A Signature of Cosmic Strings Wakes in the CMB Polarization

Rebecca J. Danos, Robert H. Brandenberger and Gil Holder

Department of Physics, McGill University, Montréal, QC, H3A 2T8, Canada

(Dated: March 3, 2010)

We calculate a signature of cosmic strings in the polarization of the cosmic microwave background (CMB). We find that ionization in the wakes behind moving strings gives rise to extra polarization in a set of rectangular patches in the sky whose length distribution is scale-invariant. The length of an individual patch is set by the co-moving Hubble radius at the time the string is perturbing the CMB. The polarization signal is largest for string wakes produced at the earliest post-recombination time, and for an alignment in which the photons cross the wake close to the time the wake is created. The maximal amplitude of the polarization relative to the temperature quadrupole is set by the overdensity of free electrons inside a wake which depends on the ionization fraction $f$ inside the wake. The signal can be as high as 0.06µK in degree scale polarization for a string at high redshift (near recombination) and a string tension $\mu$ given by $G\mu = 10^{-7}$.

PACS numbers: 98.80.Cq

I. INTRODUCTION

In recent years there has been renewed interest in the possibility that cosmic strings contribute to the power spectrum of curvature fluctuations which give rise to the large scale structure and cosmic microwave background (CMB) anisotropies which we see today. One of the reasons is that many inflationary models constructed in the context of supergravity models lead to the formation of gauge theory cosmic strings at the end of the inflationary phase [1]. Secondly, in a large class of brane inflation models the formation of cosmic superstrings [2] at the end of inflation is generic [3], and in some cases (see [4]) these strings are stable (see also [5] for reviews on fundamental cosmic strings). Cosmic superstrings are also a possible remnant of an early Hagedorn phase of string gas cosmology [6].

In models which admit stable strings or superstrings, a scaling solution of such strings inevitably [2] results as a consequence of cosmological dynamics (see e.g. [8] for reviews on cosmic strings and structure formation). In a scaling solution, the network of strings looks statistically the same at any time $t$ if lengths are scaled to the Hubble radius at that time. The distribution of strings is dominated by a network of “infinite” strings [1] with mean curvature radius and separation being of the order of the Hubble radius. The scaling solution of infinite strings is maintained by the production of string loops due to the interaction of long strings. This leads to a distribution of string loops with a well defined spectrum (see e.g. [6]) for all radii $R$ smaller than a cutoff radius set by the Hubble length. Whereas the scaling distribution of the infinite strings is reasonably well known as a result of detailed numerical simulations of cosmic string evolution (see [10] for some references), there is still substantial uncertainty concerning the distribution of string loops. It is, however, quite clear that the long strings dominate the energy density of strings. The distinctive signals of strings which we will focus on are due to the long strings.

Cosmic strings give rise to distinctive signatures in both the CMB and in the large-scale structure. These signatures are a consequence of the specific geometry of space produced by strings. As studied initially in [11], space perpendicular to a long straight string is locally flat but globally looks like a cone whose tip coincides with the location of the string (the smoothing out of the cone as a consequence of the internal structure of the cosmic string was worked out in [12]). The deficit angle is given by

$$\alpha = 8\pi G \mu,$$ (1)

where $\mu$ is the string tension and $G$ is Newton’s constant. Hence, a cosmic string moving with velocity $v$ in the plane perpendicular to its tangent vector will lead to line discontinuities in the CMB temperature of photons passing on different sides of the string. The magnitude of the temperature jump is [13]

$$\frac{\delta T}{T} = 8\gamma(v)\nu G\mu,$$ (2)

where $\gamma$ is the relativistic gamma factor associated with the velocity $v$.

As a consequence of the deficit angle [11], a moving string will generate a cosmic string wake, a wedge-shaped region behind the string (from the point of view of its velocity), a region with twice the background density [14] (see Figure 1). Causality (see e.g. [15]) limits the depth of the distortion of space due to a cosmic string. The details were worked out in [16] where it was shown that the deficit angle goes to zero quite rapidly a distance $t$ from the string. Hence, the depth of the string wake is given by the same length. String wakes lead to distinctive signatures in the topology of the large-scale structure, signatures which were explored e.g. in [17].

