Accelerating cosmologies from M/String theory compactifications

Shibaji Roy

Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Calcutta-700 064, India

Abstract

We point out that the solution of \((4+n)\)-dimensional gravity coupled to the dilaton and an \(n\)-form field strength can give rise to a flat 4-dimensional universe (with a scale factor) of the type proposed recently under time dependent compactifications. The compact internal spaces could be hyperbolic, flat or spherical and the solution is identical to the space-like two brane or S2-brane. As has been shown previously for SM2 solution with a fixed field strength we show that for \(n = 7\) (where the dilaton is vanishing and with a general field strength), 6 the corresponding SM2 and SD2 solutions can give accelerating cosmologies in Einstein frame for both hyperbolic and flat internal spaces, thereby meeting the challenge of obtaining such a solution from M/String theory compactifications.

\(^1\)E-Mail: roy@theory.saha.ernet.in
Since the discovery of the astronomical observation [1, 2] supported by the recent measurement [3, 4] of cosmic microwave background that our universe is undergoing an accelerated expansion, it has been a major challenge [5, 6, 7] to obtain such models from M/string theory compactifications. Recently Townsend and Wohlforth (TW) [8] have shown in a beautiful paper that such accelerated cosmologies can arise from a solution of \((4 + n)\)-dimensional vacuum Einstein equation compactified on \(n\)-dimensional hyperbolic space of time varying volume. For \(n = 7\) this implies that realistic cosmology can result from M-theory compactification on a hyperbolic space. Interestingly, although the original theory does not violate the strong energy condition, such compactification does violate this condition and accelerated expansion is obtained in Einstein frame circumventing the “no-go” theorem [5] which forbids acceleration in standard compactification.

In this paper we show that not only the solution of vacuum Einstein equation, but also that of the \((4 + n)\)-dimensional gravity coupled to the dilaton and an \(n\)-form field strength gives rise to the flat 4-dimensional universe (with a scale factor) of the type discussed by TW. The solution of the above system has already been obtained [9] under the name space-like branes or S-branes [10]. S\(_p\)-branes are time-dependent solutions with \((p + 1)\)-dimensional Euclidean world-volume and apart from time they have \((d - p - 2)\)-dimensional hyperbolic, flat or spherical spaces as transverse spaces. They can be understood to arise as a time-like tachyonic kink solution of non-BPS D\((p + 1)\) branes [14] in string theory and might be useful to understand the time-like holography of the dS/CFT correspondence [15]. It is clear from above that in order to get a 4-dimensional world \(p\) should be 2 and so we will look into the S2-brane solution of \((4 + n)\)-dimensional theory. For \(n = 7\), the dilaton will be put to zero and the corresponding solution would be the SM2-brane solution of M-theory, whereas, for \(n = 6\), the corresponding solution is the SD2-brane solution of string theory. We will first show that all S2-brane solutions in \(d = n + 4\) gives rise to the flat, homogeneous, isotropic 4-dimensional universe of the type discussed by TW. Then we show that for \(n = 7, 6\) both\(^3\) the SM2-brane and SD2-brane solutions give accelerating cosmologies in Einstein frame for only hyperbolic and flat space compactifications with time varying volume. We would like to point out that in the context of SM2-brane solution \((n = 7)\) accelerating cosmologies arising for both hyperbolic and flat space compactifications were first shown by Ohta [16]. However, the solution used in [16] has a slightly different form from the Chen-Gal’tsov-Gutperle (CGG) [9] solution we use here to demonstrate the accelerating cosmology in the sense that the field-strength in the former case has been chosen to a particular value which is not necessary in our analysis.

The action for the \((4 + n)\)-dimensional gravity coupled to the dilaton and an \(n\)-form

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\(^2\)See [11, 12, 13] for some related works on S-branes.

