Reionization from cosmic string loops

Ken D. Olum* and Alexander Vilenkin†

Institute of Cosmology, Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA

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Loops formed from a cosmic string network at early times would act as seeds for early formation of halos, which would form galaxies and lead to early reionization. With reasonable guesses about astrophysical and string parameters, the cosmic string scale $G\mu$ must be no more than about 3×10^{-8} to avoid conflict with the reionization redshift found by WMAP. The bound is much stronger for superstring models with a small string reconnection probability. For values near the bound, cosmic string loops may explain the discrepancy between the WMAP value and theoretical expectations.

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I. INTRODUCTION

Cosmic strings are linear topological defects which may have been formed in the early universe via phase transitions [1] or through brane annihilation in superstring theory [2]. Once formed, cosmic strings exist at any time in a ''network'' of loops and infinite strings. The network evolves in a scaling regime in which any linear measure of the network properties is a constant fraction of the horizon size. This dynamic is maintained by the production of loops via reconnection on long strings, and the subsequent evaporation of loops by gravitational radiation.

The energy scale of strings can be given by the dimensionless number $G\mu$, where μ is the linear energy density on the string and G is Newton's constant. In the early days, cosmic strings were a candidate for the source of structure in the universe, either through accretion of matter onto string loops or onto the wakes of moving strings. This scenario, which required $G\mu \gtrsim 10^{-6}$, has been conclusively ruled out by microwave background observations, and current observations limit $G\mu$ to be less than about 2×10^{-7} [3].

Nevertheless, even at smaller $G\mu$, there will be some amount of structure formed by cosmic strings, in particular, through accretion around loops. Localized seeds like loops can form nonlinear structures at very early times. This could result in early star formation and in reionization of the universe. Even a small percentage of baryons in stars leads to reionization. The time of reionization is constrained by WMAP observations [4], yielding a bound on the string parameter $G\mu$.

The idea that strings could cause reionization has been discussed by a number of authors [5–8]. All these papers assumed that the effect of strings on structure formation is mostly through wakes formed behind rapidly moving long strings. The effect of loops was neglected because the loops were assumed to be too small and too short-lived. The resulting bound on $G\mu$ was $G\mu \lesssim 10^{-6}$. Here, we reconsider these results in the light of recent cosmic string simulations.

The formation of stars by string loops depends on the loop sizes being large enough to accrete sufficient matter for a galaxy. Early simulations [9] found loops at a large fraction of the horizon size, in accordance with theoretical expectations. However, later simulations [10,11] found loops at much smaller sizes, essentially the minimum resolution of the simulations. This recently led us, in collaboration with Vitaly Vanchurin, to develop a flat-space simulation [12] which does not have a minimum resolution size. We found [13] that loops were formed with lengths of about $1/10$ of the simulation time (which plays the role of the horizon in our simulation). This pattern established only after a long transient period dominated by very small loops, comparable to the initial scale of the network. We believe that it was this transient regime that was observed in earlier simulations.[1]

In the expanding universe, stretching of strings and redshifting of moving segments would tend to smooth out the string network and discourage the formation of very small loops. Since we found even without expansion that loops are formed at large sizes, we expect that in an expanding universe, loop sizes will be large, although we would not expect the same ratio of loop size to cosmic time as in flat space.

Here, we will show that large loop sizes could indeed lead to early reionization, yielding a stringent bound on $G\mu$.

II. LOOP DISTRIBUTION

The string loops of interest to us here will be those which formed during the radiation era but have not yet decayed at t_{eq}. The energy density of loops that were chopped off the network in one Hubble time is comparable to the energy

[1] More recent simulations [14,15] found evidence of loop scaling, but the loop sizes were still very small, less than 0.001 of the horizon. However the amount of time simulated was significantly shorter than in [12,13], so we expect these simulations were still in the transient regime.

*Electronic address: kdo@cosmos.phy.tufts.edu
†Electronic address: vilenkin@cosmos.phy.tufts.edu

density of long strings. However, the loop energy redshifts like matter, while the long string energy redshifts like radiation. So, if loops are long and live much longer than a Hubble time, they dominate the energy of the network and play the dominant role in structure formation.

We will assume there is a scaling process of production, which means that

$$n(l, t) = t^{-5} f(x) \quad \text{with} \quad x = l/t \tag{1}$$

where $n(l, t)dl$ is the number density of loops produced with length between l and $l + dl$ in unit time in unit spatial volume. We will take the loop production to be given by a power law distribution up to a certain fraction of the cosmic time,

$$f(x) = Ax^{-\beta} \quad \text{for } x < \alpha \tag{2}$$

and zero otherwise. We could also include a small-scale cutoff on $f(x)$, on the grounds that gravitational back reaction smooths the string and prevents small loops from forming. But, as we will see below, $f(x)$ at these small scales is not important.

