attached to a periodic array of D-branes localized at $X = 2\pi n\sqrt{\alpha'}$, with $n \in Z$. Conversely, as λ is decreased from $1/2$, the branes are smeared over the spacelike direction transverse to the branes. Wick rotating back to the original Lorentzian direction, the smearing corresponds to slowing down the decay, with the lifetime ΔX^0 related to the smearing of the branes. Reference [14] proposed that generic, suitably symmetric, D-brane configurations in the complexified time plane correspond to time-dependent closed string backgrounds. The D-brane configurations act as sources for the spacetime fields and backreact to the geometry. It is of great interest to find spacetime solutions which are sourced by the brane arrays. Additional discussion and some example solutions can be found, e.g., in [15].

Let us now return to the spacetimes of Fig. 1 with the origin of time X^0 at the big bang. Could one consider brane decay in such backgrounds? In the case of (a), if the crunch and the bang are time reverses of each other, one could attempt to construct a full S-brane centered at the big bang. However, the spatial slices pass through zero size, and one would need to take this into account. For example, if the spacetime is modeled as a Misner space, one could attempt to construct a full brane solution where the tachyon rolls with respect to the Misner time rather than with respect to the Minkowski time. In the case of (b), if the two branches of the spacetime emanating from X^0 are mapped to each other under T reversal, it should again be possible to introduce the full S-brane. But now there is an additional complication because the spacetime is not globally time orientable. Let us simplify the problem by not requiring that the spatial sections undergo expansion. As a simple toy model, one can consider the Lorentzian orbifold $R^{1,d}/Z_2 \times M_D$, where Z_2 acts as a (C)PT reflection

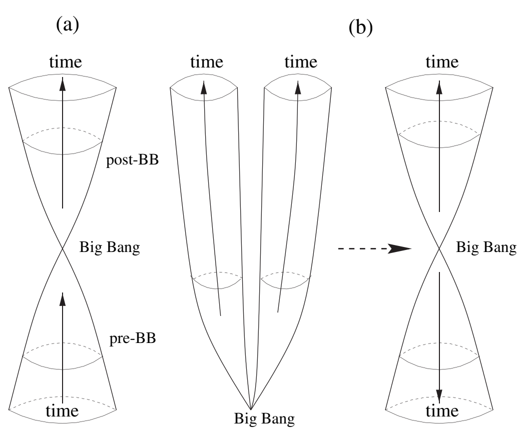

FIG. 1. (a) The pre-big-bang (BB) scenario and (b) the creation of two universes from the big bang, which is interpreted as a spacetime Z_2 orbifold.

$$(X^0, X^1, \ldots, X^d) \to (-X^0, -X^1, \ldots, -X^d) \quad (3)$$

in $R^{1,d}$, and M_D is a Euclidean space of dimension $D = 25 - d$ (this would be replaced by $9 - d$ in the superstring). *A priori*, $0 \le d \le 25$. This orbifold has been investigated in [16,17] in bosonic string and type II superstring theories. The quantization of untwisted and twisted sectors is straightforward. It was found that ghosts are absent at tree level. In supersymmetric theory, the partition function vanishes just as in the corresponding Euclidean orbifold. There are no closed causal curves after the proper definition of the time function on the fundamental domain. The covering space is then a Minkowski space, except that the time's arrow points in opposite directions on the two half-spaces, as in Fig. 1(b). (If $d > 0$, the spatial slice at $X^0 = 0$ is reduced in half due to the P reflection). Moreover, there is no dangerous backreaction as the stress tensor vanishes everywhere after the big-bang initial slice.

Since the tachyonic deformation on the open string world sheet is symmetric with respect to the time reversal, the full brane survives the orbifold Z_2 identification. Consider the closed string boundary state description of the full brane. The starting point of the boundary state construction is the Wick rotation to the Euclidean signature. The boundary state $|B\rangle$ can be written in terms of the underlying $SU(2)_L \times SU(2)_R$ symmetry with the generators $J^{\pm} = e^{\pm iX/\sqrt{\alpha'}}$; $J^3 = i\partial X$, as a linear combination of Ishibashi states $|j, m, n\rangle\rangle$ labeled by the $SU(2)$ quantum numbers. The Z_2 reflection $X \mapsto -X$ acts on the $SU(2)$ generators by

$$J^{\pm} \to J^{\mp}; \qquad J^3 \to -J^3. \quad (4)$$

The boundary state is symmetric with respect to interchanging m, $-m$, so it is invariant under (4). The same will be true after the inverse Wick rotation back to Lorentzian signature. But there is an important subtlety involved, first discussed in [16]. When the boundary state $|B\rangle$ is expressed in the standard oscillator and momentum basis, it is a linear superposition of on-shell closed string states $|\psi_i, k_i\rangle$ with $k_i^2 = -M_i^2$. But, after the inverse Wick rotation, the Z_2 reflection acts in time, so it also acts on center-of-mass energy as $k^0 \mapsto -k^0$. Therefore, the on-shell states $|\psi_i, k_i\rangle$ in the sum must be doubled to reflect the symmetry of the choice of branch $k^0 = \pm\omega_{\vec{k}}$:

$$|\psi_i, k_{iE}\rangle \mapsto \begin{pmatrix} |\psi_i, k_i^0, \vec{k}_i\rangle \\ |\psi_i, -k_i^0, -\vec{k}_i\rangle \end{pmatrix}. \quad (5)$$

For more discussion, see [10,16].

The physical interpretation of the resulting boundary state is different from that of the standard full S-brane. Rather than corresponding to formation and decay of an unstable brane, it corresponds to a brane decaying into closed strings propagating in opposite directions in the covering space, as depicted in Fig. 2 (X^0, $\tilde{X}^0 > 0$ coordinatize the two sheets).

