Signatures of Cosmic Strings in High Redshift 21-cm Intensity Maps

Robert Brandenberger
McGill University

21cm Workshop, McGill, Oct. 9 2019

Plan

Outline

1. Motivation
2. Kaiser-Stebbins Effect and Cosmic String Wakes
3. Signatures of Cosmic String Wakes in 21cm Maps
4. Conclusions

Cosmic Strings

T. Kibble, J. Phys. A **9**, 1387 (1976); Y. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).

- 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 → gravitational effects on space-time → important in cosmology.

Relevance to Particle Physics I

- Cosmic string solutions exist 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.
- Seeing a cosmic string in the sky would provide a guide to particle physics beyond the Standard Model!

Relevance to Particle Physics II

- Cosmic strings are characterized by their tension μ which is associated with the energy scale η 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: $G\mu \leq 1.3 \times 10^{-7}$ otherwise a 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 "Grand Unified" models.

Lowering the upper bound on the string tension by two orders of magnitude would rule out **all** grand unified models yielding cosmic string solutions.

Relevance to Cosmology

Strings can produce many good things for cosmology:

- String-induced mechanism of baryogenesis (R.B., A-C. Davis and M. Hindmarsh, 1991).
- Explanation for the origin of primordial magnetic fields which are coherent on galactic scales (X.Zhang and R.B. (1999)).
- Origin of high redshift supermassive black holes (S. Bramberger, R.B., P. Jreidini and J. Quintin, 2015).
- Origin of globular clusters (A. Barton, R.B. and L. Lin, 2015; R.B., L. Lin and S. Yamanouchi, 2015).
- Origin of fast radio bursts (R.B., B. Cyr and A. Iyer, 2017).

It is interesting to find evidence for the possible existence of cosmic strings.

Key Points

- Cosmic strings → nonlinearities already at arbitrarily high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic string wakes lead to perturbations which are non-Gaussian.
- Cosmic string wakes 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).

Cosmic String Review

A. Vilenkin and E. Shellard, *Cosmic Strings and other Topological Defects* (Cambridge Univ. Press, Cambridge, 1994).

- Strings form after symmetry breaking phase transitions.
- Prototypical example: Complex scalar field ϕ with “Mexican hat" potential:

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2$$

- 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.
- Trapped energy along the defect lines.
- Existence of cosmic strings requires: $\Pi_1(\mathcal{M}) \neq 1$.

Formation of Strings

T. Kibble, Phys. Rept. **67**, 183 (1980).

- By causality, the values of ϕ in $\mathcal{M}$ cannot be correlated on scales larger than *t*.
- Hence, there is a probability $\mathcal{O}(1)$ that there is a string passing through a surface of side length *t*.
- Causality → network of cosmic strings persists at all times.

Sketch of the Scaling Solution

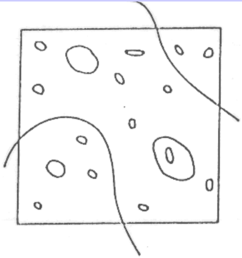


Figure 39. Sketch of the scaling solution for the cosmic string network. The box correspo
to one Hubble volume at arbitrary time t.

Network of strings consists of

- “Long” strings.
- String loops.

Plan

Kaiser-Stebbins Effect

N. Kaiser and A. Stebbins, Nature **310**, 391 (1984).

- 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

$$\frac{\delta T}{T} = 8\pi\gamma(v)vG\mu\,,$$

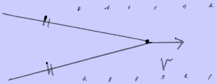
- → network of line discontinuities in CMB anisotropy maps.
- *N.B. characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.*

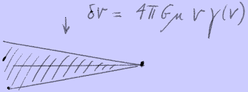
Cosmic String Wake

J. Silk and A. Vilenkin, Phys. Rev. Lett. **53**, 1700 (1984).

Consider a cosmic string moving through the primordial gas:

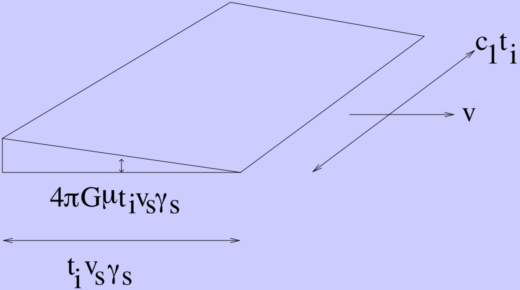
Wedge-shaped region of overdensity 2 builds up behind the moving string: wake.





Closer look at the wedge

- Consider a string at time t_i $[t_{rec} < t_i < t_0]$
- moving with velocity v_s
- with typical curvature radius $c_1 t_i$



Gravitational accretion onto a wake

L. Perivolaropoulos, R.B. and A. Stebbins, Phys. Rev. D **41**, 1764 (1990).

- Initial overdensity → gravitational accretion onto the wake.
- Accretion computed using the Zeldovich approximation.
- **Result**: comoving thickness $q_{nl}(t) \sim a(t)$.