---

1. Any string with a mean curvature radius comparable or greater than the Hubble radius or which extends beyond the Hubble radius is called “infinite” or “long”.

---

[1] ArXiv:1003.0905v1 [astro-ph.CO] 3 Mar 2010
Strings tension of about above, thus leading to an upper bound \[23–27\] on the trum of cosmological perturbations is thus bounded from the case of inflation-generated fluctuations. The con-
and “active” as opposed to “coherent” and “passive” as
Hubble scales. Hence, the fluctuations are “incoherent”
that the string network is continuously seeding the grow-
position space than in Fourier space \[13, 28–30\] and recent
signatures of cosmic strings are easier to identify in po-
the left panel. From the point of view of an observer sitting
from the last scattering surface to the observer
it turns out the residual ionization from decoupling is
The shocks, in turn, can ionize the gas - although as
behind the string (relative to the string motion) matter flow-
ing past the string receives a velocity kick towards the plane
determined by the direction of the string and the velocity vec-
tor (right panel). This velocity kick towards the plane leads
to a wedge-shaped region behind the string with twice the
background density (the shaded region in the right panel).

Wakes formed at arbitrarily early times are non-linear
density perturbations. For wakes formed by strings
present at times \(t_i > t_{rec}\), where \(t_{rec}\) is the time of re-
combination, the baryonic matter inside the wake un-
dergoes shocks \[18\] (see e.g. \[19\] for a detailed study).
The shocks, in turn, can ionize the gas - although as
it turns out the residual ionization from decoupling is
larger. Photons passing through these ionized regions on
their way from the last scattering surface to the observer
can thus be polarized - and it is this polarization signa-
ture which we aim to study here.

The tightest constraints on the contribution of scal-
ing strings to structure formation (and thus the tight-
est upper bound on the tension \(\mu\) of the strings) comes
from the analysis of the angular power spectrum of
CMB anisotropies. As discussed in \[20–22\], the angular
power spectrum does not have the acoustic ringing which
inflation-seeded perturbations generate. The reason is
that the string network is continuously seeding the grow-
ning mode of the curvature fluctuation variable on super-
Hubble scales. Hence, the fluctuations are “incoherent”
and “active” as opposed to “coherent” and “passive” as
in the case of inflation-generated fluctuations. The con-
tribution of cosmic strings to the primordial power spec-
trum of cosmological perturbations is thus bounded from
above, thus leading to an upper bound \[23, 27\] on the
string tension of about \(G\mu < 3 \times 10^{-7}\).

Past work on CMB temperature maps has shown that
signatures of cosmic strings are easier to identify in po-

tion space than in Fourier space \[13, 28, 30\] and recent
studies show that high angular resolution surveys such as
the South Pole Telescope project \[31\] have the potential
of improving the limits on the string tension by an order of magnitude \[32–34\].

To date there has been little work on CMB polarization
due to strings. Most of the existing work focuses
on the angular power spectra of the polarization. Based
on a formalism \[22\] (see also \[35\]) to include cosmic de-
fects as source terms in the Boltzmann equations used
in CMB codes, the power spectra of temperature and
temperature polarization maps were worked out \[36\] in
the case of models with global defects such as global cos-
mic strings. Since in cosmic defect models vector and
tensor modes are as important as the scalar metric fluc-
tuations \[22, 37\], a significant B-mode polarization is in-
duced. In fact, in the case of global strings with a tension
close to the upper bound mentioned above, whereas the
amplitude of the temperature and E-mode polarization
power spectra are so small as to make the string signal
invisible compared to the signal from the scale-invariant
spectrum of adiabatic fluctuations (e.g. produced in in-
flation), the contribution of strings dominates the amplitu-
de of the B-mode polarization power spectrum. In the
case of local strings, these conclusions were confirmed in
the more recent analyses of \[23, 24, 27, 35, 39\]. The max-
imal amplitude of the B-mode polarization power spec-
trum for strings with \(G\mu = 3 \times 10^{-7}\) was shown to be
taken on at angular harmonic values of \(l \sim 500\) and to
be of the order \(0.3 \mu K^2\) \[39\]. However, the analyses of
\[23, 26, 27, 38, 39\] do not take into account the effects
of the gravitational accretion onto cosmic string wakes.
In related work, the conversion of E-mode to B-mode po-
larizaton via the gravitational lensing induced by cosmic
strings was studied in \[40\].

