Searching for Cosmic Strings in New Observational Windows

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Outline

1. Introduction
2. Cosmic String Review
3. Kaiser-Stebbins Effect and Cosmic String Wakes
4. Signatures of Cosmic Strings in CMB Polarization
5. Signatures of Cosmic Strings in 21cm Maps
6. Conclusions
Introduction

Cosmic String Review

Kaiser-Stebbins Effect and Cosmic String Wakes

Signatures of Cosmic Strings in CMB Polarization

Signatures of Cosmic Strings in 21cm Maps

Conclusions
Cosmic Strings


**Introduction**

- Cosmic String = linear topological defect in a quantum field theory.
- 1st analog: line defect in a crystal
- 2nd analog: vortex line in superfluid or superconductor
- Cosmic string = line of trapped energy density in a quantum field theory.
- Trapped energy density $\rightarrow$ gravitational effects on space-time $\rightarrow$ important in cosmology.
Cosmic strings are predicted in many particle physics models beyond the “Standard Model”.

Cosmic strings are predicted to form at the end of inflation in many inflationary models.

Cosmic strings may survive as cosmic superstrings in alternatives to inflation such as string gas cosmology.

In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.

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Cosmic strings are characterized by their tension $\mu$ which is associated with the energy scale $\eta$ at which the strings form ($\mu \sim \eta^2$).

Searching for the signatures of cosmic strings is a tool to probe physics beyond the Standard Model at energy ranges complementary to those probed by the LHC.

Cosmic strings are constrained from cosmology: strings with a tension which exceed the value $G\mu \sim 1.5 \times 10^{-7}$ are in conflict with the observed acoustic oscillations in the CMB angular power spectrum (Dvorkin, Hu and Wyman, 2011).

Existing upper bound on the string tension rules out large classes of particle physics models.

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Cosmic strings can produce many good things for cosmology:

- Explanation for the origin of primordial magnetic fields which are coherent on galactic scales (X. Zhang and R.B. (1999)).
- Explanation for cosmic ray anomalies (R.B., Y. Cai, W. Xue and X. Zhang (2009)).
- Origin of supermassive black holes (R.B., in prep.).

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It is interesting to find evidence for the possible existence of cosmic strings.
Important lessons from this talk:

- Cosmic strings → nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic strings lead to perturbations which are non-Gaussian.
- Cosmic strings predict specific geometrical patterns in position space.
- 21 cm surveys provide an ideal arena to look for cosmic strings (R.B., R. Danos, O. Hernandez and G. Holder, 2010).
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Cosmic strings form after symmetry breaking phase transitions.

Prototypical example: Complex scalar field $\phi$ with “Mexican hat" potential:

$$V(\phi) = \frac{\lambda}{4} (|\phi|^2 - \eta^2)^2$$  \hspace{1cm} (1)

Vacuum manifold $\mathcal{M}$: set up field values which minimize $V$. 

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Scalar Field Potential

\[ V_T(\phi) \]

- \( T >> T_c \)
- \( T = T_c \)
- \( T << T_c \)
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Prototypical example: Complex scalar field $\phi$ with "Mexican hat" potential:

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Vacuum manifold $\mathcal{M}$: set up field values which minimize $V$.

At high temperature: $\phi = 0$.

At low temperature: $|\phi| = \eta$ - but phase uncorrelated on super-Hubble scales.

$\rightarrow$ defect lines with $\phi = 0$ left behind.
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Cosmic string core: points with $|\phi| \ll \eta$.

Criterium for the existence of cosmic strings: $\Pi_1(\mathcal{M}) \neq \infty$. 
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Criterium for the existence of cosmic strings: $\Pi_1(M) \neq \infty$. 
Symmetric cosmic string configuration (uniform along z axis, with core at $\rho = 0$):

$$\phi(\rho, \theta) = f(\rho)\eta e^{i\theta}$$  \hspace{1cm} (3)

$$f(\rho) \rightarrow 1 \text{ for } \rho > w$$  \hspace{1cm} (4)

$$f(\rho) \rightarrow 0 \text{ for } \rho < w$$  \hspace{1cm} (5)

Important features:

- **Width** $w \sim \lambda^{-1/2} \eta^{-1}$
- **Mass per unit length** $\mu \sim \eta^2$ (independent of $\lambda$).
By causality, the values of $\phi$ in $M$ cannot be correlated on scales larger than $t$.

Hence, there is a probability $O(1)$ that there is a string passing through a surface of side length $t$.

Causality $\rightarrow$ network of cosmic strings persists at all times.
By *causality*, the values of $\phi$ in $\mathcal{M}$ cannot be correlated on scales larger than $t$.

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*Causality* $\rightarrow$ network of cosmic strings persists at all times.
Correlation length $\xi(t) < t$ for all times $t > t_c$.