\(^3\)One may think that since SD2-brane solution can be constructed from SM2 solution by an analogue of direct dimensional reduction as in the static case, it is not necessary to study both the cases together. However we point out that there are more parameters in the SD2 solution than in the SM2 solution. It is not clear how new parameters would be generated by dimensional reduction and it would be interesting to understand reduction procedure in this case.
field strength in Einstein frame is given by,

$$S_{4+n} = \frac{1}{16\pi G_{4+n}} \int d^{4+n}x \sqrt{-g(4+n)} \left( R_{(4+n)} - \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} n! e^{a\phi} F_n^2 \right)$$  \tag{1}$$

This action has been solved by CGG [9] and the solution is given as,

$$ds^2 = -e^{2A(t)} dt^2 + e^{2B(t)} dx_{(3)}^2 + e^{2C(t)} d\Sigma_{n,\sigma}^2$$

$$\phi(t) = \frac{a(n+2)}{(n-1)} B(t) + c_1 t + c_2$$

$$F_n = b \epsilon(\Sigma_{n,\sigma})$$  \tag{2}$$

Here $A(t), B(t), C(t)$ are functions of $t$ which are chosen to satisfy a gauge condition $-A + 3B + nC = 0$ to simplify the equations of motion. So, the functions $A, B, C$ can be expressed in terms of two functions $f(t)$ and $g(t)$ as follows,

$$A(t) = ng(t) - \frac{3}{(n-1)} f(t), \quad B(t) = f(t), \quad C(t) = g(t) - \frac{3}{(n-1)} f(t)$$  \tag{3}$$

Also in the above $dx_{(3)}^2$ is the line element of 3-dimensional Euclidean space and $d\Sigma_{n,\sigma}^2$ is that of the hyperbolic space (for $\sigma = -1$), flat space (for $\sigma = 0$) and spherical space (for $\sigma = +1$), with $R_{ab} = \sigma(n-1)\bar{g}_{ab}$. $a$ is the dilaton coupling to the $n$-form field strength and $c_1, c_2$ are integration constants. $b$ is the field strength parameter and $\epsilon(\Sigma_{n,\sigma})$ is the unit volume form of $\Sigma_{n,\sigma}$.

By solving the field equations the functions $f(t)$ and $g(t)$ can be obtained as,

$$f(t) = \frac{2}{\chi} \ln \frac{\alpha}{\cosh[\frac{\chi a}{2}(t - t_0)]} + \frac{1}{\chi} \ln \frac{(n+2)\chi}{(n-1)b^2} - \frac{a}{\chi} (c_1 t + c_2)$$  \tag{4}$$

$$g(t) = \begin{cases} 
\frac{1}{(n-1)} \ln \frac{\beta}{\sinh[(n-1)\beta(t-t_1)]}, & \text{for } \sigma = -1 \\
\pm \beta(t - t_1), & \text{for } \sigma = 0 \\
\frac{1}{(n-1)} \ln \frac{\beta}{\cosh[(n-1)\beta(t-t_1)]}, & \text{for } \sigma = +1 
\end{cases}$$  \tag{5}$$

where $\chi = 6 + a^2(n + 2)/(n - 1)$ and the constants $\alpha, \beta$ and $c_1$ satisfy

$$\frac{3c_1^2}{\chi} + \frac{(n+2)\chi a^2}{2(n-1)} - n(n-1)\beta^2 = 0$$  \tag{6}$$

Also note that for an $n$-form field strength the dilaton coupling $a = 2(4-n)/(n+2)$ for $n < 7$ and we will put it to zero for $n = 7$. Eqs.(2) – (6) represent the S2-brane supergravity solution in $(4 + n)$-dimensions. The metric in (2) is given in the Einstein frame.