Similarly to what was found in the analysis of CMB
temperature maps from cosmic strings, we expect that a
position-space analysis will be more powerful at revealing
the key non-Gaussian signatures of strings in CMB polar-
ization. Hence, in this work we derive the position space
signature of a cosmic string wake in CMB polarization
maps.

In the following section we briefly review cosmic string
wakes. In Section 3 we then analyze the polarization sig-
nature of wakes, and we conclude with some discussion.

II. COSMIC STRING WAKES

Since the strings are relativistic, they generally move
with a velocity of the order of the speed of light. There
will be frequent intersections of strings. The long strings
will chop off loops, and this leads to the conclusion that
the string distribution will be statistically independent

\[\text{FIG. 1: Sketch of the mechanism by which a wake behind a moving string is generated. Consider a string perpendicular to the plane of the graph moving straight downward. From the point of view of the frame in which the string is at rest, matter is moving upwards, as indicated with the arrows in the left panel. From the point of view of an observer sitting behind the string (relative to the string motion) matter flowing past the string receives a velocity kick towards the plane determined by the direction of the string and the velocity vector (right panel). This velocity kick towards the plane leads to a wedge-shaped region behind the string with twice the background density (the shaded region in the right panel).}\]
on time scales larger than the Hubble radius \(^3\).

In this work, we place one string of length \(c_1 t_i\) \(^4\) at a specified time \(t_i\) and assume it is moving in transverse direction with a velocity \(v_s\). This string segment will generate a wake, and it is the signal of one of these wakes in the CMB polarization which we will study in the following.

A string segment laid down at time \(t_i\) will generate a wake whose dimensions at that time are the following:

\[
c_1 t_i \times t_i v_s \gamma_s \times 4 \pi G \mu t_i v_s \gamma_s , \tag{3}
\]

In the above, the first dimension is the length in direction of the string, the second is the depth which depends on \(v_s\) (\(\gamma_s\) is the associated relativistic \(\gamma\) factor), and the third is the average thickness.

Once the wake is formed, its planar dimensions will expand as the universe grows in size, and the thickness (defined as the region of non-linear density) will grow by gravitational accretion. The accretion of matter onto a cosmic string wake was studied in \([43, 44]\) in the case of the dark matter being cold, and in \([44, 45]\) in the case of the dark matter being hot \(^5\). We are interested in the case of cold dark matter.

We consider mass planes at a fixed initial comoving distance \(q\) above the center of the wake. The corresponding physical height is

\[
h(q, t_i) = a(t_i)[q - \psi(q, t_i)] , \tag{4}
\]

where \(\psi(q, t)\) is the comoving displacement induced by the gravitational accretion onto the wake. For cold dark matter, the initial conditions for \(\psi(q)\) are \(\psi(q, t_i) = \psi(q, t_i) = 0\). The goal of the analysis is to find the thickness of the wake at all times \(t > t_i\). The thickness is defined as the physical height \(h\) above the center of the wake of the matter shell which is beginning to fall towards the wake, i.e. for which \(h(q, t) = 0\). In the Zel’dovich approximation, we first consider the equation of motion for \(h\) obtained by treating the source (the initial surface density \(\sigma\) of the wake) in the Newtonian limit, i.e.

\[
\dot{h} = \frac{\partial \Phi}{\partial h} , \tag{5}
\]

where \(\Phi\) is the Newtonian gravitational potential given by the Poisson equation

\[
\frac{\partial^2 \Phi}{\partial h^2} = 4 \pi G [\rho + \sigma \delta(h)] \tag{6}
\]

\((\rho(t)\) being the background energy density), and then by linearizing the resulting equation in \(\psi\). The mean surface density is

\[
\sigma(t) = 4 \pi G \mu t_i v_s \gamma_s (\frac{t}{t_i})^{2/3} \rho(t) . \tag{7}
\]

The result of the computation of the value of the comoving displacement \(q_{nl}\) which is “turning around” at the time \(t\) for a wake laid down at time \(t_i\) is \([44]\)

\[
q_{nl}(t, t_i) = \psi_0 (\frac{t}{t_i})^{2/3} \tag{8}
\]

with

\[
\psi_0(t_i) = \frac{24 \pi}{5} G \mu v_s \gamma_s (z(t_i) + 1)^{-1/2} t_0 . \tag{9}
\]

