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Eternally inflating cosmologies from intersecting spacelike branes

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Abstract

Intersecting spacelike braneworld cosmologies are investigated. The time axis is set on the scale parameter of extra space, which may include more than one timelike metric. Obtained are eternally inflating (i.e. undergoing late-time inflation) Robertson-Walker spacetime and extra space with a constant scale factor. In the case of multibrane solutions, some dimensions are static or shrink. The fact that the largest supersymmetry algebra contains 32 supercharges in 4 dimensions imposes a restriction on the geometry of extra space.

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keywords: Spacelike braneworld, Accelerating cosmologies

1 Introduction

The first observational evidence that the present universe is still inflating (late-time inflation) was shown by Riess *et al.* [1] and Perlmutter *et al.* [2], separately. Later observations [3, 4, 5, 6] supported this claim.

If the cosmological constant is equal to zero or absorbed into ρ and P , then the condition for inflation can be written as

$$\rho + 3P < 0,$$

where ρ is the energy density of the universe and P is its pressure. Because the left-hand side of this equation is always positive for ordinary

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matter, radiation and dark matter, the existence of dark energy is regarded as indispensable in accounting for late-time inflation. Although we have yet to unmask dark energy, some potential candidates, such as the cosmological constant and quintessence, have been proposed. If we define the ratio of P to ρ as

$$w \equiv \frac{P}{\rho},$$

then $w = -1$, if the cosmological constant is identified as dark energy. On the other hand, w usually fluctuates if quintessence assumptions are adopted. Recent observations [5, 6, 7, 8] support the former candidate. If the cosmological constant is the only source of late-time inflation, it will be a very small positive value, but not zero. Although the cosmological constant can be chosen arbitrarily within the limits of general relativity, it should be zero if general relativity is to be regarded as a low-energy effective theory of M-theory/superstring theory.

Many models of cosmological inflation have been posited based on M-theory/superstring theory. However, one no-go theorem [9] suggests that 4-dimensional de Sitter spacetime could not be realized by the ordinary compactification methods available under M-theory/superstring theory. One way to overcome this problem [10] would be to put S-branes, which are time-dependent spacelike branes, into the model [11, 12, 13, 14, 15]. As D p -branes are objects which extend in p space dimensions and a time dimension, S q -branes extend in $(q + 1)$ space dimensions in ordinary notation. It is known that accelerating S-brane solutions exist and that eternal inflation is possible if both internal and external spaces are hyperbolic [16, 17]. Higher-order quantum corrections have been added to the action, and solutions which include exponentially expanding braneworld and static extra space have been found numerically [18, 19]. In a recent paper [20], we pointed out the existence of singular single-brane solutions to Einstein gravity coupled to a dilaton and an n -field. One of these analytic solutions includes a 4-dimensional exponentially expanding Robertson-Walker spacetime consisting of an SM2-brane and a time axis, and an extra hyperbolic space H^{D-p-2} with a constant scale factor.

In this paper, our starting point is Einstein gravity coupled to a dilaton and one or some n -form fields, which yield multibrane solutions, as a low-energy effective theory of M-theory/superstring theory. In order to obtain singular solutions, we set the time axis on the scale parameter of extra space, which may include more than one timelike metric, in contrast to our previous paper, in which only one timelike

metric was considered. We obtain eternally inflating (i.e. undergoing late-time inflation) Robertson-Walker spacetime and extra space with a constant scale factor. With multibrane solutions, some dimensions are static or shrink. The required intersection rule is shown to be the same as that suggested for regular solutions in other papers [21, 22, 23, 24]. The last section is devoted to an examination of these solutions in relation to the real Universe. The fact that the largest supersymmetry algebra contains 32 supercharges in 4 dimensions imposes a restriction on the geometry of extra space.