Now we note that using eq.(3) the metric in (2) can be written as,

$$ds^2 = e^{-ng(t) + \frac{3a}{(n-1)} f(t)} ds_E^2 + e^{2g(t) - \frac{6}{(n-1)} f(t)} d\Sigma_{n,\sigma}^2$$  \tag{7}$$
where,
\[ ds_{E}^2 = -S^6 dt^2 + S^2 dx^2_{(3)} \]  \hspace{1cm} (8)
and the function \( S(t) \) is defined as,
\[ S(t) = e^{\frac{4g(t)}{S(t)}} e^{-\frac{(n+2)}{2(n-1)}f(t)} \]  \hspace{1cm} (9)
Now using (7) we can reduce the action (1) to four dimensions and it has the form [17, 18]
\[ S_4 = \frac{1}{16\pi G_4} \int d^4 x \sqrt{-g} \left( R - \frac{1}{2} \partial_{\mu} \phi \partial^\mu \phi - \frac{n(n+2)}{2} \partial_{\mu} \psi \partial^\mu \psi - V(\phi, \psi) \right) \]  \hspace{1cm} (10)
where,
\[ V(\phi, \psi) = \frac{b^2}{2} e^{-\frac{2(n-4)}{n+2} \phi - 3n \psi} - \sigma n(n-1) e^{-(n+2)\psi} \]  \hspace{1cm} (11)
The radion field \( \psi \) in the above can be read off from (7) as \( \psi = g(t) - 3f(t)/(n-1) \). The qualitative behavior of the 4-dimensional cosmology can be studied [18] by analyzing the potential \( V(\phi, \psi) \) given in (11). However, we will study the cosmology directly from the 4-dimensional metric given in (8).

Note that the 4-dimensional metric \( ds_{E}^2 \) is given in the Einstein frame and it takes the standard form of flat, homogeneous, isotropic universe with a scale factor \( S(t) \) if we define the time coordinate \( \eta \) as \( d\eta = S^3(t) dt \). Thus we have shown that S2-brane solution of \((4 + n)\)-dimensional theory can be reduced to TW form. The 4-dimensional universe will be expanding if \( \frac{dS}{d\eta} > 0 \), which implies
\[ m(t) = \frac{n dg}{2 dt} - \frac{(n+2) df}{2(n-1) dt} > 0 \]  \hspace{1cm} (12)
Furthermore the expansion will be accelerating if \( \frac{d^2S}{d\eta^2} > 0 \), which implies,
\[ \frac{1}{\sqrt{2}} \left( \frac{dm(t)}{dt} \right)^{1/2} - m(t) > 0 \]  \hspace{1cm} (13)
We will first look at the case when the dilaton is vanishing. From the dilaton equation in (2), we have \( a = c_1 = c_2 = 0 \). Also from (6) we get for \( \alpha = 1^4 \)
\[ \beta = \frac{\sqrt{3(n+2)/n}}{(n-1)} \]  \hspace{1cm} (14)
Note that we have \( \chi = 6 \) in this case. So, the function \( f(t) \) in (4) reduces to
\[ f(t) = -\frac{1}{6} \ln \frac{b^2(n-1) \cosh^2 3t}{6(n+2)} \]  \hspace{1cm} (15)
\(^4\)It is easy to see that for general \( \alpha \), the arguments of the hyperbolic functions appearing in (17) and (18) will simply be multiplied by this parameter, but this parameter can be absorbed by scaling \( t \) appropriately.
In the above we have set $t_0 = 0$. Now in the following we consider the three cases $\sigma = -1, 0, +1$ separately.

(a) Internal space is hyperbolic ($\sigma = -1$)

In this case the function $g(t)$ is given as

$$g(t) = \frac{1}{(n-1)} \ln \frac{\sqrt{3(n+2)/n}}{(n-1) \sinh(\sqrt{3(n+2)/n} |t|)}$$

(16)

For the accelerating expansion the conditions (12) and (13) in this case give,

$$m(t) = -\sqrt{\frac{3n(n+2)}{2(n-1)}} \coth(\sqrt{3(n+2)/nt}) + \frac{(n+2)}{2(n-1)} \tanh 3t > 0$$

(17)

$$\sqrt{3} \left[ \frac{(n+2)}{(n-1)} \left( \frac{1}{\sinh^2(\sqrt{3(n+2)/nt})} + \frac{1}{\cosh^2 3t} \right) \right]^{1/2} - m(t) > 0$$

(18)

