Available online at www.sciencedirect.com
SCIENCE DIRECT®
C. R. Physique 5 (2004) 1021–1029
COMPTES RENDUS PHYSIQUE
http://france.elsevier.com/direct/COMREN/
String theory and fundamental forces/Théorie des cordes et forces fondamentales

Cosmic superstrings II

Edmund J. Copeland [a], Robert C. Myers [b,*], Joseph Polchinski [c]

[a] *Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QJ, UK*
[b] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada*
[c] *Kavli Institute for Theoretical Physics, Santa Barbara, CA 93106-4030, USA*

Available online 11 November 2004

Presented by Guy Laval

Abstract

Modern string theory provides a rich array of objects which could potentially appear as cosmic strings in our observable four-dimensional universe. However, there are many possible decay modes which would prevent the appearance of such strings. We investigate the conditions under which metastable strings can exist, and we find that such strings are present in many models. Hence cosmic strings give a potentially large window into string physics. ***To cite this article: E.J. Copeland et al., C. R. Physique 5 (2004).***

Résumé

Supercordes Cosmiques II. La théorie moderne des supercordes fournit un choix riche d'objets qui pourraient potentiellement apparaître en tant que cordes cosmiques dans notre univers quadridimensionnel observable. Cependant, il y a beaucoup de modes possibles de désintégration qui empêcheraient l'apparition de telles cordes. Nous étudions les conditions dans lesquelles des cordes métastables peuvent exister, et nous constatons que de telles cordes sont présentes dans beaucoup de modèles. Par conséquent les cordes cosmiques ouvrent une fenêtre potentiellement grande vers la physique des supercordes. ***Pour citer cet article : E.J. Copeland et al., C. R. Physique 5 (2004).***

Keywords: Superstring theory; Cosmic strings; Cosmology

Mots-clés : Théorie des supercordes ; Cordes cosmiques ; Cosmologie

1. Introduction

The following is a summary of the work appearing in [1].

While superstring theory is certainly a theory of strings, the usual expectation is that these strings are microscopic in size. In this contribution, we will ask the question whether it is possible that in the evolution of the early universe some of these strings could have expanded to a macroscopic size. Such strings with cosmological extent could then be seen as cosmic strings with astronomical observations in the present day. This preamble explains the title above up to the annotation 'II'. The latter is added

* Corresponding author.
E-mail addresses: e.j.copeland@sussex.ac.uk (E.J. Copeland), rmyers@perimeterinstitute.ca (R.C. Myers), joep@kitp.ucsb.edu (J. Polchinski).

1631-0705/$ – see front matter
doi:10.1016/j.crhy.2004.10.008

because the title is actually borrowed from [2], in which Witten asked this same question some twenty years ago. At that time, he argued that this scenario was unlikely given the understanding of string theory at that time.

While we will argue that this conclusion should be revised with our modern perspective of string theory, it is useful recall the discussion appearing in [2]. In 1985, string theorists had constructed the five consistent superstring theories: type I, heterotic $E_8 \times E_8$, heterotic $SO(32)$, type IIa and type IIb. The type I theory is an open string theory and so any macroscopic string will rapidly fragment by the formation of endpoints. By this process, the macroscopic string will be converted on a stringy time scale to microscopic open strings, i.e. the ordinary quantum excitations of the theory. In the heterotic theories, there are Chern–Simons couplings between the two-form sourced by the strings and the gauge fields. As a result, macroscopic heterotic strings always appear as the boundaries of axion domain walls whose tension is again string scale. The tension of these domain walls would cause any macroscopic strings to collapse on cosmological time scales [3]. At the time of Ref. [2], a long type II string was thought to be stable, however, the absence of gauge fields made these theories unlikely to be phenomenologically interesting. Much later in 1995, [4] made clear that NS5-brane instantons will lead to the appearance of an axion potential and domain walls, which would lead to the collapse of macroscopic type II strings. Hence the details of the microphysics of string theory seemed to prevent the appearance of cosmic fundamental strings. Still Witten's discussion closed with the observation that superstring theories give rise to rich low energy phenomenologies, which might still give rise to 'conventional' cosmic strings in the form of magnetic or electric flux tubes. Even setting aside the microscopic details, the idea that fundamental strings might appear as cosmic strings faced other challenges in the pre-1995 era. First and foremost, fundamental strings were believed to have tensions μ close to the Planck scale, whereas the isotropy of the cosmic microwave background implied (even before COBE) that any string of cosmic size must have $G\mu \lesssim 10^{-5}$ [5]. From this point of view, the microscopic instabilities were a good thing, as otherwise string theory would have been at odds with experimental observation. Of course, inflation provides a simple explanation for the absence of cosmic fundamental strings of such high tension. Such strings would arise as relics from a very early Planck scale era of the universe, and so inflation would dilute them away in the same way as other topological defects were eliminated [6]. Hence inflation would present another theoretical obstacle to the idea of observable cosmic superstrings.