This corresponds to a physical height of

\[
h(t, t_i) = a(t) [q_{nl}(t, t_i) - \psi(q_{nl}, t)] \simeq a(t)q_{nl}(t, t_i) = \psi_0 \frac{z_i + 1}{(z + 1)^2} , \tag{10}
\]

where \(z_i\) and \(z\) are the redshifts corresponding to the times \(t_i\) and \(t\), respectively. These formulas agree with what is expected from linear cosmological perturbation theory: the fractional density perturbation should increase linearly in the scale factor which means that the comoving width of the wake must grow linearly with \(a(t)\).

Let us return to the geometry of the string segment. The tangent vector to the string and the direction of motion of the string determine a two dimensional hypersurface in space (the “string plane”). If neither the string tangent vector nor the velocity vector have a radial component (radial with respect to the co-moving point of our observer), then the photons will cross each point of the string wake at the same time, and the wake will correspond to a rectangle in the sky whose planar dimensions are

\[
c_1 t_1 \times t_1 v_s \gamma_s . \tag{11}
\]

However, if the normal vector of the string plane is not radial, then one of the planar dimensions will be reduced by a trigonometric factor \(\cos(\theta)\) depending on the angle \(\theta\) between the normal vector and the radial vector. In

\(^3\) Hence, to model the effects of strings we will make use of a toy model introduced in \([42]\) and used in most analytical work on cosmic strings and structure formation since then: we divide the time interval between recombination and the current time \(t_0\) into Hubble expansion time steps. In each time step, there is a distribution of straight string segments moving in randomly chosen directions with velocities chosen at random between 0 and 1 (in units of the speed of light). The centers and directions of these string segments are random, and the string density corresponds to \(N\) strings per Hubble volume, where \(N\) is an integer which is of the order 1 according to the scaling of the string network. The distribution of string segments is uncorrelated at different Hubble times.

\(^4\) The constant \(c_1\) is of the order 1 and depends on the correlation length of the string network as a function of the Hubble radius and must be determined from numerical simulations of cosmic string evolution.

\(^5\) If the strings have lots of small-scale structure then they will have an effective tension which is less than the effective energy density \([42]\). This will lead to a local gravitational attraction of matter towards the string, a smaller transverse velocity, and hence to string filaments instead of wakes. The gravitational accretion onto string filaments was studied in \([44]\).
addition, photons which we detect today did not pass the
wake at the same time. This will lead to a gradient of the
polarization signal across the projection of the wake onto
the CMB sky. To simplify the analysis, in the following
we will assume that $\theta$ is small.

In the following section we will need the expression for
the number density $n_e(t, t_i)$ of free electrons at time $t$ in
a wake which was laid down at the time $t_i$. The initial
number density is

$$n_e(t, t_i) \simeq f \rho_B(t_i) m_p^{-1} , \quad (12)$$

where $f$ is the ionization fraction, $\rho_B$ is the energy
density in baryons, and $m_p$ is the proton mass. Taking into
account that for $t > t_i$ the number density redshifts as the
inverse volume we get

$$n_e(t, t_i) \simeq f \rho_B(t_i) m_p^{-1} \left( \frac{z(t) + 1}{z(t_i) + 1} \right)^3 . \quad (13)$$

### III. ANALYSIS

If unpolarized cosmic microwave background radiation
with a quadrupolar anisotropy scatters off free electrons,
then the scattered radiation is polarized (see e.g. [48] for
reviews of the theory of CMB polarization). The magni-
tude of the polarization depends on the Thomson cross
section $\sigma_T$ and on the integral of the number density of
electrons along the null geodesic of radiation. Our start-
ing formula is

$$P(n) \simeq \frac{1}{10} \left( \frac{3}{4\pi} \right)^{1/2} \tau_T Q , \quad (14)$$

where $P(n)$ is the magnitude of polarization of radiation
from the direction $n$, $Q$ is the temperature quadrupole, and

$$\tau_T = \sigma_T \int n_e(\chi) d\chi , \quad (15)$$

where the integral is along the null geodesic in terms of
conformal time.