2 Intersecting S-brane solution

We consider Einstein gravity coupled to a dilaton field ϕ and m kinds of n -form fields F_n as a low-energy effective theory of M-theory/superstring theory, whose action I is

$$I = \frac{1}{16\pi G} \int d^D x \sqrt{\pm g} \left[R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \sum_{A=1}^m \frac{1}{2 \cdot n_A!} e^{\alpha_A \phi} F_{n_A}^2 \right], \quad (1)$$

where the sign in front of g should be selected as appropriate. α_A is the dilaton coupling constant given by

$$\alpha_A = \begin{cases} 0 & (\text{M - theory}) \\ -1 & (\text{NS - NS sector}) \\ \frac{5-n_A}{2} & (\text{R - R sector}), \end{cases}$$

and the bare cosmological constant is assumed to be zero. $D=11$ for M-theory and $D=10$ for superstring theories.

We assume the following metric form:

$$ds^2 = \sum_{i=1}^{p+1} e^{2u_i} dx^i dx^i + \sum_{a,b=p+2}^D e^{2v} \eta_{ab} dy^a dy^b, \quad (2)$$

where

$$\eta_{ab} = \{ \text{diag.} (\underbrace{+, \dots, +}_{D-p-1-s}, \underbrace{-, \dots, -}_s) \}. \quad (3)$$

We use x^i , $i = 1, \dots$, and $p+1$ as the coordinates of the space where the branes exist. A recent study has posited singular single-brane solutions for the case where only one minus sign is to be included in the metric [20]. General orthogonally intersecting solutions where the metric functions u and v and fields ϕ and F depend only on one timelike coordinate have also been proposed [23]. A D-brane solution

which depends on all the extra space coordinates has been suggested [24].

We assume that the metrics and fields do not depend only on the timelike coordinates y^a , $a = D - s + 1, \dots$, and D , but also on the other perpendicular coordinates y^a , $a = p + 2, \dots$, and $D - s$. That is to say,

$$\begin{aligned} u &= u(y) \equiv u(y^{p+2}, \dots, y^D), \\ v &= v(y) \equiv v(y^{p+2}, \dots, y^D), \\ \phi &= \phi(y) \equiv \phi(y^{p+2}, \dots, y^D), \\ F &= F(y) \equiv F(y^{p+2}, \dots, y^D). \end{aligned}$$

The field strength for an electrically charged S_p -brane is given by

$$(F_n)_{i_1 \dots i_{n-1} a}(y) = \epsilon_{i_1 \dots i_{n-1}} \partial_a E(y), \quad (4)$$

where

$$n = q + 2.$$

The magnetically charged case is given by

$$(F_n)^{a_1 \dots a_n} = \frac{1}{\sqrt{\pm g}} e^{-\alpha \phi} \epsilon^{a_1 \dots a_n b} \partial_b E(y), \quad (5)$$

where

$$n = D - q - 2.$$

The field equations are

$$\begin{aligned} & -\partial^2 u_i - (\partial u_i) \left\{ \sum_{k=1}^{p+1} (\partial u_k) + (D - p - 3)(\partial v) \right\} \\ &= \sum_{A=1}^m \frac{\delta_{A,i}}{2(D-2)} e^{\epsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} (\partial E_A)^2, \end{aligned} \quad (6)$$

$$\begin{aligned} & \eta_{ab} \left[-\partial^2 v - (\partial v) \left\{ (D - p - 3)(\partial v) + \sum_{k=1}^{p+1} (\partial u_k) \right\} \right] - \sum_{k=1}^{p+1} \partial_a u_k \partial_b u_k \\ & - \partial_a \partial_b \left[(D - p - 3)v + \sum_{k=1}^{p+1} u_k \right] - (D - p - 3) \partial_a v \partial_b v \\ & + \partial_a v \left[(D - p - 3) \partial_b v + \sum_{k=1}^{p+1} \partial_b u_k \right] + (a \leftrightarrow b) \\ &= \sum_{A=1}^m \frac{1}{2} e^{\epsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} \left[\partial_a E_A \partial_b E_A - \frac{q_A + 1}{D - 2} \eta_{ab} (\partial E_A)^2 \right] \\ & + \frac{1}{2} \partial_a \phi \partial_b \phi, \end{aligned} \quad (7)$$