Plan

1. Motivation
2. Kaiser-Stebbins Effect and Cosmic String Wakes
3. Signatures of Cosmic String Wakes in 21cm Maps
4. Conclusions

Motivation

R.B., D. Danos, O. Hernandez and G. Holder, arXiv:1006.2514; O. Hernandez, Yi Wang, R.B. and J. Fong, arXiv:1104.3337.

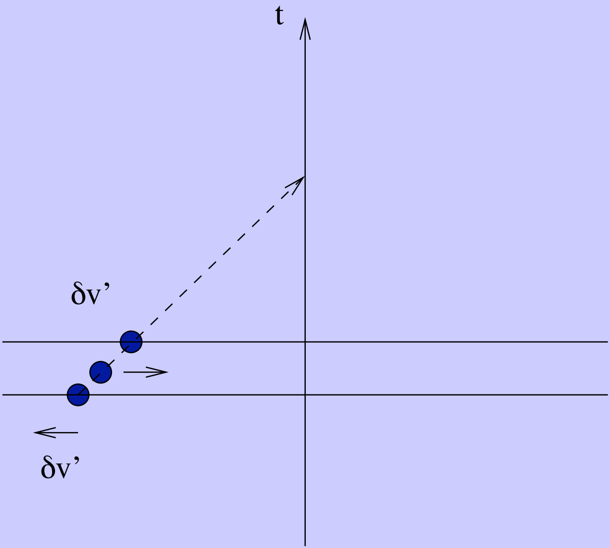
- 21 cm surveys: new window to map the high redshift universe, in particular the “dark ages".
- Cosmic strings produce nonlinear structures at high redshifts.
- These nonlinear structures will leave imprints in 21 cm maps. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)
- 21 cm surveys provide 3-d maps → potentially more data than the CMB.
- → 21 cm surveys is a promising window to search for cosmic strings.

The Effect

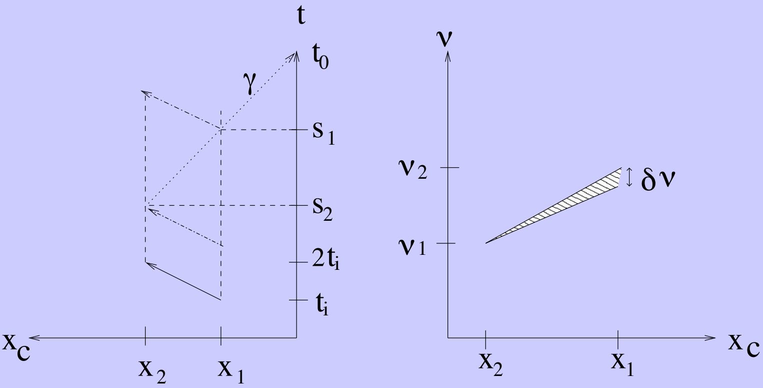
- $10^3 > z > z_H$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 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").

The Effect (II)

- String wake is a nonlinear overdensity in the baryon distribution with special geometry which emits/absorbs 21cm radiation.
- Low string tensions: signal is absorption.
- At high redshifts ($z > z_H$) the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.


t
δv'
δv'

Geometry of the signal



Brightness temperature

Brightness temperature:

$$T_b(\nu) \, = \, T_S\left(1 - e^{-\tau_\nu}\right) + T_\gamma(\nu) e^{-\tau_\nu} \, ,$$

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:

$$\delta T_b(\nu) \, = \, \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z}$$

Application to Cosmic String Wakes

Thickness in redshift space:

$$\begin{aligned}\frac{\delta\nu}{\nu} &= \frac{24\pi}{15} G\mu v_s \gamma_s (z_i + 1)^{1/2} (z(t) + 1)^{-1/2} \\ &\simeq 3 \times 10^{-5} (G\mu)_6 (v_s \gamma_s) \,,\end{aligned}$$

using $z_i + 1 = 10^3$ and $z + 1 = 30$ in the second line.

Relative brightness temperature:

$$\begin{aligned}\delta T_b(\nu) &= [0.07\ \mathrm{K}] \frac{x_c}{1 + x_c} (1 - \frac{T_\gamma}{T_K})(1 + z)^{1/2} \\ &\sim 200 mK \quad \text{for} \quad z + 1 = 30 \,.\end{aligned}$$

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

Comments

Cosmic string signal persists at lower redshifts.

But it is harder to calculate.

- Reionization.
- Nonlinearities.
- Disruption of string wakes (D. Cunha, O. Hernandez, R.B., arXiv:1508.02317)
- Numerical simulations in progress (D. Cunha et al, in preparation).

Plan

Conclusions I

- Searching for cosmic strings in the sky is a way to probe particle physics beyond the Standard Model from **top down.**
- Current bounds on the cosmic string tension already rule out a large class of GUT models.
- Improving the bounds will allow us to better constrain particle physics beyond the Standard Model.

Conclusions II

- Cosmic strings → nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic string wakes lead to perturbations which are non-Gaussian.
- Cosmic string wakes predict specific geometrical patterns in position space.
- Cosmic string wakes produce distinct wedges in redshift space with enhanced 21cm absorption.