Let us now estimate the contribution to the polarization
amplitude from CMB radiation passing through a
single wake at time $t$, assuming that the wake was laid
down at the time $t_i$ and has thus had time to grow from
time $t_i$ to the time $t$ when the photons are crossing it.
We assume that the photons cross in perpendicular direc-
tion. Since the wake is thin, we can estimate the integral
in Eq. (15) by

$$\tau_T \sim 2 \sigma_T n_e(t, t_i) (z(t) + 1) h(t, t_i) \quad (16)$$

where the factor 2 is due to the fact that the width of the
wake is twice the height, and the redshift factor comes
from the Jacobean transformation between $\chi$ and posi-
tion. Inserting Eq. (16) into the expression (14) for the
polarization amplitude and using the value for the height
and the number density of electrons obtained in the previous section we find

$$\frac{P}{Q} \simeq \frac{1}{5} \left( \frac{3}{4\pi} \right)^{1/2} \sigma_T f \rho_B(t_i) m_p^{-1} \times (z(t) + 1)^2 \psi_0(t_i) . \quad (17)$$

Inserting the formula for $\psi_0(t_i)$ from Eq. (19), expressing
the baryon density at $t_i$ in terms of the current baryon
density, and the latter in terms of the baryon fraction
$\Omega_B$ and the total energy density $\rho_c$ at the current
time $t_0$, we obtain

$$\frac{P}{Q} \simeq \frac{24\pi}{25} \left( \frac{3}{4\pi} \right)^{1/2} \sigma_T f G \nu s \gamma_s \times \Omega_B \rho_c(t_0) m_p^{-1} (z(t) + 1)^2 (z(t_i) + 1)^{1/2} . \quad (18)$$

From Equation (18) we see that the polarization signal is
larger for wakes laid down early, i.e. close to the time of
recombination. For fixed $t_i$, the signal is largest for con-
fugurations where the photons we observe today cross the
wake at the earliest possible time, i.e. for the largest $z(t)$
(obviously, $t$ is constrained to be larger than $t_i$, other-
wise our formula for the height is not applicable). To get
an order of magnitude estimate of the magnitude of the
polarization signal, we take $z(t_i) \sim z(t) \sim 10^7$. Inserting
the value of the Thomson cross section, the proton mass
and the current time we get

$$\frac{P}{Q} \sim f G \nu s \gamma_s \Omega_B \left( \frac{z(t) + 1}{10^3} \right)^2 \left( \frac{z(t_i) + 1}{10^3} \right)^{3/7} . \quad (19)$$

The ionization fraction of baryonic matter drops off af-
after recombination, but it does not go to zero. As already
discussed in [49, 50], there is remnant residual ionization
of the matter. As computed in [50] (see also [51], the
residual ionization fraction $f$ tends to a limiting value of
between $10^{-5}$ and $10^{-4}$ at late times after recombina-
tion.

Shocks inside the wake will lead to extra ionization.
However, the resulting contribution to the ionization
fraction is negligible for the range of string tensions we
are interested in. To see this, we follow the analysis of
[18]. A particle streaming towards a cosmic string wake has
velocity

$$v_i = 4\pi G \nu s \gamma_s \quad (20)$$

and kinetic energy $m v_i^2$. The particles will undergo
shocks and thermalize. Equating the initial kinetic en-
dergy density with the final thermal energy density (as-
suming that the particles are distributed according to an
approximate ideal gas law) yields a temperature inside
the wakes of

$$T \simeq 7 \times 10^3 \left( \frac{G \mu}{2 \times 10^{-6}} \right)^2 (v s \gamma_s)^2 K . \quad (21)$$

We then compute the Boltzmann factor to determine the
ratio of ionized Hydrogen to ground state Hydro-
gen which is the ionization fraction. For string tensions
of order $10^{-6}$ this results in ionization fractions of the order $10^{-9}$ which is considerably less than the residual ionization. For more realistic string tensions compatible with current bounds, $10^{-7}$, the ionization fraction due to shocks is negligible compared to the residual ionization fraction. At the temperatures considered for a string tension of $10^{-7}$ at lower redshifts there would be star formation and hence an ionization fraction due to that effect since the wake would contain molecular hydrogen and satisfy the appropriate conditions. However, this is not an issue at redshifts under consideration.