Of course, 1995 was a watershed year for string theory and marked the beginning of a remarkable time when new ideas and discoveries were introduced in our field at an explosive rate. In the modern post-1995 era, our perspective of string theory is very different than when [2] was written. First of all, we no longer regard string theory to be solely a theory of strings. Rather we know that extended objects like D-branes, NS5-branes and M-branes play an important role in defining the theory and governing the physics of certain situations. Hence in addition to fundamental strings or F-strings, there are many new branes that could appear as one-dimensional objects in our observable four dimensions. Of course, there are D-strings but also any of the above extended branes may be partially wrapped on a compact cycles in the internal space to leave one noncompact dimension. Further the dualities that relate the various different kinds of string theories may at the same time relate fundamental strings in one setting to these other 'strings' in another, placing them all on a more or less equal footing. Hence if we are to consider the possibility of F-strings appearing as cosmic strings, we should consider the possibility of cosmic strings with any of these 'braney' origins.

Viable or interesting compactification scenarios is another aspect of string theory where our perspective has evolved dramatically since 1995. Today, we commonly consider 'exotic' compactifications with large extra dimensions [7] and/or large warp factors [8]. As will be discussed below, both of these features allow for strings with much lower tensions. Given these changes in our present-day perspective on superstrings, it is timely to revisit this subject, and ask whether some of these strings may be observed as cosmic superstrings.

2. Cosmic superstrings revisited

Recall the theoretical challenges which the cosmic superstring idea faced in the pre-1995 era:

(i) The strings would have Planck scale tension;
(ii) The strings would be diluted away by inflation;
(iii) The strings would be unstable.

We will now re-address each of these issues in light of the modern perspective of superstring/M-theory.

2.1. String tension

As mentioned above, compactifications with large extra dimensions [7] and/or large warp factors [8] allow for strings with much lower tensions. For large extra dimensions, one proceeds as with a standard Kaluza–Klein reduction. Hence looking at the reduction of the Einstein term in, e.g., the ten-dimensional supergravity action:

$$\frac{1}{16\pi G_{10}} \int \mathrm{d}^{10}x\, R \simeq \frac{V_6}{16\pi G_{10}} \int \mathrm{d}^4x\, R \equiv \frac{1}{16\pi G_4} \int \mathrm{d}^4x\, R. \tag{1}$$

Hence the four-dimensional Planck length is a derived quantity related to that in higher dimensions as

$$\ell_{4\text{d-Pl}}^2 = \frac{\ell_{10\text{d-Pl}}^6}{V_6}\ell_{10\text{d-Pl}}^2 = (2\pi^2)^3 g_s^2 \frac{\ell_s^6}{V_6}\ell_s^2, \tag{2}$$

using the result $16\pi G = (2\pi)^7 g_s^2 \ell_s^8$ for type II strings. Of course, Eq. (2) applies for any Kaluza–Klein reduction of a ten-dimensional string theory. The new feature introduced in a scenario with large extra dimensions is, of course, that one considers a compactification with $V_6 \gg \ell_s^6$ and so the observed four-dimensional Planck length is much smaller than the fundamental Planck length of the original theory. Therefore, in such a scenario, the fundamental string tension is small in comparison with the observed Planckian scale, i.e.,

$$\mu_{F1} = \frac{1}{2\pi\ell_s^2} \ll \frac{1}{\ell_{4\text{d-Pl}}^2}. \tag{3}$$

In a warped compactification [8], the internal volume need not be large, and so the Planck scale and the string scale may be of the same order of magnitude. Instead, warping produces a small 'effective' tension for certain strings. The warped spacetime metric takes the form

$$\mathrm{d}s^2 = \mathrm{e}^{2A(y)} g_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + \mathrm{d}s_\perp^2(y). \tag{4}$$

Here $g_{\mu\nu}$ is the metric observed by low energy observers. That is, this is the metric with which the 'clocks and rulers' of low energy experiments are defined. Above this metric is multiplied by a conformal factor which depends on coordinates y^a of the internal space. By definition, we will set $\mathrm{e}^A = 1$ in the bulk of the internal space. However, the expectation is that there will be throats with strong warping where $\mathrm{e}^{A_o} \ll 1$. Such scenarios are simply constructed in the context of the type IIb theories [9].

Now if a fundamental string falls to the bottom of such a throat, it will have an effective tension which is much less than the fundamental string tension. Consider a string with tension μ_{fun}. Hence at a generic point in the internal space, a segment of string with length D carries an energy $\mu_{\text{fun}}D$. However, at the bottom of the throat, if a segment of string is measured to span a distance D, its proper length is only $\mathrm{e}^{A_o}D$ and so the string carries a much lower energy. Also accounting for the red-shifting of clocks at the bottom of the throat, one finds

$$\mu_{\text{eff}} = \mathrm{e}^{2A_o}\mu_{\text{fun}} \ll \mu_{\text{fun}}. \tag{5}$$

The gravitational potential of the warped throat also plays the important role of confining any strings which fall into the throat to remain this portion of the internal space.

One can also understand the above from a ten-dimensional perspective where the string tension is fixed throughout the spacetime. However, the internal wavefunction of the massless four-dimensional graviton follows the warp factor in Eq. (4). Hence it is peaked in the bulk of the internal space and exponentially suppressed at the bottom on a throat. Then the reduced effective tension reflects the weakness of the overlap of this wavefunction with the strings, i.e., the weakness with which the four-dimensional graviton couples to strings in the throat.