$$\begin{aligned}
& \partial_a \left[e^{\sum_{k=1}^{p+1} u_k + (D-p-3)v} \eta^{ab} \partial_b \phi \right] \\
= & \sum_{A=1}^m \frac{\varepsilon_A \alpha_A}{2} e^{\varepsilon_A \alpha_A \phi - \sum_{k \in q_A} u_k + \sum_{j \notin q_A} u_j + (D-p-3)v} (\partial E_A)^2, \quad (8)
\end{aligned}$$

$$\partial_a \left[e^{\varepsilon_A \alpha_A \phi - \sum_{k \in q_A} u_k + \sum_{j \notin q_A} u_j + (D-p-3)v} \eta^{ab} \partial_b E_A \right] = 0, \quad (9)$$

and the Bianchi identity is

$$\partial_{[a} F_{\dots]} = 0. \quad (10)$$

In these equations, we have introduced notations defined as

$$\begin{aligned}
& \eta^{ab} \eta_{bc} = \delta_c^a \\
& \partial^2 \equiv \eta^{ab} \partial_a \partial_b, \\
& (\partial f)(\partial g) \equiv \eta^{ab} (\partial_a f)(\partial_b g) \\
\varepsilon_A = & \begin{cases} +1 & (F_{n_A} \text{ is an electric field strength}) \\ -1 & (F_{n_A} \text{ is a magnetic field strength}) \end{cases} \\
\delta_{A,i} = & \begin{cases} D - q_A - 3 & (i \in q_A) \\ -(q_A + 1) & (i \notin q_A). \end{cases}
\end{aligned}$$

To simplify the calculation, we assume

$$\sum_{k=1}^{p+1} u_k(y) + (D-p-3)v(y) = 0. \quad (11)$$

Then, the above field equations and the Bianchi identity become

$$-\partial^2 u_i = \sum_{A=1}^m \frac{\delta_{A,i}}{2(D-2)} e^{\varepsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} (\partial E_A)^2, \quad (12)$$

$$\begin{aligned}
& -\eta_{ab} \partial^2 v - \sum_{k=1}^{p+1} \partial_a u_k \partial_b u_k - (D-p-3) \partial_a v \partial_b v \\
= & \sum_{A=1}^m \frac{1}{2} e^{\varepsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} \left[\partial_a E_A \partial_b E_A - \frac{q_A + 1}{D-2} \eta_{ab} (\partial E_A)^2 \right] \\
& + \frac{1}{2} \partial_a \phi \partial_b \phi, \quad (13)
\end{aligned}$$

$$\partial^2 \phi = \frac{\varepsilon_A \alpha_A}{2} e^{\varepsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} (\partial E_A)^2, \quad (14)$$

$$\partial_a \left[e^{\varepsilon_A \alpha_A \phi - 2 \sum_{k \in q_A} u_k} \eta^{ab} \partial_b E_A \right] = 0. \quad (15)$$

The Bianchi identity (10) is trivially satisfied in the electric case, as is the field equation (9) in the magnetic case.

We write candidates for the solution of the above equations (12) ~ (15) which satisfy assumption (11) as

$$E_A(y) = iH_A(y), \quad (16)$$

$$u_i(y) = \sum_{A=1}^m \frac{\delta_{A,i}}{2(D-2)} \ln H_A(y), \quad (17)$$

$$v(y) = \sum_{A=1}^m \frac{-(q_A + 1)}{2(D-2)} \ln H_A(y), \quad (18)$$

$$\phi(y) = \sum_{A=1}^m \frac{-\varepsilon_A \alpha_A}{2} \ln H_A(y), \quad (19)$$

where

$$H_A(y) \equiv \frac{Q_A}{h(y)}, \quad (20)$$

with Q_A as a constant.

Substituting (16) ~ (21) into (12) ~ (15), we find sufficient conditions

$$\partial^2 h(y) = 0 \quad (21)$$

and

$$-\varepsilon_A \varepsilon_B \alpha_A \alpha_B - 2(\bar{q} + 1) + \frac{2(q_A + 1)(q_B + 1)}{D - 2} = 0, \quad (22)$$

where $\bar{q} + 1$ represents dimensions on which q_A -brane and q_B -brane cross. (22) is the intersection rule, which has already been suggested for regular solutions in other papers [21, 22, 23, 24].