For $n = 7$ the above conditions reduce exactly to the conditions (17) and (18) of ref. [16]. However, note that in our case the metric as well as the scale factor $S(t)$ in (9) depend explicitly on the field strength parameter $b$ through the function $f(t)$ given in (15). But the scale factor in [16] does not appear to contain the field strength as it is set to a particular value. In fact the term involving the field strength is simply an additive constant to the function $f(t)$ and therefore does not affect the conditions (12), (13) for the accelerating expansion. It is therefore not necessary to set it to a particular value. Since the solution of (17) and (18) has already been studied in [16], for $n = 7$, we will not repeat it here. We just mention that the above conditions could be satisfied simultaneously for only negative value of $t$ in a certain interval. In terms of the true time coordinate $\eta$ of the 4-dimensional world, this means accelerating expansion occurs for some interval in the positive time. The plots of the l.h.s. of (17) and (18) for $n = 7$ were given in [16].

(b) Internal space is flat ($\sigma = 0$)

In this case $g(t) = \pm \sqrt{\frac{3(n+2)/n}{(n-1)}} t$, where we have taken the same value of $\beta$ as in (14). Then the conditions (12) and (13) give,

$$m(t) = \pm \frac{1}{2} \sqrt{\frac{3n(n+2)}{(n-1)}} + \frac{(n+2)}{2(n-1)} \tanh 3t > 0$$

(19)

$$\sqrt{3} \left[ \frac{(n+2)}{(n-1)} \frac{1}{\cosh 3t} \right]^{1/2} - m(t) > 0$$

(20)

For $n = 7$, these conditions are exactly the same as in [16]. An accelerated expansion has been found for a certain period of $t$ in the region $t < 0$, with the positive sign of the
first term in (19). The solutions of these equations for \( n = 7 \) has been studied and the plot of the functions on the l.h.s. of the conditions (19) and (20) showing an accelerated expansion has been given there. Unlike in the hyperbolic case there is no singularity at \( t = 0 \) here.

(c) Internal space is spherical (\( \sigma = +1 \))

In this case the conditions (12) and (13) can not be satisfied simultaneously, indicating that there is no accelerated expansion of the 4-dimensional universe when the theory is compactified on spherical space\(^6\).

Let us now look at the case when the dilaton is non-vanishing. For \( n = 6 \), the corresponding solution is SD2-brane of type IIA string theory. We will find a very similar behavior of the 4-dimensional universe as in SM2 case. The function \( f(t) \) in this case has the form,

\[
f(t) = -\frac{1}{\chi} \ln \frac{\cosh^2(\chi \alpha t/2) e^{\frac{2(4-n)}{(n+2)} c_1 t b^2(n-1)}}{a^2(n+2) \chi}
\]

The value of \( \chi \) and dilaton coupling \( a \) were given before. We have chosen \( c_2 = t_0 = 0^7 \) and the value of the parameter \( \beta \) is chosen\(^8\) as before in (14). Then the relation between the parameters \( c_1 \) and \( \alpha \) is given from (6) as,

\[
\frac{3c_1^2}{\chi} + \frac{(n + 2) \chi \alpha^2}{2(n - 1)} - \frac{3(n + 2)}{(n - 1)} = 0 \tag{22}
\]

Again we will discuss the three cases \( \sigma = -1, 0, +1 \) separately.

(a') Internal space is hyperbolic (\( \sigma = -1 \))

The function \( g(t) \) has exactly the same form as in case (a) before. The conditions for the accelerated expansion (12) and (13) therefore give,

\[
m(t) = -\sqrt{3} \frac{n + 2}{2(n - 1)} \coth(\sqrt{3} (n + 2)/nt) + \frac{(n + 2) \alpha}{2(n - 1)} \tanh(\chi \alpha t/2) + \frac{(4 - n) c_1}{(n - 1) \chi} > 0 \tag{23}
\]

\[
\frac{1}{2} \left[ \frac{(n + 2)}{(n - 1)} \left( \frac{3}{\sinh^2(\sqrt{3}(n + 2)/nt)} \right) + \frac{\chi \alpha^2}{2} \cosh^2(\chi \alpha t/2) \right]^{1/2} - m(t) > 0 \tag{24}
\]