Note that even though the extra ionization inside the wake is negligible compared to the overall ionization level, the wake is a locus of extra energy density. Thus, even if the ionization fraction is homogeneous in space, the inhomogeneous distribution of matter will lead to a specific polarization signature.

The position space signal of the polarization produced by a wake will be very specific: for a wake whose normal vector is in radial direction, it will be a rectangle in the sky with angular dimensions corresponding to the comoving size

\[ c_1 t_z (z(t_i) + 1) \times v_s \gamma_s t_z (z(t_i) + 1) \]  

(see Eq. 21). If the angle of the normal of the string plane to the radial normal vector is $\theta \neq 0$, then one of the planar dimensions is reduced by a factor of $\cos(\theta)$. However, the light travel time through the wake is increased by a factor of $[\cos(\theta)]^{-1}$. Thus, the wake becomes a bit smaller but the signal strength increases. The average amplitude of the polarization is given by Eq. 18 - a value obtained using the average thickness of the wake. However, since the thickness of the wake increases linearly in direction of the string motion, the amplitude of the polarization signal will also increase linearly in this direction. A second source for the linear increase in the amplitude is the fact that $z(t_i)$ is increasing as we go away from the tip of the cone (by an amount corresponding to one Hubble expansion time when comparing the tip of the cone to the end). The direction of the polarization vector depends on the relative orientation between the string and the CMB quadrupole. In Figure 2 we give a sketch of the signal. The amplitude of the polarization is proportional to the length of the arrow, the direction of the polarization is given by the direction of the arrow. Since the direction of the variation of the polarization strength is determined by the string and is therefore uncorrelated with the direction of the CMB quadrupole, on the average the E-mode and B-mode strengths of the polarization signal will be the same.

Let us now discuss the magnitude of our effect. We will consider the value $G_\mu = 3 \times 10^{-7}$ which is the current upper bound on the string tension \[23\] (using the assumptions about the cosmic string scaling solution made in these papers). Wakes produced close to the time of recombination inherit the ionization fraction of the universe at that time. Taking a value of $f = 10^{-3}$ (which is smaller than the ionization fraction until redshift $z \approx 600$), we obtain a polarization amplitude of $P \sim 10^{-2}$ $\mu$K which is larger than the background in the B-mode polarization arising from weak lensing of the primordial perturbations \[52, 53\] for l-values of about 100.

It is instructive to compare our polarization signal from a cosmic string wake with the expected noise due to the Gaussian fluctuations. In Fig. 3 we have superimposed the map of the Q-mode polarization from a cosmic string wake laid down during the first Hubble time after recombination with a corresponding Q-mode map due to Gaussian noise of the concordance $\Lambda$CDM model. The string parameters are the same as mentioned in the previous paragraph. We chose the orientation of the string relative to the CMB quadrupole such that the power in the Q-mode is half the total power. As the value of the CMB quadrupole we used $30\mu$K. To render the string signal visible in the Q-mode map (in which the noise is much larger than in a B-mode map) we multiplied the string signal by 100. In this case the string signal is clearly visible by eye. The brightest edge (the vertical edge on the right side) corresponds to the position of the string when it begins to generate the wake, not at the position at the end of the time interval being considered (the vertical edge on the left).

Note the difference compared to the Kaiser-Stebbins effect in the CMB temperature maps: in this case the brightest edge corresponds to the location
FIG. 3: The Q-mode polarization signal of a single wake which is taken to be perpendicular to the line of sight between us and the center of the string segment, superimposed on the Gaussian noise signal which is expected to dominate the total power spectrum. The string signal is multiplied by a factor of 100 to render it visible by eye. The tip of the wake (position of the string at the time the wake is laid down) is the vertical bright edge of the right side, and the string velocity vector is pointing horizontally to the left. At the final string position the wake thickness vanishes and there is no polarization discontinuity line. We have assumed that the variation of the quadrupole vector across the plane of the wake is negligible and that the quadrupole vector is at an angle relative to the plane of the wake such that the Q-mode picks up half of the polarization power.

of the string when the photons are passing by it.