3 Eternally inflating braneworld

Now, consider a metric which depends only on the scale parameter r of either the entire, or a part of, the spacetime perpendicular to the brane:

$$r \equiv \sqrt{-\eta_{ab} y^a y^b}, \quad -\eta_{ab} y^a y^b > 0. \quad (23)$$

Note that r is a timelike coordinate. To satisfy (21),

$$h = r^{-(D-p-3)}. \quad (24)$$

Then, the metric of this spacetime is

$$ds^2 = \sum_{i=1}^{p+1} e^{2u_i} dx^i dx^i - e^{2v} (dr^2 - r^2 d\Sigma_{D-p-2}^2), \quad (25)$$

where $d\Sigma_{D-p-2}$ is the line element of a hypersurface with a unit scale factor. If $s = 1$ in (3), this hypersurface is a $(D-p-2)$ -dimensional hyperbolic space H^{D-p-2} with a unit scale factor. Meanwhile, it becomes a $(D-p-2)$ -dimensional unit *timelike* spherical surface $-S^{D-p-2}$ if $s = D-p-1$.

We define cosmic time t as

$$\begin{aligned} dt &\equiv e^v dr \\ &= C r^{(D-p-3)} \sum \frac{-(q_A+1)}{2(D-2)} dr, \end{aligned} \quad (26)$$

where

$$C = \prod_{A=1}^m Q_A^{\frac{-(q_A+1)}{2(D-2)}}. \quad (27)$$

It is most interesting that the case

$$(D-p-3) \sum_{A=1}^m \frac{(q_A+1)}{2(D-2)} = 1 \quad (28)$$

is satisfied. In this case, as

$$t = C \ln r, \quad (29)$$

and

$$e^{2v} = C^2 r^{-2}, \quad (30)$$

the metric (25) becomes

$$ds^2 = -dt^2 + \sum_{i=1}^{p+1} e^{2u_i} dx^i dx^i + C^2 d\Sigma_{D-p-2}^2. \quad (31)$$

Note that the scale factor of the extra space is independent of t in this metric. On the other hand, because

$$e^{2u_i} = \left(\prod_{A=1}^m Q_A^{\frac{\delta_{A,i}}{D-2}} \right) e^{\frac{D-p-3}{C(D-2)} \sum_A \delta_{A,i} t}, \quad (32)$$

the i -th dimension exponentially expands if $\sum_A \delta_{A,i}$ is positive, is static if $\sum_A \delta_{A,i} = 0$, or shrinks if $\sum_A \delta_{A,i}$ is negative.

The solutions satisfying the above condition (28) are given in the tables in Subsections 3.1, 3.2 and 3.3 for M-theory, IIA superstring theory and IIB superstring theory, respectively. In these tables, we use the following symbols:

symbol	dimension
\oplus	exponentially expands
\ominus	exponentially shrinks
\odot	static
\bullet	constitutes cosmic time and static extra space
\circ	exponentially shrinks

3.1 M-theory

1 brane

M2	\oplus	\oplus	\oplus										
Other dim.				\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

M5	\oplus	\oplus	\oplus	\oplus	\oplus	\oplus							
Other dim.							\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

2 branes

M2	\oplus	\oplus	\oplus										
M2	\oplus			\oplus	\oplus								
Other dim.						\circ	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

M2	\oplus	\oplus	\circ										
M5	\oplus	\oplus		\circ	\circ	\circ	\circ						
Other dim.								\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

3 branes

M2	\oplus	\circ	\circ										
M2	\oplus			\circ	\circ								
M2	\oplus					\circ	\circ						
Other dim.								\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

M2	\oplus	\oplus		\circ									
M2	\oplus		\oplus		\circ								
M2		\oplus	\oplus			\circ							
Other dim.							\circ	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