In any event, what we have seen is that in such compactifications, which are 'exotic' by the standards of 1985, the string tension and the observed Planck scale are decoupled. Hence the existence of cosmic superstrings would not present an obvious contradiction with the early observations of the CMB isotropy.

2.2. Strings in inflation

In the opening discussion, it was suggested that if fundamental strings had a Planck scale tension, then they would naturally arise as relics from the initial Planck scale phase of the universe. Hence a later inflationary stage would dilute these strings away along with any other topological defects produced in the very early universe. However, since we have just established that we might expect strings to have tensions much lower than the Planck scale, it is natural to think that they might be formed in a much later and less energetic stage in the evolution of the universe. Hence to avoid the dilution of cosmic superstrings by inflation, one need only construct a model where they are formed after or at the end of inflation.

Indeed, it was first noticed in [10] that D-strings are formed upon the exit from inflation in scenarios involving collisions of D-branes and anti-D-branes. It was further argued in [11] that in fact brane-antibrane scenarios [10,12] of inflation, generically lead to the copious production of lower-dimensional D-branes that are one-dimensional in the noncompact directions. Further, [11] pointed out that zero-dimensional defects (monopoles) and two-dimensional defects (domain walls) are not produced; either of which would be phenomenologically dangerous.

These scenarios give a stringy or geometric realization of hybrid inflation and so D-string production can be seen as a special case of the production of strings in hybrid inflation. For this analogy, the D1-branes can be regarded as topological defects in the tachyon field that mediates D3–$\overline{\text{D3}}$ annihilation [13]. Hence in the present cosmological context, their production is described by the standard Kibble mechanism [14]. Now fundamental strings do not have a classical description in terms of these same variables, but S-duality would relate D-string production in the collision of a D3-brane with an anti-D3-brane to the production of fundamental strings. Hence one should expect that both D-strings and F-strings are produced at the end of brane inflation [1,15].

In fact, given both F-strings and D-strings, there will also be (p,q)-strings [16], which are bound states of p F1-branes and q D1-branes [17]. Their tension in the ten-dimensional type IIb theory is

$$\mu_{p,q} = \frac{1}{2\pi \ell_s^2}\sqrt{(p - Cq)^2 + \mathrm{e}^{-2\Phi} q^2}, \tag{6}$$

where C and Φ are the Ramond-Ramond scalar and the dilaton, respectively, both evaluated at the location of the string. The tension (and existence) of these bound-state strings would have to be re-evaluated in the relevant cosmological context, e.g., in the SUSY-breaking vacuum of the late universe.[1]

Hence brane-antibrane inflation provides a concrete scenario which has the potential to produce a rich network of 'superstrings' at the end of inflation, and so these strings may still be present as cosmic strings in the present-day universe.

2.3. *String instabilities*

Having found that the first two challenges above can be avoided, we are left to consider the stability of potential cosmic superstrings. It was noticed in [2] that there are two potential instabilities: fragmentation in open string theories or confinement by axion domain walls. Unfortunately, with the rich array of strings and compactifications which modern string theory presents, we can in fact identify an even longer list of possible instabilities:

(i) Breakage on space-filling branes;
(ii) Confinement by axion domain walls;
(iii) 'Baryon decay';
(iv) Tachyon decay.

However, these mechanisms are all *potential* instabilities. We find that the existence of stable macroscopic strings will depend on the specific details of a given model. More accurately, one must investigate whether a particular compactification will support long strings which are at least metastable on the relevant cosmological timescales. Hence certain classes of string models may still give rise to cosmic superstrings but others do not. As an example in the next section, we will consider the string theory inflation model of Kachru, Kallosh, Linde, Maldacena, McAllister, and Trivedi ($\mathbb{KLMT}$) [18]. First, let us discuss the various instabilities above in more detail.

2.3.1. *Breakage on space-filling branes*

The fragmentation of a type I string is the prototype example of string breakage. The modern interpretation is that the string forms new endpoints by attaching to a spacetime-filling D9-brane. Similarly, the fundamental type II string (F-string) can end on any D-brane, and so in any type II model with Dp-branes filling the noncompact dimensions, there will be an amplitude for the string to break. Of course, for $p < 9$ the D-brane does not fill all of the *compact* dimensions, and this breakage can be suppressed if there is a transverse separation between the strings and D-branes. Hence the latter allows metastable strings to exist in some models with space-filling branes.

Various chains of dualities can be used to determine which strings will break on certain space-filling branes. For example, performing an S-duality transformation of the F1/D3 system shows that a D-string can end on a D3-brane and so will be unstable in compactifications with space-filling D3-branes. From there, one argues with T-duality that a string arising from a D3-brane wrapped on a two-cycle can end on a D5-brane which wraps the same cycle and fills the noncompact dimensions.

One also has the description of lower dimensional D-branes breaking on higher dimensional branes in terms of the smaller branes dissolving into various fluxes of the worldvolume gauge field on the larger branes. This point of view is also useful to determine whether certain combinations of strings and space-filling branes are unstable. For example, one finds that a D-string cannot break on a D7-brane [1]. Similarly, a D-string attaching to a D5-brane is a marginal case. In ten dimensions, a parallel D1/D5 system is supersymmetric and so saturates the BPS bound. One would have to re-examine this system in detail given the specific details of supersymmetry breaking to determine whether or not an instability arises.