On the fundamental domain (corresponding to the upper half space), we then obtain a brane at the origin of time, decaying into closed string states. Reference [9] proposed a contour integration prescription (essentially specifying a Fourier transform) for the computation of particle production from the decaying brane. We can use the same prescription here on the fundamental domain. On the covering space, it corresponds to a double contour, with branches approaching the origin along the imaginary time axes of X^0, $\tilde{X}^0$ and then proceeding along the real time axis into the opposite X^0, $\tilde{X}^0 > 0$ directions. The physical interpretation is otherwise the same as in [9], except that now there is no spacetime before $X^0 = \tilde{X}^0 = 0$—the nucleation of the brane can truly be viewed as a big-bang-like event. The average total number density and total energy density of the emitted closed strings can be calculated in a similar manner as in [9], with similar results [10].

If all the closed strings in the spacetime originate from the brane decay, the latter would then serve as an initial condition. However, the spacetime is the covering space of an orbifold, so it contains twisted sector strings as well. How would they be connected with the decaying brane? In other words, what is their role in the initial condition proposal—can the twisted strings also be associated with a decaying brane?

It turns out that on the spacetime orbifold there is another class of S-branes or decaying branes to consider. We call these *fractional S-branes*. They are constructed as follows. Start again by the Wick rotation $X^0 \mapsto iX$ to Euclidean signature. One obtains an array of D-branes at $X = 2\pi n\sqrt{\alpha'}$ by setting $\lambda = 1/2$. The boundary state of the decaying brane is usually constructed by first compactifying X at self-dual radius, $X \sim X + 2\pi\sqrt{\alpha'}$, in which case the deformation acts as an $SU(2)$ rotation, and finally a projection back to infinite radius is performed to obtain the boundary state. Now consider the Z_2 orbifold identification where Z_2 acts by $X \mapsto -X$. Then $X = 0$ becomes an orbifold fixed point. In the array of D-branes at $X = 2\pi n\sqrt{\alpha'}$, the brane at $X = 0$ may be replaced by a fractional D-brane. If we compactify at self-dual radius as before, after the Z_2 identification to S^1/Z_2, there are two

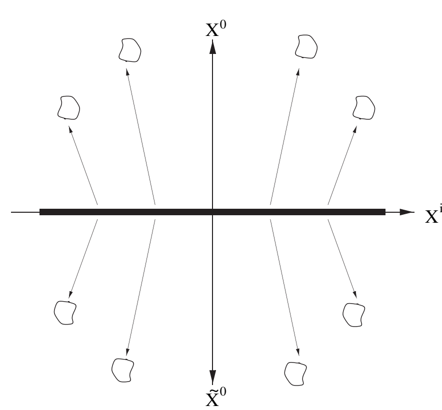

FIG. 2. Brane decay on the orbifold covering space.

fixed points, at $X = 0$ and $X = \pi\sqrt{\alpha'}$. Reference [18] studied the conformal field theory of a free boson on this orbifold and found that there are 8 fractional boundary states at the fixed points $X_0 = 0, \pi\sqrt{\alpha'}$, where the Dirichlet or Neumann untwisted sector boundary states are combined with twisted sector boundary states. Extending and elaborating a previous analysis in [19], we have shown how the tachyonic deformation interpolates through the 8 fractional boundary states as λ is varied. It is notable that the process has a dual description in terms of a free boson on a circle—without orbifold singularities—where it corresponds to moving an ordinary D-brane around the circle. We have also constructed a projection back to the infinite radius.

We have also considered a more straightforward approach, starting with the open string action with tachyonic deformations at the opposite end points,

$$\delta S = -\lambda \int_{\partial_1 \Sigma} \cos(X/\sqrt{\alpha'}) - \tilde{\lambda} \int_{\partial_2 \Sigma} \cos(X/\sqrt{\alpha'}),$$

and computed the annulus partition function with the Z_2 reflection, using the fermionization technique of [20]. After reinterpreting this in closed string variables, the result factorizes into a form corresponding to closed string propagation between two deformed boundary states. The result is in agreement with the construction starting from the self-dual radius. Details will appear in [10].

Discussion.—We have considered S-branes on a spacetime orbifold and shown that this leads to a new class of S-branes that we have called fractional S-branes. Our construction is a toy model for the initial singularity of a spacetime where a (fractional) S-brane may be thought of as the stringy initial state at the origin of time (note that we have *not* discussed any notion of assigning a relative probability to any one such configuration).

There are several interesting directions for further study and potential applications. A space-filling brane decaying homogeneously may be thought of as corresponding to homogeneous initial conditions. Customarily, homogeneity in brane cosmological models is obtained by a collision of two branes which must be initially aligned to be parallel, amounting to a careful fine-tuning. In our proposal there is only a single brane. Note that the homogeneous decay is the simplest case (being described by a simple exactly marginal boundary deformation in string theory), but should not be taken as a prediction. As the mathematical tools and general understanding of the properties of S-branes and associated spacetime solutions develop, we expect our construction to be one step towards big-bang cosmological toy models where a decaying brane at the finite origin of time leads to a holographic interpretation of the spacetime that is created.

It would also be interesting to investigate our proposal in the context of string/brane gas cosmology [21]. Instead of a space-filling infinite brane, one could start with all the spacelike dimensions being compact. Initially the brane decay produces massive (nonwinding and winding) closed strings which cascade to lighter modes, interact, and presumably thermalize in the end. The total energy of the system is the initial mass of the unstable brane. The brane decay might be used to "explain" the origin of the hot string gas which drives the expansion of some of the compact directions.

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