M5	\oplus	\oplus	\circ	\circ	\circ	\circ							
M5	\oplus	\oplus	\circ	\circ			\circ	\circ					
M5	\oplus	\oplus			\circ	\circ	\circ	\circ					
Other dim.									\bullet	\bullet	\bullet	\bullet	\bullet

4 branes

M2	\oplus	\circ	\circ										
M2	\oplus			\circ	\circ								
M5	\oplus	\circ		\circ		\circ	\circ	\circ					
M5	\oplus		\circ		\circ	\circ	\circ	\circ					
Other dim.									\bullet	\bullet	\bullet	\bullet	\bullet

M2	\oplus	\oplus		\circ									
M2	\oplus		\oplus		\circ								
M5		\oplus	\oplus	\circ	\circ	\circ	\circ						
M5	\oplus	\oplus	\oplus			\circ	\circ	\ominus					
Other dim.									\bullet	\bullet	\bullet	\bullet	\bullet

5 branes

M2	\oplus	\oplus			\odot						
M2			\oplus	\oplus	\odot						
M2	\oplus		\oplus			\odot					
M2		\oplus		\oplus		\odot					
M5	\oplus	\oplus	\oplus	\oplus			\ominus	\ominus			
Other dim.									\bullet	\bullet	\bullet

6 branes

M2	\oplus	\oplus			\odot						
M2	\oplus		\oplus			\odot					
M2	\oplus			\oplus			\odot				
M2		\oplus	\oplus	\oplus	\odot						
M2		\oplus		\oplus		\odot					
M2		\oplus	\oplus				\odot				
Other dim.								\circ	\bullet	\bullet	\bullet

3.2 IIA superstring theory

2 branes

D0	\oplus										
D2		\oplus	\oplus	\oplus							
Other dim.					\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

F1	\oplus	\oplus									
NS5	\oplus	\oplus	\odot	\odot	\odot	\odot					
Other dim.							\bullet	\bullet	\bullet	\bullet	\bullet

D2	\oplus	\oplus	\odot								
D4	\oplus	\oplus		\odot	\odot	\odot					
Other dim.							\bullet	\bullet	\bullet	\bullet	\bullet

3 branes

D0	\oplus										
F1	\oplus	\odot									
D4	\oplus		\odot	\odot	\odot	\odot					
Other dim.							\bullet	\bullet	\bullet	\bullet	\bullet

F1	\oplus	\odot									
D2	\oplus		\odot	\odot							
D2	\oplus				\odot	\odot					
Other dim.							\bullet	\bullet	\bullet	\bullet	\bullet

F1	\oplus	\oplus									
D2	\oplus		\oplus	\odot							
D2		\oplus	\oplus		\odot						
Other dim.						\circ	\bullet	\bullet	\bullet	\bullet	\bullet

D4	\oplus	\oplus	\odot	\odot	\odot					
D4	\oplus	\oplus	\odot			\odot	\odot			
NS5	\oplus	\oplus		\odot	\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\oplus	\odot							
NS5	\oplus	\oplus		\odot	\odot	\odot	\odot			
D6	\oplus	\oplus	\odot	\odot	\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

4 branes

D0	\oplus									
D4	\oplus	\odot	\odot	\odot	\odot					
D4	\oplus	\odot	\odot			\odot	\odot			
D4	\oplus			\odot	\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

F1	\oplus	\odot								
D2	\oplus		\odot	\odot						
D4	\oplus		\odot		\odot	\odot	\odot			
NS5	\oplus	\odot		\odot	\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

F1	\oplus	\oplus								
D2	\oplus		\oplus	\odot						
D4		\oplus	\oplus	\odot	\odot	\odot				
NS5	\oplus	\oplus	\oplus		\odot	\odot	\ominus			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\odot	\odot							
D2	\oplus			\odot	\odot					
D2	\oplus					\odot	\odot			
D6	\oplus	\odot	\odot	\odot	\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\oplus		\odot						
D2	\oplus		\oplus		\odot					
D2		\oplus	\oplus			\odot				
D6	\oplus	\oplus	\oplus	\odot	\odot	\odot	\ominus			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\odot	\odot							
D2	\oplus			\odot	\odot					
D4	\oplus	\odot		\odot		\odot	\odot			
D4	\oplus		\odot		\odot	\odot	\odot			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\oplus		\odot						
D2	\oplus		\oplus		\odot					
D4		\oplus	\oplus	\odot	\odot	\odot				
D4	\oplus	\oplus	\oplus		\odot	\ominus				
Other dim.								\bullet	\bullet	\bullet