In summary, stability of macroscopic strings requires that there be no space-filling branes on which the string can end, or that the decay be suppressed by transverse separation.

[1] We would like to thank Jeff Harvey for a discussion on this point.

2.3.2. Confinement by axion domain walls

An essential feature of any BPS p-brane is that it must source a $(p+1)$-form field. Hence if cosmic superstrings arise from having such branes wrap an internal $(p-1)$-cycle, $\mathcal{K}_{p-1}$, a two-form potential $C_{[2]}$ will couple to the world-sheet of the effective strings in four dimensions. In the four-dimensional theory, this two-form may be replaced by a scalar axion ϕ, as usual: $\mathrm{d}C_{[2]} = *_4\mathrm{d}\phi +$ source terms. The strings are electric sources for $C_{[2]}$ and so magnetic or topological sources for ϕ. That is, on any contour C encircling the string, the axion field (appropriately normalized) changes by 2π:

$$\oint_C \mathrm{d}x \cdot \partial\phi = 2\pi. \tag{7}$$

Now consider a Euclidean $(6-p)$-brane instanton, which couples magnetically to the original $(p+1)$-form, wrapping a $(7-p)$-cycle $\mathcal{K}_{7-p}$ that intersects $\mathcal{K}_{p-1}$ once. This brane is an electric source for ϕ, and so the instanton amplitude is proportional to $\mathrm{e}^{\mathrm{i}\phi}$. Since all supersymmetries are ultimately broken, the fermion zero modes in the instanton amplitude are lifted, and this produces a periodic potential for ϕ. From Eq. (7) it follows that ϕ cannot sit in the minimum of this potential everywhere as we encircle the string — there is a kink where it changes by 2π and passes over the maximum of the potential. Since the kink in ϕ intersects any contour C that circles the string, it defines a domain wall ending on the string. Unless the domain wall tension is exceedingly small this will cause the strings to collapse rapidly [3]. One might note, however, that scenarios with large extra dimensions have the potential to produce an exponential suppression of the domain wall tension.

2.3.3. 'Baryon decay'

Certain string models support form field fluxes on internal cycles, which give rise to an interesting interplay between low energy gauge fields and the axions associated with four-dimensional strings, as well as a new mechanism for string breakage. As an example, consider a type IIb compactification with a three-cycle $\mathcal{K}_3$ with a nonvanishing RR three-form flux:

$$\int_{\mathcal{K}_3} F_{(3)} = M, \tag{8}$$

Now consider a D3-brane wrapped on the same cycle. This is a localized particle in four dimensions, which we refer to loosely as a baryon, because of the role it plays in gauge/string duality [19]. Now the background flux couples to the worldvolume gauge field providing a background charge density, $\mathrm{d}*\mathrm{d}A = -F_{(3)}$. As spatial sections of the D3-brane are closed, the net flux (8) would lead to an inconsistency unless other sources are introduced to produce a net vanishing charge. The latter is precisely accomplished by having M F1-branes end on the baryon.

Hence, if $M = 1$ the fundamental strings can break by the production of baryon–antibaryon pairs. If $M \geqslant 2$ then instead the baryon is a vertex at which M F-strings meet. In this case, baryon–antibaryon pairs can mediate the decay of (p,q) strings to $(p-M,q)$ strings. The baryon is then a 'bead' at which a (p,q) string and a $(p-M,q)$ string join, and it will accelerate rapidly in the direction of the higher-tension string. This decay mechanism becomes ineffective and hence the strings are stable for $|p| \leqslant M/2$. More generally, if

$$\int_{\mathcal{K}_3} F_{(3)} = M, \qquad \int_{\mathcal{K}_3} H_{(3)} = M' \tag{9}$$

then the baryon is a vertex at which M F-strings and M' D-strings end. In this case, baryon–antibaryon pairs would allow (p,q) strings to decay to $(p-M, q-M')$ strings.

2.3.4. Tachyon decay

An additional form of string breakage may come from the tachyonic decay of an unstable D-brane. This is similar to fragmentation on space-filling branes in that the D-brane turns into ordinary quanta on a stringy time scale by decays everywhere along its length. An unstable D-brane can typically be seen as being constructed from a D–$\overline{\mathrm{D}}$ pair – for a review see [13]. The tachyon mediating the decay of the brane is an open string stretching between them. As with breakage, this decay can also be suppressed by a transverse separation of the brane–antibrane pair.

3. An example: The $\mathbb{K}$L$\mathbb{M}$T model

We now apply the previous analysis to the $\mathbb{K}$L$\mathbb{M}$T model [18], which provides an excellent test case for cosmic superstrings. Our final result is that the nature of the cosmic strings in this model depends on precisely how the Standard Model fields and the moduli stabilization are introduced. We identify three possibilities: (a) no strings; (b) D1-branes only (or fundamental strings only); (c) (p,q) strings with an upper bound on p.