For \( n = 6, \chi = 32/5 \) and the relation (22) simplifies to

\[
\frac{15c_1^2}{32} + \frac{128\alpha^2}{25} = 24/5 \tag{25}
\]

\(^6\)However, we would like to point out that this conclusion is valid when the parameter \( t_0 = 0 \). An accelerating expansion can be found even in this case for \( t_0 < 0 \) as noted in [18, 20].

\(^7\)Note that when \( c_2 = 0 \), the parameter \( \beta \) can not be removed by renaming other parameters as is done in [12].

\(^8\)We have chosen this value for convenience. Here unlike in SM2 case \( \beta \) does not get fixed to this particular value and there is a freedom. However, the essential behavior for the conditions of accelerating expansion does not change much for different values of \( \beta \).
Since the parameters are real we note from (25) that $c_1$ lies between $-3.2$ and $+3.2$ and taking $\alpha \geq 0$, we get $0 \leq \alpha \leq 0.97$. The conditions (23) and (24) simplify for $n = 6$ to,

$$m(t) = -\frac{6}{5} \coth(2t) + \frac{4\alpha}{5} \tanh(16\alpha t/5) - \frac{c_1}{16} > 0 \quad (26)$$

$$\sqrt{\frac{2}{5} \left( \frac{3}{\sinh^2(2t)} + \frac{16\alpha^2}{5} \frac{1}{\cosh^2(16\alpha t/5)} \right)^{1/2}} - m(t) > 0 \quad (27)$$

We do not get solutions of the above two conditions simultaneously for the whole range of parameters $c_1$ and $\alpha$ mentioned above. We plot the l.h.s. of both the conditions (26) and (27) versus $t$ in fig.1 for $c_1 = 1$ and $\alpha = 0.92$. The plot shows very similar behavior as those obtained in refs.[8, 16] i.e. the conditions are satisfied simultaneously for some interval of negative $t$ and beyond that the universe is decelerating for both $t \rightarrow 0^-$ ($\eta \rightarrow \infty$) and $t \rightarrow -\infty$ ($\eta \rightarrow 0$). Note that there is a singularity of the scale factor $S(t)$ at $t = 0$. However, this remains unobservable since it is at an infinite proper time in the future of any event with $t < 0$ and an infinite proper time in the past of any event with $t > 0$. So, our universe will separate into two regions with $t < 0$ and $t > 0$. Also note that we have studied the evolution for particular values of the parameters $c_1$ and $\alpha$. There are in fact a large class of solutions of the 4-dimensional world which would exhibit accelerated expansions. The values of the parameters might get fixed by the detailed knowledge of the evolution of the universe.
(b’) Internal space is flat \((\sigma = 0)\)

The function \(g(t)\) in this case is as given in (b) above. The conditions (12) and (13) give,

\[
m(t) = \pm \frac{1}{2} \frac{\sqrt{3n(n+2)}}{(n-1)} + \frac{(n+2)\alpha}{2(n-1)} \tanh(\chi\alpha t/2) + \frac{(4-n)c_1}{(n-1)\chi} > 0 \quad (28)
\]

\[
\frac{1}{2\sqrt{2}} \left[ \frac{(n+2)\chi^2}{(n-1)} \right]^{1/2} \frac{1}{\cosh(\chi\alpha t/2)} - m(t) > 0 \quad (29)
\]