5 branes

F1	\oplus	\oplus								
F1			\oplus	\oplus						
D2	\oplus		\oplus		\odot					
D2		\oplus		\oplus	\odot					
NS5	\oplus	\oplus	\oplus	\oplus		\ominus	\ominus			
Other dim.								\bullet	\bullet	\bullet

6 branes

F1	\oplus	\oplus								
F1			\oplus	\oplus						
D2	\oplus		\oplus		\odot					
D2		\oplus		\oplus	\odot					
D2		\oplus	\oplus			\odot				
D2	\oplus			\oplus		\odot				
Other dim.							\circ	\bullet	\bullet	\bullet

3.3 IIB superstring theory

1 brane

D3	\oplus	\oplus	\oplus	\oplus						
Other dim.					\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

2 branes

F1	\oplus	\oplus								
F1			\oplus	\oplus						
Other dim.					\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

D1	\oplus	\oplus								
D1			\oplus	\oplus						
Other dim.					\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

F1	\oplus	\oplus								
D1	\oplus		\oplus							
Other dim.				\circ	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

F1	\oplus	\oplus								
NS5	\oplus	\oplus	\odot	\odot	\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

D1	\oplus	\oplus							
D5	\oplus	\oplus	\odot	\odot	\odot	\odot			
Other dim.							\bullet	\bullet	\bullet

D3	\oplus	\oplus	\odot	\odot					
D3	\oplus	\oplus			\odot	\odot			
Other dim.							\bullet	\bullet	\bullet

3 branes

F1	\oplus		\odot						
F1		\oplus		\odot					
D3	\oplus	\oplus			\odot	\odot			
Other dim.							\bullet	\bullet	\bullet

F1	\oplus	\odot							
D1	\oplus		\odot						
D3	\oplus			\odot	\odot	\odot			
Other dim.							\bullet	\bullet	\bullet

F1	\oplus	\oplus							
D1	\oplus		\oplus						
D3		\oplus	\oplus	\odot	\odot				
Other dim.						\circ	\bullet	\bullet	\bullet

D1	\oplus		\odot						
D1		\oplus		\odot					
D3	\oplus	\oplus			\odot	\odot			
Other dim.							\bullet	\bullet	\bullet

D3	\oplus	\oplus	\odot	\odot					
NS5	\oplus	\oplus	\odot		\odot	\odot	\odot		
D5	\oplus	\oplus		\odot	\odot	\odot	\odot		
Other dim.								\bullet	\bullet

4 branes

F1	\oplus	\oplus							
F1			\oplus	\oplus					
D1	\oplus		\oplus						
D1		\oplus		\oplus					
Other dim.					\circ	\circ	\bullet	\bullet	\bullet

F1	\oplus	\odot							
D1	\oplus		\odot						
NS5	\oplus	\odot		\odot	\odot	\odot	\odot		
D5	\oplus		\odot	\odot	\odot	\odot	\odot		
Other dim.								\bullet	\bullet

F1	\oplus	\odot									
D3	\oplus		\odot	\odot	\odot						
D3	\oplus		\odot			\odot	\odot				
NS5	\oplus	\odot		\odot	\odot	\odot	\odot				
Other dim.									\bullet	\bullet	\bullet

F1	\oplus	\oplus									
D3	\oplus		\oplus	\odot		\odot					
D3		\oplus	\oplus		\odot	\odot					
NS5	\oplus	\oplus	\oplus	\odot	\odot		\ominus				
Other dim.									\bullet	\bullet	\bullet