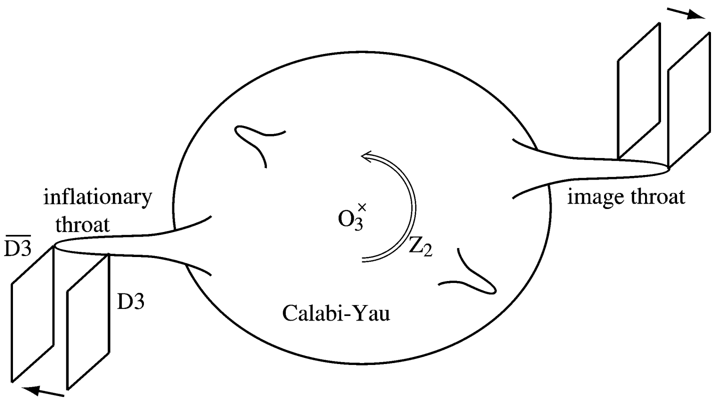

Fig. 1. Schematic picture of the $\mathbb{KLMT}$ geometry: a warped Calabi–Yau manifold with throats, identified under a $\mathbf{Z}_2$ orientifold.

3.1. General framework

The $\mathbb{KLMT}$ model is based on IIB string theory on a Calabi–Yau orientifold. The internal space is orientifolded by a $\mathbf{Z}_2$ symmetry that has isolated fixed points, which become O3-planes.[2] The spacetime metric is warped as in Eq. (4). Brane inflation is realized with a D3-brane falling towards an $\overline{\mathrm{D3}}$-brane at the bottom of one of the throats. There is a large warp factor $e^{A_0} \ll 1$ at the bottom of the inflationary throat. The resulting redshift has the important role of suppressing both the inflationary scale and the scale of string tension, as measured by four-dimensional observers. Note that in Fig. 1 the covering manifold has pairs of throats which are identified under the $\mathbf{Z}_2$ but not a single throat identified with itself; most importantly we envisage that there is no O3-plane in the inflationary throat.

As discussed, the D3–$\overline{\mathrm{D3}}$ annihilation in the inflationary throat is expected to produce copious amounts of F-strings and D-strings, with effective tensions as in Eq. (5). Of course, in this context, one should expect the formation of (p,q) strings for general (relatively prime) p and q. There is also another possibility, which however can be quickly disposed of. In the $\mathbb{KLMT}$ model, the throat is a Klebanov–Strassler geometry [20], whose cross section is topologically $S^2 \times S^3$. A D3-brane wrapped on the S^2 also gives a string in four dimensions. However, the S^2 is topologically trivial, it collapses to a point at the end of the throat [20], and so this string can break rapidly. It remains to discuss the stability of the (p,q) strings.

3.2. Instabilities without branes

Here we focus on instabilities apart from such breakage on space-filling branes. Hence these would be potential instabilities even when no such branes remain in the inflationary throat.

The first observation is that the (p,q) strings are not BPS. The orientifold projection removes the massless four-dimensional modes of the $B_{\mu\nu}$ and $C_{\mu\nu}$ forms which couple to the F- and D-strings [9]. Further one finds that this projection in the $\mathbb{KLMT}$ model turns a D1-brane in the inflationary throat into an anti-D1-brane in its image throat. The four-dimensional D-string is thus in this construction a D1–$\overline{\mathrm{D1}}$ bound state, a potentially unstable configuration. However, the distance between the D-string and its image should be somewhat greater than ℓ_s, so the D1–$\overline{\mathrm{D1}}$ strings are stretched and nontachyonic. Even without a tachyon it is possible for the D1-string to fluctuate into the other throat (or to the O3-plane) and annihilate with the $\overline{\mathrm{D1}}$. However, one can argue that the gravitational potential confining the strings to their respective throats is strong enough to suppress this decay and produce strings which are metastable on cosmological time scales.

The decay proceeds through the appearance of a hole in the Euclidean world-sheet, in which the D1 and $\overline{\mathrm{D1}}$ have annihilated. At the edge of this hole the D1-brane crosses over to the image throat and annihilates with the $\overline{\mathrm{D1}}$. The rate is given by the usual Schwinger expression for this instanton,

$$e^{-B}, \quad B = \pi\sigma^2/\rho. \tag{10}$$

Here ρ is the action per unit area, i.e., the tension $e^{2A_0}/2\pi\ell_s^2 g_s$. The parameter σ is the action per unit length for the boundary of the hole. Since the D1-brane passes through the unwarped bulk of the Calabi–Yau, this is of order $R/2\pi\ell_s^2 g_s$ where R is the distance between the throat and its image. The warp factor dominates the result,

$$B \sim e^{-2A_0} \sim 10^8, \tag{11}$$

[2] The following results extend to the more general F theory construction essentially unchanged.

where the numerical value is taken from [18]. Hence the warping suppresses the decay by the impressive factor e^{-B}, even though the D1 and its image are only a few string units apart! The decay of the F-string and all the other (p,q) strings are similarly stabilized, because they involve world-sheets that stretch from one throat to its image, through the unwarped region.

Next, let us consider decay via baryon pair production. The only relevant baryons are the D3-branes that wrap the S^3 in the Klebanov–Strassler throat. All other three-cycles pass through the bulk of the Calabi–Yau, and so the masses of the corresponding baryon are at the string scale, unsuppressed by the warp factor. For these the pair production rate is then suppressed by the same factor (11).