Dynamics of $\xi(t)$ is governed by a Boltzmann equation which describes the transfer of energy from long strings to string loops.
Analysis of the Boltzmann equation shows that $\xi(t) \sim t$ for all $t > t_c$:

- If $\xi(t) \ll t$ then rapid loop production and $\xi(t)/t$ increases.
- If $\xi(t) \gg t$ then no loop production and $\xi(t)/t$ decreases.

Sketch of the scaling solution:

**Figure 39.** Sketch of the scaling solution for the cosmic string network. The box corresponds
History I

- Cosmic strings were popular in the 1980’s as an **alternative to inflation** for producing a scale-invariant spectrum of cosmological perturbations.

- Cosmic strings lead to **incoherent and active** fluctuations (rather than coherent and passive like in inflation).

- Reason: strings on super-Hubble scales are entropy fluctuations which seed an adiabatic mode which is growing until Hubble radius crossing.

- Boomerang CMB data (1999) on the acoustic oscillations in the CMB angular power spectrum ruled out cosmic strings as the main source of fluctuations.

- Interest in cosmic strings collapsed.
Supergravity models of inflation typically yield cosmic strings after reheating (R. Jeannerot et al., 2003).

Brane inflation models typically yield cosmic strings in the form of cosmic superstrings (Sarangi and Tye, 2002; Copeland, Myers and Polchinski, 2004).


→ renewed interest in cosmic strings as supplementary source of fluctuations.

Best current limit from angular spectrum of CMB anisotropies: $\sim 5\%$ of the total power can come from strings (see e.g. Dvorkin, Hu and Wyman, 2011).

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Geometry of a Straight String


Space away from the string is **locally flat** (cosmic string exerts no gravitational pull).

Space perpendicular to a string is **conical with deficit angle**

\[ \alpha = 8\pi G \mu , \]
Photons passing by the string undergo a relative Doppler shift

\[ \frac{\delta T}{T} = 8\pi \gamma(v) v G \mu, \]
→ network of line discontinuities in CMB anisotropy maps.

*N.B. characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.*

Need to analyze position space maps.
10^0 \times 10^0 \text{ map of the sky at } 1.5' \text{ resolution}
→ network of line discontinuities in CMB anisotropy maps.

Characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.

Need to analyze position space maps.

Edges produced by cosmic strings are masked by the “background" noise.
Temperature map Gaussian + strings
network of line discontinuities in CMB anisotropy maps.

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Edge detection algorithms: a promising way to search for strings

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Edge detection algorithms: a promising way to search for strings

Consider a cosmic string moving through the primordial gas:

Wedge-shaped region of overdensity 2 builds up behind the moving string: wake.
Consider a string at time $t_i \ [t_{\text{rec}} < t_i < t_0]$ moving with velocity $v_s$ with typical curvature radius $c_1 t_i$.
Gravitational accretion onto a wake

- Initial overdensity $\rightarrow$ gravitational accretion onto the wake.
- Accretion computed using the Zeldovich approximation.
- Focus on a mass shell a physical distance $w(q, t)$ above the wake:

$$w(q, t) = a(t)(q - \psi),$$

- Gravitational accretion $\rightarrow \psi$ grows.
- Turnaround: $\dot{w}(q, t) = 0$ determines $q_{nl}(t)$ and thus the thickness of the gravitationally bound region.
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Result: $q_{nl}(t) \sim a(t)$. 

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Wake is a region of enhanced free electrons.

CMB photons emitted at the time of recombination acquire extra polarization when they pass through a wake.

Statistically an equal strength of E-mode and B-mode polarization is generated.

Consider photons which at time $t$ pass through a string segment laid down at time $t_i < t$.

\[
\frac{P}{Q} \simeq \frac{24\pi}{25} \left(\frac{3}{4\pi}\right)^{1/2} \sigma_T f G \mu v_s \gamma_s \\
\times \Omega_B \rho_c(t_0) m_p^{-1} t_0 (z(t) + 1)^2 (z(t_i) + 1)^{1/2}
\]
Signature in CMB Polarization II

Inserting numbers yields the result:

\[ \frac{P}{Q} \sim fG\mu v_s\gamma_s\Omega_B \left( \frac{Z(t) + 1}{10^3} \right)^2 \left( \frac{Z(t_i) + 1}{10^3} \right)^3 \times 10^7. \]

Characteristic pattern in position space:
Cosmic strings produce direct B-mode polarization.  

→ gravitational waves not the only source of primordial B-mode polarization.

Cosmic string loop oscillations produce a scale-invariant spectrum of primordial gravitational waves with a contribution to $\delta T/T$ which is comparable to that induced by scalar fluctuations (see e.g. A. Albrecht, R.B. and N. Turok, 1986).

→ a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.

If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).
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Motivation

- 21 cm surveys: **new window** to map the high redshift universe, in particular the “dark ages”.
- Cosmic strings produce **nonlinear structures** at high redshifts.
- These nonlinear structures will leave imprints in **21 cm maps**. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)
- 21 cm surveys provide 3-d maps $\rightarrow$ potentially more data than the CMB.
- $\rightarrow$ 21 cm surveys is a promising window to search for cosmic strings.
10^3 > z > 10: baryonic matter dominated by neutral H.

- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").
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The Effect (II)

- **String wake is a nonlinear overdensity** in the baryon distribution with **special geometry** which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.
- At high redshifts the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.
**The Effect (II)**

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Geometry of the signal

\[ x_2 \quad x_1 \quad x_C \]

\[ t \quad t_0 \quad \gamma \quad s_1 \quad s_2 \quad 2t_i \quad t_i \]

\[ \nu \quad \nu_1 \quad \nu_2 \quad \delta \nu \]

\[ x_2 \quad x_1 \quad x_C \]
Frequency dispersion

\[ \frac{\delta \nu}{\nu} = 2\sin(\theta) \tan(\theta) \frac{H_w}{c}, \]
Brightness temperature:

\[ T_b(\nu) = T_S(1 - e^{-\tau_\nu}) + T_\gamma(\nu)e^{-\tau_\nu}, \]

Spin temperature:

\[ T_S = \frac{1 + x_c}{1 + x_c T_\gamma/T_K} T_\gamma. \]

\( T_K \): gas temperature in the wake, \( x_c \) collision coefficient

Relative brightness temperature:

\[ \delta T_b(\nu) = \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z} \]
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**Relative brightness temperature:**

\[ \delta T_b(\nu) = \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z} \]
Optical depth:

\[ \tau_\nu = \frac{3c^2A_{10}}{4\nu^2} \left( \frac{h\nu}{k_B T_S} \right) \frac{N_{\text{HI}}}{4} \phi(\nu), \]

\( N_{\text{HI}} \) column number density of hydrogen atoms.

Line profile:

\[ \phi(\nu) = \frac{1}{\delta\nu} \text{ for } \nu \in \left[ \nu_{10} - \frac{\delta\nu}{2}, \nu_{10} + \frac{\delta\nu}{2} \right], \]
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Line profile:

\[ \phi(\nu) = \frac{1}{\delta\nu} \text{ for } \nu \in \left[ \nu_1 - \frac{\delta\nu}{2}, \nu_1 + \frac{\delta\nu}{2} \right], \]
Application to Cosmic String Wakes

Wake temperature $T_K$:

$$T_K \simeq [20 \, \text{K}](G\mu)^2(v_s\gamma_s)^2 \frac{Z_i + 1}{z + 1},$$

determined by considering thermalization at the shock which occurs after turnaround when $w = 1/2w_{max}$ (see Eulerian hydro simulations by A. Sornborger et al, 1997).

Thickness in redshift space:

$$\frac{\delta \nu}{\nu} = \frac{24\pi}{15} G\mu v_s\gamma_s (Z_i + 1)^{1/2} (z(t) + 1)^{-1/2}$$

$$\simeq 3 \times 10^{-5} (G\mu)^6(v_s\gamma_s),$$

using $Z_i + 1 = 10^3$ and $z + 1 = 30$ in the second line.
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using $z_i + 1 = 10^3$ and $z + 1 = 30$ in the second line.
Relative brightness temperature:

\[
\delta T_b(\nu) = [0.07 \text{ K}] \frac{x_c}{1 + x_c} \left( 1 - \frac{T_\gamma}{T_K} \right) (1 + z)^{1/2} \\
\sim 200 \text{ mK} \quad \text{for} \quad z + 1 = 30.
\]

Signal is emission if \( T_K > T_\gamma \) and absorption otherwise.

Critical curve (transition from emission to absorption):

\[
(G\mu)_6^2 \sim 0.1 (v_s \gamma_s)^{-2} \frac{(z + 1)^2}{z_i + 1}
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Scalings of various temperatures

Top curve: \((G_{\mu})_6 = 1\), bottom curve: \((G_{\mu})_6 = 0.3\)
Wakes also form for $T_K < T_g$, but no shock heating.

The wakes are more dilute $\rightarrow$ thicker but less dense.

$$h_w(t)|_{T_K < T_g} = h_w(t)|_{T_g = 0} \frac{T_g}{T_K}$$

This allows the exploration of smaller values of $G_\mu$. 
Extension 2: Cosmic String Loops

- Cosmic string loops seed nonlinear objects at high redshift.
- Spherical accretion
- Average overdensity 64 (compared to 4 for a wake)
  → higher brightness temperature!
- But: no string-specific geometrical signal
  → harder to identify loop signals compared to wake signals.
Cosmic strings → **nonlinearities already at high redshifts.**

**Signatures of cosmic strings more pronounced at high redshifts.**

Cosmic strings lead to perturbations which are **non-Gaussian.**

Cosmic strings predict specific geometrical patterns in position space.

**21 cm surveys** provide an ideal arena to look for cosmic strings.

Cosmic string wakes produce distinct wedges in redshift space with enhanced 21cm absorption or emission.