Without boosting the string signal by a large factor, it would not be visible by eye. However, the distinctive lines in the map can be searched for by edge detection algorithms such as the Canny algorithm which was used to study the string signal in CMB temperature maps. In the studies of [34] it was found that the cosmic string lines in temperature maps can be picked out if the string signal accounts for less than 0.2% of the power. Thus, it should be able to easily pick out the string signal in the Q-mode polarization maps. In B-mode polarization maps the string signal would be much easier to detect.

IV. CONCLUSIONS AND DISCUSSION

In this Letter we have discussed a position space signal of a cosmic string wake in CMB polarization maps. In the same way that the line discontinuities in the CMB temperature maps predicted by the Kaiser-Stebbins (KS) effect yield a promising way to constrain/detect cosmic strings in the CMB (see e.g. [23, 30, 32, 34]), we believe that the signal discussed in this paper will play a similar role once CMB polarization maps become available.

We have shown that a single wake will produce a rectangular patch in the sky of dimensions given by equation (22), average magnitude given by equation (18) and amplitude increasing linearly in one direction across the patch. For a value of the string tension $G \mu = 3 \times 10^{-7}$ (the current upper limit), the amplitude of the signal is within the range of planned polarization experiments for wakes produced sufficiently close to the surface of recombination. These wakes are also the most numerous ones. The brightest edge in the polarization map corresponds to the beginning location of the string, not the final location. Since the KS discontinuity in the CMB temperature map will occur along the line corresponding to the final position, the polarization signal discussed here provides a cross-check on a possible string interpretation of a KS signal.

A scaling distribution of strings will yield a distribution of patches in the sky, the most numerous ones and the ones with the largest polarization amplitude being set by wakes laid down at times close to the time of recombination which are crossed by the CMB photons at similarly early times.

Acknowledgments

This work is supported in part by a NSERC Discovery Grants and by funds from the CRC Program to RB and GH, by a Killam Research Fellowship awarded to R.B, and by CIFAR (GH). We thank Andrew Frey and Oscar Hernandez for useful discussions.

[1] R. Jeannerot, “A Supersymmetric SO(10) Model with Inflation and Cosmic Strings,” Phys. Rev. D 53, 5426 (1996) [arXiv:hep-ph/9509365]; R. Jeannerot, J. Rocher and M. Sakellariadou, “How generic is cosmic string formation in SUSY GUTs,” Phys. Rev. D 68, 103514 (2003) [arXiv:hep-ph/0308134].
[2] E. Witten, “Cosmic Superstrings,” Phys. Lett. B 153, 243 (1985).
[3] S. Sarangi and S. H. H. Tye, “Cosmic string production towards the end of brane inflation,” Phys. Lett. B 536, 185 (2002) [arXiv:hep-th/0204074].
[4] E. J. Copeland, R. C. Myers and J. Polchinski, “Cosmic F- and D-strings,” JHEP 0406, 013 (2004) [arXiv:hep-th/0312067].
[5] A. C. Davis and T. W. B. Kibble, “Fundamental cosmic strings,” Contemp. Phys. 46, 313 (2005) [arXiv:hep-th/0505050]; M. Sakellariadou, “Cosmic Superstrings,” arXiv:0802.3379 [hep-th].
[6] R. H. Brandenberger and C. Vafa, “Superstrings In The Early Universe,” Nucl. Phys. B 316, 391 (1989); A. Nayeri, R. H. Brandenberger and C. Vafa, “Producing a scale-invariant spectrum of perturbations in a Hagedorn phase of string cosmology,” Phys. Rev. Lett.
[33] A. Stewart and R. Brandenberger, “Edge Detection, Cosmic Strings and the South Pole Telescope,” arXiv:0809.0865 [astro-ph].

[34] R. J. Danos and R. H. Brandenberger, “Canny Algorithm, Cosmic Strings and the Cosmic Microwave Background,” [arXiv:0811.2004] [astro-ph]; R. J. Danos and R. H. Brandenberger, “Searching for Signatures of Cosmic Superstrings in the CMB,” arXiv:0910.5722 [astro-ph.CO].

[35] A. J. Albrecht, R. A. Battye and J. Robinson, “A detail study of defect models for cosmic structure formation,” Phys. Rev. D 59, 023508 (1999) [arXiv:astro-ph/9711121].

[36] U. Seljak, U. L. Pen and N. Turok, “Polarization of the Microwave Background in Defect Models,” Phys. Rev. Lett. 79, 1615 (1997) [arXiv:astro-ph/9704231].