The S^3 in the throat carries M units of RR flux $F_{(3)}$ [20,9]. We will assume that $M \gtrsim 12$, which is a lower bound required for the stability of the original $\overline{\text{D3}}$ in the inflationary throat [21]. Thus as discussed above, baryon-mediated decays will not destabilize the (p,q) strings with small p, and there may still be a rich spectrum.

The tunnelling rate may again be determined by a calculation analogous to that above, and one obtains a decay rate for $(p,q) \to (p-M,q)$ of order of e^{-B} with

$$B \sim 0.2 \times \frac{qM^2}{2p-M} \tag{12}$$

for $p > M/2$. There is no suppression from the warp factor because the decay takes place entirely in the throat, and the decay will be rapid on a cosmological time scale for a wide range of parameters.

3.3. Space-filling branes

A key feature, which will distinguish models within the general framework described above, is what branes remain in the inflationary throat after the end of inflation. In the $\mathbb{KLMT}$ model there must be additional space-filling branes for two reasons: (a) there must be the branes on which the Standard Model fields live; and (b) the moduli stabilization in this model involves one or more anti-D3-branes located in a throat. Either of these branes may be placed in the inflationary throat.

The calculations in the previous section shows that any space-filling branes outside the inflationary throat are irrelevant. In order to break on one of these, the string must fluctuate out of the throat, which again is immensely suppressed (11).

Now suppose that the stabilizing $\overline{\text{D3}}$-brane(s) are in the same throat in which inflation occurs. That is, inflation is driven by N D3-branes and $\Delta + N$ $\overline{\text{D3}}$-branes for some $\Delta > 0$, so that after annihilation Δ $\overline{\text{D3}}$-branes remain. In this case the F-strings and D-strings can both break, as can all the (p,q) strings, and there are no cosmic strings. Of course, stabilizing $\overline{\text{D3}}$-branes may not be present in more general constructions – see, e.g., [22] – which may then avoid this problem.

Now let us consider the Standard Model branes. In the $\mathbb{KLMT}$ model it is natural to introduce D3-branes and/or $\overline{\text{D3}}$-branes, as well as D7-branes in the F theory constructions. Reference [23] gives constructions of the Standard Model in terms of local configurations with these ingredients. These local constructions can then be incorporated into the $\mathbb{KLMT}$ model. In order to reduce the supersymmetry of the low energy theory, it is necessary that the D3-branes (or $\overline{\text{D3}}$-branes) be fixed at an appropriate singularity, for example an orbifold fixed-point. The D7-branes are typically needed for anomaly cancellation, and they must also pass through this singularity.

If the Standard Model 3-branes and the associated singularity are located in the inflationary throat, then as before all the (p,q) strings are unstable to breakage. Alternatively, the 3-branes and the singularity may be outside the inflationary throat but one or more of the D7-branes pass through the bottom of the throat. In this case, the fundamental strings will break but the D-strings will not. Hence, the only cosmic string is the D-string. One caveat in this argument is that if the gauge field on the D7-brane is confined in some way, then again a larger set of (p,q) strings will be stable.

4. Observational consequences

The string tension is paramount amongst the physical properties of the strings determining the evolution of cosmic string networks and their signatures. For the models of [11], which are based on unwarped compactifications with the moduli fixed by hand, the authors find a range

$$10^{-11} \lesssim G\mu \lesssim 10^{-6}\,, \tag{13}$$

with a narrower range around 10^{-7} for their favored models based on branes at small angles. For the $\mathbb{KLMT}$ model, combining Eqs. (3.7), (3.9), and (C.12) of [18] gives

$$\frac{G^2 e^{4A_0}}{(2\pi\alpha')^2 g_s} = \frac{\delta_H^3}{32\pi C_1^3 N_e^{5/2}}, \tag{14}$$

where C_1 is a model-dependent constant of order unity and N_e is the number of e-foldings for the observed fluctuations. Inserting the numerical values [18] $\delta_H = 1.9 \times 10^{-5}$, $C_1 = 0.39$, and $N_e = 60$ gives 4×10^{-20} for the right-hand side. The left-hand side is simply the product of the values of $G\mu_{\mathrm{eff}}$ for the F-string and the D-string, assuming for simplicity that the RR scalar C vanishes. Thus,

$$\sqrt{G\mu_{\mathrm{F}} G\mu_{\mathrm{D}}} \sim 2 \times 10^{-10}, \qquad \mu_{\mathrm{F}}/\mu_{\mathrm{D}} = g_{\mathrm{s}}. \tag{15}$$

With g_{s} in the range 0.1 to 1, $G\mu_{\mathrm{eff}}$ for both strings would be in the range 10^{-10} to 10^{-9}.

After their formation at the end of inflation, string networks decay by the combined process of intercommutation (i.e., long strings decay into smaller loops) and gravitational radiation. Assuming gravitational radiation dominates, and that the decay proceeds at the maximum rate consistent with causality, the distribution of strings will scale with the horizon volume. For such a scaling distribution of cosmic strings, the current upper bound on $G\mu$ comes from the power spectrum of the CMB: $G\mu \lesssim 0.7 \times 10^{-6}$ [24] (see also [25]). Considering non-gaussianities in the CMB has improved this limit slightly to around $G\mu \lesssim 0.3 \times 10^{-6}$ [26].

