Cosmic F- and D-strings

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and after

1. Before the 2nd S.S. revolution.
2. Stability of cosmic strings.
3. The KLMT model.
4. Observational consequences.

1. $t < 1995$: There was a clear distinction between fundamental and cosmic strings.

   Fundamental strings had tension $\mu$ close to the Planck scale: e.g. heterotic:

   $$ G\mu = \frac{\alpha_{GUT}}{16\pi} \gtrsim 10^{-3} $$

   Cosmic strings must have

   $$ G\mu \lesssim 10^{-5} $$

   from $\delta T/T$. (deficit angle $\Delta = 4\pi G\mu$)

   Thus cosmic strings had to be magnetic or electric flux tubes in the low energy theory.
Why don't fundamental strings of cosmic length exist?

a. inflation \((V^{1/4} < m^{1/2})\)

b. decay (Witten 1985)

A long type I string breaks into pieces on a stringy time scale:

- A long heterotic string always bounds an axion domain wall, which makes it contract and disappear.

Axion domain walls: Fundamental heterotic string couples \[ B_{\mu\nu} \, dx^\mu \, dx^\nu \]

\[ B_{\mu\nu} \approx \text{axion } \phi \text{ in effective 4-d theory:} \]

\[ \mathcal{L}[B_{\mu\nu}, \phi] = \frac{1}{2} \partial_{\mu}\phi \partial^{\mu}\phi + \text{Chern-Simons} \]

Direct (electric) coupling to \(B_{\mu\nu} = \) topological (magnetic) coupling to \(\phi\):

\[ \Delta \phi = 2\pi \]

Chern-Simons coupling of \(B_{\mu\nu} \rightarrow \)

Axion coupling \(\phi F \wedge F\)

Gauge instantons produce \(V(\phi) \propto \cos \phi\)

\[ V(\phi) \]

0 \hspace{1cm} 2\pi \Rightarrow \text{domain wall}

Type II? Wrapped NS5-instantons
After the revolution:

A. More kinds of string:
   - F-strings, D-strings, partly wrapped NS-, D-, M-branes.
B. Possible lower string scale due to large compact dimensions, warping.
C. Dualities relate various objects, including gauge theory flux tubes.

⇒ must revisit question of cosmic strings.

Cosmic strings from brane inflation:

Jones, Stoica, Tye; Sarangi, Tye;
Pogosian, Tye, Wassermeier, Wyman.

\[ D(p-2) \rightarrow Dp \] + radiation

K-theory: \( \overline{D}D \) annihilation can produce lower dimensional D-branes (defects in tachyon field)

Kibble theory: "must"...

Here strings, not monopoles or domain walls.

Models: \( 10^{-11} \lesssim G_{\mu} \lesssim 10^{-6} \)

\( \left( \frac{\delta T}{T} \rightarrow H \rightarrow m \right) \) (tori)

Current bound: \( G_{\mu} \lesssim 10^{-6} \) (power spectrum)
Necessary conditions for strings to be cosmologically interesting:

- \( G_M \) not too large  
- Produced after inflation  
- Stable  

Naïve extrapolation of Witten (1985):

BPS strings confined by domain walls.
Non-BPS strings unstable.

The actual story is more interesting, and model-dependent.

2. Stability.

- Breakage: prototype is type I string

\[ \rightarrow \]

Modern interpretation: endpoints attach to spacetime-filling D9-brane

A type II F-string can decay on any Dp-brane that fills the non-compact directions (\( p \geq 3 \))

Possible source of stability: transverse separation - mod \( \alpha' H^2 \)
5. Domain walls

Every BPS string couples to form a field = 4d axion, every axion gets a potential from some instanton; difficult to see how domain wall tension can be suppressed \( \Rightarrow \) need non-BPS strings.

c. Tachyonic decay:

\[ \text{tachyonic open string} \]

- breakage

Can be suppressed by transverse separation

\[ \text{D} \quad \overline{\text{D}} \]
Puzzle: what if a string appears to have both instabilities: it can't, because the boundary of a boundary is zero! What happens?

\[ \int_{D_1} C + \int_{D_3} C \wedge F \quad C = C_{\mu
u} \]

- Topological coupling \( C_{\mu
u} \) = electric coupling of axion \( \phi \): \( (\partial \phi + A_{\mu})^2 \)

\( A_{\mu} \) eats \( \phi \) \( \Rightarrow \) no domain wall.

But \( U(1) \) is Higgsed so flux can't spread: string can't break; it's stable!

(Non-perturbative decays? ???)