The parameters \(c_1\) and \(\alpha\) are related by eq.(22). For \(n = 6\) we get from above,

\[
m(t) = \pm \frac{6}{5} + \frac{4\alpha}{5} \tanh(16\alpha t/5) - \frac{c_1}{16} > 0 \quad (30)
\]

\[
\frac{4\sqrt{2}}{5} \alpha \frac{1}{\cosh(16\alpha t/5)} - m(t) > 0 \quad (31)
\]

with the parameter relation given in eq.(25). Here also we do not get the solutions of (30) and (31) in the whole range of parameters \(c_1\) and \(\alpha\) given earlier. We plot the l.h.s. of both the conditions (30) and (31) in fig.2 for \(c_1 = 1\) and \(\alpha = 0.92\) and we get an accelerated expansion only for the positive sign of the first term in (30). Here there is no singularity of the functions in the l.h.s. of (30) and (31) at \(t = 0\) unlike in the hyperbolic case. The accelerated expansion occurs at certain interval of negative \(t\) as is shown in fig.2. The universe decelerates at both \(t \to -\infty\) \((\eta \to 0)\) and \(t \to \infty\) \((\eta \to \infty)\). This range is continuously connected through \(t = 0\). A similar behavior was observed for SM2 case in [16].

(c’) Internal space is spherical \((\sigma = +1)\)

Here the function \(g(t)\) is given as,

\[
g(t) = \frac{1}{(n-1)} \ln \frac{\sqrt{3(n+2)/n}}{(n-1)\cosh(\sqrt{3(n+2)/nt})} \quad (32)
\]

where we have used the same value of \(\beta\) as given in (14). So, the conditions (12) and (13) give,

\[
m(t) = \sqrt{3n(n+2)}{2(n-1)} \tanh(\sqrt{3(n+2)/nt}) + \frac{(n+2)\alpha}{2(n-1)} \tanh(\chi\alpha t/2) + \frac{(4-n)c_1}{(n-1)\chi} > 0 \quad (33)
\]

\[
\frac{1}{2\sqrt{2}} \left[ \frac{(n+2)}{(n-1)} \right]^{1/2} \frac{3}{\cosh^2(\sqrt{3(n+2)/nt})} + \frac{\chi^2}{2} \frac{1}{\cosh^2(\chi\alpha t/2)} \right]^{1/2} - m(t) > 0 \quad (34)
\]
Figure 2: The function $m(t)$ in eq.(30) and the l.h.s. of eq.(31) are plotted against $t$ for $c_1 = 1$ and $\alpha = 0.92$ and are given respectively by solid and dashed lines.

For $n = 6$ they simplify to,

$$m(t) = -\frac{6}{5} \tanh(2t) + \frac{4\alpha}{5} \tanh(16\alpha t/5) - \frac{c_1}{16} > 0$$

(35)

$$\sqrt{\frac{2}{5}} \left( -\frac{3}{\cosh^2(2t)} + \frac{16\alpha^2}{5} \frac{1}{\cosh^2(16\alpha t/5)} \right)^{1/2} - m(t) > 0$$

(36)

The parameters $c_1$ and $\alpha$ are related by eq.(25). We have checked that these conditions cannot be satisfied simultaneously either for $t < 0$ or for $t > 0$. So, there is no accelerated expansion of the 4-dimensional universe when the theory is compactified on spherical spaces. Here again this conclusion is true only for the parameter $t_0 = 0$. But when $t_0 < 0$, an accelerating expansion in this case has been obtained in [20].

To summarize, we have shown that $(4 + n)$-dimensional gravity coupled to the dilaton and an $n$-form field strength can give rise to a flat 4-dimensional universe with a scale factor of the type discussed by TW under time dependent compactification. The solutions are S2-brane solutions of $(4 + n)$-dimensional theory. For $n = 7$ (when the dilaton is put to zero) the corresponding SM2-brane solution is shown to give accelerated expansion of the 4-dimensional universe when the internal space is both hyperbolic and flat with time varying volume. Similar conclusions were found even for $n = 6$ i.e. for SD2-brane case. Here there is a freedom of the choice of the parameters $c_1$ and $\alpha$ whose exact values might be determined by the detailed knowledge of the evolution of our universe.
Note added:

After submission of the paper to the net I was informed by Lorenzo Cornalba and Miguel Costa that observations on accelerating cosmologies for a similar theory (studied in this paper) compactified on the time dependent flat internal space have been made in [21].

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