Cosmic strings produce large quantities of gravitational waves, because they are relativistic and inhomogeneous [27]. Pulsar timing measurements then place an upper bound on $G\mu$ which is currently the most stringent limit. Here the most precise measurements set a bound: $G\mu \lesssim 10^{-7}$ [28].

Strong gravitational lensing by long cosmic strings should provide a unique signature with a distinct symmetry axis as well as multiple lensing events in a given patch on the sky [29]. One such candidate has been reported recently with $G\mu \simeq 0.4 \times 10^{-6}$ [30]. While this claim may be in conflict with the best upper bound quoted above, the observers hope to confirm the cosmic string model of their gravitational lense with higher resolution images.

Remarkably, future measurements of non-Gaussian emission of gravitational waves from cusps on strings will be sensitive to cosmic strings with values of $G\mu$ seven orders of magnitude below the current bound, covering the entire range of tensions discussed above. According to [31], even LIGO 1 may be sensitive to a range around $G\mu \sim 10^{-10}$, while LIGO 2 will reach down to $G\mu \sim 10^{-11}$ and LISA to $G\mu \sim 10^{-13}$. In addition [31], pulsar timing measurements may reach a sensitivity of $G\mu \sim 10^{-11}$. Thus, gravitational waves provide a potentially large window into string physics, if we have a model in which strings are produced after inflation and are metastable.

5. Conclusions

We have found that both fundamental and Dirichlet strings might be observed as cosmic strings. The issue is model-dependent – it depends on having brane inflation to produce the strings, and on having a scenario in which the strings are stable.

Of course, if cosmic strings are discovered, one challenge will be to distinguish fundamental objects from gauge theory solitons. Indeed, this is not a completely sharp question, because these are dual descriptions of the same objects. If one can infer that the strings have intercommutation probabilities less than unity, this is a strong indication that they are weakly coupled F-strings. Discovery of a (p, q) spectrum of strings would be a promising signal for F- and D-strings. Note, however, that these throats have a dual gauge description [20] and therefore such strings can also be obtained in gauge theory; the spectrum is actually a signal of an $SL(2, \mathbf{Z})$ duality and so might arise in other ways as well. If cosmic strings are found through the gravitational radiation from cusps, determining their tensions and intercommutation properties will require a spectrum of many events. Quite generally the observational bounds can be improved by re-analysing the behavior of the string networks. Cosmic superstrings suggest looking at new regions of parameter space with smaller string tensions and smaller intercommutation probabilities [32]. The evolution of the (p, q) string networks are also more complex than those previously studied, and so one must first ask whether such networks scale as assumed above.

Nevertheless, cosmic superstrings are viable with our modern perspective of string theory and have the potential to provide a spectacular new window onto string theory through astronomical observations.

Acknowledgements

RCM would like to thank the organizers of Strings 04 in Paris for the opportunity to speak on this material, as well as for organizing a stimulating meeting in a marvellous setting. Research at the Perimeter Institute is supported in part by funds from NSERC of Canada. RCM is further supported by an NSERC Discovery grant. The work of JP is supported by National Science Foundation grants PHY99-07949 and PHY00-98395.

References

[1] E.J. Copeland, R.C. Myers, J. Polchinski, Cosmic F- and D-strings, JHEP 0406 (2004) 013, hep-th/0312067.
[2] E. Witten, Cosmic superstrings, Phys. Lett. B 153 (1985) 243.