3. Example: KLP model

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi

Orientifold of Calabi-Yau with RS-like throat

\[ z_0 < 1 \quad \Rightarrow \quad \mathbb{Z}_2 \text{ identification} \]  

\[ ds^2 = z^2 (x^+ \ldots x^6) dx^+ dx^- \cdots + \ldots \]

(+ fluxes + \( D3 + \overline{D3} \)-instantons)

Inflation from \( D3 + \overline{D3} \) in throat

\[ \overline{D3} \]

\[ D3 \]
\[ \text{Tension?} \]

\[ z_0^4 \sim \frac{V}{M_{\text{pl}}^4} \times \frac{S_H^{3/2}}{N_c^{5/2}} \sim 10^{-17} \]

\[ \mathcal{G} \mu \sim z_0 \sim 10^{-8} \text{eV} \]

(Kibble?  \( g_s = O(1) \))

+ also (Schwarz, Witten)

\( p \neq q \): \( M \propto \sqrt{p^2 + q^2 / g_s^2} \)
Stability? First, neglect all branes after inflation...

These 1-branes are non-BPS...
(\sim T\text{-}dual to type I D7-branes)
Orientifold removes \(B_{uv}, C_{uv}\) from spectrum.
(cf. \(T^6/\mathbb{Z}_2\))

\(D1 + \overline{D1}\) can annihilate, but to do so they must tunnel out of warped throat...
action \(\sim Z_0^{-2} \sim 10^8\)

amplitude \(\sim e^{-10^8}\)

\(\Rightarrow\) essentially stable

A complete model also requires

- A \(\overline{D3}\) in a throat for stabilization.
- Standard Model branes - e.g.
  \(D3\)s at orbifold singularity
  \(\overline{D3}\)s at orbifold singularity
  intersecting \(D7\)s.

- If these are all outside the inflationary throat, the \((p, q)\) strings are stable due to tunnelling suppression.

- If only the stabilizing \(\overline{D3}\) is in the inflationary throat, there are no stable strings. But this scenario has a problem with reheating: all the energy goes into the gauge field in the \(\overline{D3}\).
- If the Standard Model D3/D3 orbifold sing. is in the inflaton
  throat, D1 and F1 are unstable. However, fractional D-strings (D3's
  wrapped on collapsed S^3) exist.

  These can break on the D3 and couple to a twisted sector axiom, so they
  are stable. (Z_2 \to 3 kinds, not necessarily degenerate)

- If only a D7 intersects the
  inflationary throat, the F-strings can
  break but the D-strings are stable.

Wide range of possibilities:
- No strings
- 1 kind of string
- Several kinds of string
  - Fractional D-strings
  - (p,q) strings

4. Signatures

Strings decay through intercommutation

\[ \rightarrow \Rightarrow \]

and gravitational radiation. If this is maximally efficient, the distribution
of strings per horizon volume will be constant (scaling behavior).

This is what the simulations show.
Sensitivity/bounds -

- CMB power spectrum: \( G_\mu \lesssim 10^{-6} \)
- CMB non-Gaussianity: ?
- Lensing: \( 1\text{ arc-sec} \equiv G_\mu = 4 \times 10^{-7} \)
  (1.9" lens reported by Sazhin, et al., astro-ph/0302547)

**Gravitational waves:**

- Pulsar timing: \( G_\mu \lesssim \text{several} \times 10^{-6} \)
- BBN: \( G_\mu \lesssim \text{several} \times 10^{-6} \)
- Radiation from cusps:

From Allen + Caldwell (1991)
A complication:
Fractional and (p, q) cases have more than one kind of string, so can have

\[ \begin{align*}
1 & \quad / \quad 1 \\
2 & \quad 2 \\
3 & \quad 1
\end{align*} \]

Can lead to frozen string networks:

From Damour + Vilenkin (2001)
Scaling: $\rho \propto t^{-2}$

($w = +\frac{1}{3}$ during radiation-dom. era,
$w = 0$ during matter-dom.)

Frozen: $\rho \propto t^{-2}$

($w = -\frac{1}{3}$).

If frozen network forms, tension must be at electroweak scale.

Does it form?

\[ \frac{P}{P_{\text{scaling}}} \]

$Z_3 \sim \frac{Z_3}{\text{fractional}}$

$Z_3$ scale

$Z_8$ looks like it's freezing.

$g_5 << 1$ might inhibit freezing.
Conclusion -

- Cosmic F- and D-strings are a serious possibility.
  - Tye et al.
  - Kachru et al.
  - Damer + Vilenkin

- The results are highly model dependent, and some cases (fractional D-strings, (p,q) strings) are particularly rich.