D1	\oplus	\odot									
D3	\oplus		\odot	\odot	\odot						
D3	\oplus		\odot			\odot	\odot				
D5	\oplus	\odot		\odot	\odot	\odot	\odot				
Other dim.									\bullet	\bullet	\bullet

D1	\oplus	\oplus									
D3	\oplus		\oplus	\odot		\odot					
D3		\oplus	\oplus		\odot	\odot					
D5	\oplus	\oplus	\oplus	\odot	\odot		\ominus				
Other dim.									\bullet	\bullet	\bullet

D3	\oplus	\odot	\odot	\odot							
D3	\oplus	\odot			\odot	\odot					
D3	\oplus		\odot		\odot		\odot				
D3	\oplus			\odot		\odot	\odot				
Other dim.									\bullet	\bullet	\bullet

D3	\oplus	\oplus	\oplus				\ominus				
D3	\oplus	\oplus		\odot	\odot						
D3	\oplus		\oplus	\odot		\odot					
D3		\oplus	\oplus		\odot	\odot					
Other dim.									\bullet	\bullet	\bullet

5 branes

F1	\oplus			\odot							
F1		\oplus			\odot						
D3	\oplus	\oplus	\oplus				\ominus				
D3	\oplus		\oplus		\odot	\odot					
D3		\oplus	\oplus	\odot		\odot					
Other dim.									\bullet	\bullet	\bullet

D1	\oplus			\odot						
D1		\oplus			\odot					
D3	\oplus	\oplus	\oplus				\ominus			
D3	\oplus		\oplus		\odot	\odot				
D3		\oplus	\oplus	\odot		\odot				
Other dim.								\bullet	\bullet	\bullet

F1	\oplus			\odot						
F1		\oplus			\odot					
F1			\oplus			\odot				
D3	\oplus	\oplus	\oplus				\ominus			
NS5	\oplus	\oplus	\oplus	\odot	\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

D1	\oplus			\odot						
D1		\oplus			\odot					
D1			\oplus			\odot				
D3	\oplus	\oplus	\oplus				\ominus			
D5	\oplus	\oplus	\oplus	\odot	\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

6 branes

F1	\oplus	\oplus								
F1			\oplus	\oplus						
D1	\oplus		\oplus							
D1		\oplus		\oplus						
D3	\oplus			\oplus	\odot	\odot				
D3		\oplus	\oplus		\odot	\odot				
Other dim.							\circ	\bullet	\bullet	\bullet

4 Concluding remarks

In the previous sections, we constructed intersecting spacelike braneworld models. To examine the reality of these models, we focus on the following 9 models, which include 3 isotropically expanding space dimensions.

From M-theory, 2 models are nominated:

M2	\oplus	\oplus	\oplus							
Other dim.				\bullet	\bullet	\bullet	\bullet	\bullet	\bullet	\bullet

M2	\oplus	\oplus		\odot						
M2	\oplus		\oplus		\odot					
M2		\oplus	\oplus			\odot				
Other dim.							\circ	\bullet	\bullet	\bullet

On the other hand, 3 and 7 candidates come from IIA and IIB superstring theories, respectively:

F1	\oplus	\oplus								
D2	\oplus		\oplus	\odot						
D2		\oplus	\oplus		\odot					
Other dim.						\circ	\bullet	\bullet	\bullet	\bullet

D2	\oplus	\oplus		\odot						
D2	\oplus		\oplus		\odot					
D2		\oplus	\oplus			\odot				
D6	\oplus	\oplus	\oplus	\odot	\odot	\odot	\ominus			
Other dim.								\bullet	\bullet	\bullet

D2	\oplus	\oplus		\odot						
D2	\oplus		\oplus		\odot					
D4		\oplus	\oplus	\odot	\odot	\odot				
D4	\oplus	\oplus	\oplus			\odot	\ominus			
Other dim.								\bullet	\bullet	\bullet

F1	\oplus	\oplus								
D1	\oplus		\oplus							
D3		\oplus	\oplus	\odot	\odot					
Other dim.						\circ	\bullet	\bullet	\bullet	\bullet