[3] A. Vilenkin, A.E. Everett, Cosmic strings and domain walls in models with Goldstone and pseudogoldstone bosons, Phys. Rev. Lett. 48 (1982) 1867.
[4] K. Becker, M. Becker, A. Strominger, Nucl. Phys. B 456 (1995) 130, hep-th/9507158.
[5] M.B. Hindmarsh, T.W. Kibble, Cosmic strings, Rept. Prog. Phys. 58 (1995) 477, hep-ph/9411342;
A. Vilenkin, E.P.S. Shellard, Cosmic Strings and Other Topological Defects, Cambridge Univ. Press, Cambridge, 1994.
[6] A.H. Guth, The inflationary universe: a possible solution to the horizon and flatness problems, Phys. Rev. D 23 (1981) 347.
[7] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, The hierarchy problem and new dimensions at a millimeter, Phys. Lett. B 429 (1998) 263, hep-ph/9803315;
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, New dimensions at a millimeter to a Fermi and superstrings at a TeV, Phys. Lett. B 436 (1998) 257, hep-ph/9804398;
N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phenomenology, astrophysics and cosmology of theories with sub-millimeter dimensions and TeV scale quantum gravity, Phys. Rev. D 59 (1999) 086004, hep-ph/9807344.
[8] L. Randall, R. Sundrum, A large mass hierarchy from a small extra dimension, Phys. Rev. Lett. 83 (1999) 3370, hep-ph/9905221;
L. Randall, R. Sundrum, An alternative to compactification, Phys. Rev. Lett. 83 (1999) 4690, hep-th/9906064.
[9] S.B. Giddings, S. Kachru, J. Polchinski, Hierarchies from fluxes in string compactifications, Phys. Rev. D 66 (2002) 106006, hep-th/0105097.
[10] C.P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh, R.J. Zhang, The inflationary brane–antibrane universe, JHEP 0107 (2001) 047, hep-th/0105204.
[11] N. Jones, H. Stoica, S.H. Tye, Brane interaction as the origin of inflation, JHEP 0207 (2002) 051, hep-th/0203163;
S. Sarangi, S.H. Tye, Cosmic string production towards the end of brane inflation, Phys. Lett. B 536 (2002) 185, hep-th/0204074;
N.T. Jones, H. Stoica, S.H. Tye, The production, spectrum and evolution of cosmic strings in brane inflation, Phys. Lett. B 563 (2003) 6, hep-th/0303269.
[12] G.R. Dvali, Q. Shafi, S. Solganik, D-brane inflation, hep-th/0105203.
[13] A. Sen, Non-BPS states and branes in string theory, hep-th/9904207.
[14] T.W.B. Kibble, Topology of cosmic domains and strings, J. Phys A 9 (1976) 1387.
[15] G. Dvali, A. Vilenkin, Solitonic D-branes and brane annihilation, Phys. Rev. D 67 (2003) 046002, hep-th/0209217;
G. Dvali, A. Vilenkin, Formation and evolution of cosmic D-strings, JCAP 0403 (2004) 010, hep-th/0312007.
[16] J.H. Schwarz, An SL(2,Z) multiplet of type IIB superstrings, Phys. Lett. B 360 (1995) 13;
J.H. Schwarz, Phys. Lett. B 364 (1995) 252, hep-th/9508143.
[17] E. Witten, Bound states of strings and p-branes, Nucl. Phys. B 460 (1996) 335, hep-th/9510135.
[18] S. Kachru, R. Kallosh, A. Linde, J. Maldacena, L. McAllister, S.P. Trivedi, Towards inflation in string theory, JCAP 0310 (2003) 013, hep-th/0308055.
[19] E. Witten, Baryons and branes in anti de Sitter space, JHEP 9807 (1998) 006, hep-th/9805112;
D. Berenstein, C.P. Herzog, I.R. Klebanov, Baryon spectra and AdS/CFT correspondence, JHEP 0206 (2002) 047, hep-th/0202150.
[20] I.R. Klebanov, M.J. Strassler, Supergravity and a confining gauge theory: duality cascades and χSB-resolution of naked singularities, JHEP 0008 (2000) 052, hep-th/0007191.
[21] S. Kachru, J. Pearson, H. Verlinde, Brane/flux annihilation and the string dual of a non-supersymmetric field theory, JHEP 0206 (2002) 021, hep-th/0112197.
[22] A. Saltman, E. Silverstein, The scaling of the no-scale potential and de Sitter model building, hep-th/0402135.
[23] G. Aldazabal, L.E. Ibanez, F. Quevedo, A.M. Uranga, D-branes at singularities: a bottom-up approach to the string embedding of the standard model, JHEP 0008 (2000) 002, hep-th/0005067;
J.F.G. Cascales, M.P. Garcia del Moral, F. Quevedo, A. Uranga, Realistic D-brane models on warped throats: fluxes, hierarchies and moduli stabilization, hep-th/0312051.
[24] M. Landriau, E.P.S. Shellard, Large angle CMB fluctuations from cosmic strings with a comsological constant, astro-ph/0302166.
[25] L. Pogosian, S.H.H. Tye, I. Wasserman, M. Wyman, Observational constraints on cosmic string production during brane inflation, Phys. Rev. D 68 (2003) 023506, hep-th/0304188;
L. Pogosian, M.C. Wyman, I. Wasserman, Observational constraints on cosmic strings: Bayesian analysis in a three dimensional parameter space, astro-ph/0403268.
[26] E. Jeong, G.F. Smoot, Search for cosmic strings in CMB anisotropies, astro-ph/0406432.
[27] R.R. Caldwell, R.A. Battye, E.P.S. Shellard, Relic gravitational waves from cosmic strings: updated constraints and opportunities for detection, Phys. Rev. D 54 (1996) 7146, astro-ph/9607130.
[28] A.N. Lommen, New limits on gravitational radiation using pulsars, astro-ph/0208572.
[29] D. Huterer, T. Vachaspati, Gravitational lensing by cosmic strings in the era of wide-field surveys, Phys. Rev. D 68 (2003) 041301, astro-ph/0305006.
[30] M. Sazhin, et al., CSL-1: a chance projection effect or serendipitous discovery of a gravitational lens induced by a cosmic string?, Mon. Not. Roy. Astron. Soc. 343 (2003) 353, astro-ph/0302547;
M.V. Sazhin, O.S. Khovanskaya, M. Capaccioli, G. Longo, J.M. Alcala, R. Silvotti, M.V. Pavlov, Lens candidates in the Capodimonte Deep Field in the vicinity of the CSL1 object, astro-ph/0406516.
[31] T. Damour, A. Vilenkin, Gravitational wave bursts from cosmic strings, Phys. Rev. Lett. 85 (2000) 3761, gr-qc/0004075;
T. Damour, A. Vilenkin, Gravitational wave bursts from cusps and kinks on cosmic strings, Phys. Rev. D 64 (2001) 064008, gr-qc/0104026.
[32] M.G. Jackson, N.T. Jones, J. Polchinski, Collisions of cosmic F- and D-strings, hep-th/0405229.