[37] R. Durrer, M. Kunz and A. Melchiorri, “Cosmic Microwave Background Anisotropies from Scaling Seeds: Global Defect Models,” Phys. Rev. D 59, 123005 (1999) [arXiv:astro-ph/9811174].

[38] U. Seljak and A. Slosar, “B polarization of cosmic microwave background as a tracer of strings,” Phys. Rev. D 74, 063523 (2006) [arXiv:astro-ph/0604143].

[39] L. Pogosian, I. Wasserman and M. Wyman, “On vector contribution to CMB temperature polarization from local strings,” arXiv:astro-ph/0604141; L. Pogosian and M. Wyman, “B-modes from Cosmic Strings,” Phys. Rev. D 77, 083009 (2008) [arXiv:0711.0747 [astro-ph]].

[40] K. Benabed and F. Bernardeau, “Cosmic string lens effects on CMB polarization patterns,” Phys. Rev. D 61, 123510 (2000).

[41] J. Garcia-Bellido, R. Durrer, E. Fenu, D. G. Figueroa and M. Kunz, “The local B-polarization of the CMB: a very sensitive probe of cosmic defects,” arXiv:1003.0299 [astro-ph.CO].

[42] L. Perivolaropoulos, “COBE versus cosmic strings: An Analytical model,” Phys. Lett. B 298, 305 (1993) [arXiv:hep-ph/9208247]; L. Perivolaropoulos, “Statistics of microwave fluctuations induced by topological defects,” Phys. Rev. D 48, 1530 (1993) [arXiv:hep-ph/9212228].

[43] A. Stebbins, S. Veeraraghavan, R. H. Brandenberger, J. Silk and N. Turok, “Cosmic String Wakes,” Astrophys. J. 322, 1 (1987).

[44] R. H. Brandenberger, L. Perivolaropoulos and A. Stebbins, “Cosmic Strings, Hot Dark Matter and the Large-Scale Structure of the Universe,” Int. J. Mod. Phys. A 5, 1633 (1990).

[45] L. Perivolaropoulos, R. H. Brandenberger and A. Stebbins, “Dissipationless Clustering Of Neutrinos In Cosmic String Induced Wakes,” Phys. Rev. D 41, 1764 (1990).

[46] B. Carter, “Integrable equation of state for noisy cosmic string,” Phys. Rev. D 41, 3869 (1990); A. Vilenkin, “Effect of Small Scale Structure on the Dynamics of Cosmic Strings,” Phys. Rev. D 41, 3038 (1990).

[47] A. N. Aguirre and R. H. Brandenberger, “Accretion of hot dark matter onto slowly moving cosmic strings,” Int. J. Mod. Phys. D 4, 711 (1995) [arXiv:astro-ph/9505031].

[48] W. Hu, “Reionization Revisited: Secondary CMB Anisotropies and Polarization,” Astrophys. J. 529, 12 (2000) [arXiv:astro-ph/9907103]; O. Dore, G. Holder, M. Alvarez, I. T. Iliev, G. Mellema, U. L. Pen and P. R. Shapiro, “The Signature of Patchy Reionization in the Polarization Anisotropy of the CMB,” Phys. Rev. D 76, 043002 (2007) [arXiv:astro-ph/0701784].

[49] I. D. Novikov and Y. B. Zeldovic, “Cosmology,” Ann. Rev. Astron. Astrophys. 5, 627 (1967).

[50] P. J. E. Peebles, “Recombination Of The Primeval Plasma,” Astrophys. J. 153, 1 (1968).

[51] M. Kaplinghat, M. Chu, Z. Haiman, G. Holder, L. Knox and C. Skordis, “Probing the Reionization History of the Universe using the Cosmic Microwave Background Polarization,” Astrophys. J. 583, 24 (2003) [arXiv:astro-ph/0207591].

[52] C. M. Hirata and U. Seljak, “Reconstruction of lensing from the cosmic microwave background polarization,” Phys. Rev. D 68, 083002 (2003) [arXiv:astro-ph/0306354].

[53] G. P. Holder, K. M. Nollett and A. van Engelen, “On Possible Variation in the Cosmological Baryon Fraction,” arXiv:0907.3919 [astro-ph.CO].