D1	\oplus	\oplus								
D3	\oplus		\oplus	\odot		\odot				
D3		\oplus	\oplus		\odot	\odot				
D5	\oplus	\oplus	\oplus	\odot	\odot		\ominus			
Other dim.								\bullet	\bullet	\bullet

D3	\oplus	\oplus	\oplus				\ominus			
D3	\oplus	\oplus		\odot	\odot					
D3	\oplus		\oplus	\odot		\odot				
D3		\oplus	\oplus		\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

F1	\oplus			\odot						
F1		\oplus			\odot					
D3	\oplus	\oplus	\oplus				\ominus			
D3	\oplus		\oplus		\odot	\odot				
D3		\oplus	\oplus	\odot		\odot				
Other dim.								\bullet	\bullet	\bullet

D1	\oplus			\odot						
D1		\oplus			\odot					
D3	\oplus	\oplus	\oplus				\ominus			
D3	\oplus		\oplus		\odot	\odot				
D3		\oplus	\oplus	\odot		\odot				
Other dim.								\bullet	\bullet	\bullet

F1	\oplus			\odot						
F1		\oplus			\odot					
F1			\oplus		\odot					
D3	\oplus	\oplus	\oplus				\ominus			
NS5	\oplus	\oplus	\oplus	\odot	\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

D1	\oplus			\odot						
D1		\oplus			\odot					
D1			\oplus		\odot					
D3	\oplus	\oplus	\oplus				\ominus			
D5	\oplus	\oplus	\oplus	\odot	\odot	\odot				
Other dim.								\bullet	\bullet	\bullet

Because each multi-brane model includes a shrinking space dimension, its classical dimension would reduce with the passage of time. Therefore, change of the behavior of other dimensions might be caused.

First, we investigate the restrictions caused by the fact that the largest supersymmetry algebra in 4 dimensions is $N = 8$ and that it contains 32 (real) supercharges. This is expected to hold in our models. In 11 dimensions, the number of real components of the smallest representation is 32, if the Majorana condition is satisfied. Hence, the number of the timelike coordinates $s = 1, 2, 5$ and 6 is allowed in the above-mentioned M-theory model. On the other hand, $s = 1, 2$ and 4 are allowed, as the Majorana condition or the Weyl condition must be satisfied in the superstring theory model. If $s = 1$, the extra space is a $(D - p - 2)$ -dimensional hyperbolic space H^{D-p-2} , whereas if $s = D - p - 1$, it is a compact $(D - p - 2)$ -dimensional *timelike* sphere.

Some studies have pointed out the importance of compact hyperbolic manifolds for internal space. Modding out H^{D-p-2} by an appropriate freely acting discrete subgroup of the isometry group of H^{D-p-2} , a compact hyperbolic manifold is obtained. These studies posit a model in which the universe is the direct product of a Robertson-Walker spacetime and a compact hyperbolic manifold [25, 26, 27].

Secondly, we compare expansion of our braneworld with late-time inflation of the Universe. For simplicity, we neglect a curvature term and think of an *effective* cosmological constant Λ as the only content of the Universe. Then, the Friedmann equation of a Λ -dominated universe is

$$H^2 = \frac{\Lambda}{3},$$

where H is the present Hubble parameter

$$H \sim 10^{-26} \text{m}^{-1}.$$

Comparing its metric

$$ds^2 = -dt^2 + e^{\sqrt{\frac{\Lambda}{3}}t} d\mathbf{x}^2$$

with (32), we obtain

$$\sqrt{\frac{\Lambda}{3}} = \frac{D-p-3}{2C(D-2)} \sum_A \delta_{A,i}. \quad (33)$$

Because

$$\frac{D-p-3}{2(D-2)} \sum_A \delta_{A,i} \sim O(1),$$

the scale factor of extra dimensions C is estimated as

$$C \sim \Lambda^{-1/2}. \quad (34)$$

Therefore,

$$C \sim H^{-1} \sim (\Lambda_{\text{late}})^{-1/2} \sim 10^{26} \text{m}. \quad (35)$$

This value is comparable to the present size of the Universe.

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