We can fix A in Eq. (2) as follows. The scaling network is characterized by some interstring distance $d(t) = \gamma t$, defined so that the density in long strings is $\rho_\infty = \mu/d^2$. Conservation of energy then gives

$$\int_0^\infty xf(x)dx = \frac{1}{\gamma^2}(1 - \langle v^2\rangle) \tag{3}$$

so from Eq. (2),

$$A = \frac{2-\beta}{\alpha^{2-\beta}\gamma^2}(1 - \langle v^2\rangle) \tag{4}$$

Here, $\langle v^2\rangle$ is the square of string velocity averaged along the length of long strings.

A loop of length l evaporates by gravitational radiation in time $\tau(l) \sim l/(\Gamma G\mu)$, where Γ is a number of order 50. We will use a simple model in which loops older that $\tau(l)$ have evaporated, while those younger than $\tau(l)$ still have their original sizes. This approximation is accurate for loops with $l \gg \Gamma G\mu t$. The length distribution of such loops in the radiation era is then given by

$$N(l, t) = \frac{g}{t^{3/2} l^{5/2}} \int_0^\infty x^{3/2} f(x)dx, \tag{5}$$

where $g = \sqrt{1 - v_i^2}$ and v_i is the initial center of mass velocity of the loops. With $f(x)$ given by Eq. (2), as long as $\beta < 5/2$ the integral is dominated by large x (i.e., by loops formed at the earliest possible t), with the cut off given by Eq. (3). Thus, for $l < \alpha t$,

$$N(l, t) = \frac{\mathcal{N}}{t^{3/2} l^{5/2}} \tag{6}$$

with

$$\mathcal{N} = \frac{g(2-\beta)\sqrt{\alpha}}{(5/2-\beta)\gamma^2}(1 - \langle v^2\rangle) \tag{7}$$

In [13] we found loops emitted with significant substructure, so that their center of mass velocities are low and $g \sim 1$. The specific simulations of [13] found $\alpha \approx 0.1$, $\gamma \approx 0.04$, $\beta \approx 1.6$, $\langle v^2\rangle = 0.4$, so

$$\mathcal{N}_{\text{flat}} \sim 50. \tag{8}$$

But since these simulations were done in flat space, there is no reason to think that this value is correct for the radiation-dominated universe. A somewhat better motivated estimate can be obtained by assuming that the parameters γ and $\langle v^2\rangle$ characterizing the long string network have been correctly determined in the early simulations [10,11], and that the loop sizes are comparable to the interstring distance, as in flat space, after the true scaling regime sets in. Then $\alpha \sim \gamma \sim 0.25$, $\langle v^2\rangle \sim 0.4$, and $\mathcal{N} \sim 2$. We shall assume that

$$\mathcal{N} \gtrsim 2 \tag{9}$$

in what follows. A more accurate estimate must await long-duration expanding-universe string simulations.

III. FORMATION OF HALOS AND REIONIZATION

At the time of matter-radiation equality, t_{eq}, loops start to accrete dark matter. In about one Hubble time, the mass of a loop-seeded halo becomes comparable to that of the loop itself, so that the subsequent decay of the loop has little effect on the accretion process. At some $t > t_{\text{eq}}$, the halo seeded by a loop of length l will have accreted mass

$$M(l) \sim \mu l \left(\frac{t}{t_{\text{eq}}}\right)^{2/3} = \mu l \frac{1 + z_{\text{eq}}}{1 + z} \tag{10}$$

in cold dark matter. The number density of halos formed around loops that existed at t_{eq} will be

$$n(l, t) \sim \frac{\mathcal{N}}{t_{\text{eq}}^{3/2} l^{5/2}} \left(\frac{1+z}{1+z_{\text{eq}}}\right)^3 \tag{11}$$

Once the halo exceeds the Jeans mass, it will start to accrete baryons as well as dark matter. After recombination, the Jeans mass (including both dark matter and baryons) is about $10^5 M_\odot$, but a halo must exceed some larger threshold $M_{\min}$ in order to be able to cool and form stars. Thus only loops with length at least

$$l_{\min} = \frac{M_{\min}(1 + z)}{\mu(1 + z_{\text{eq}})} \tag{12}$$

will form luminous galaxies by redshift z.

The total mass density of such galaxies is

$$\mu \frac{1+z_{\rm eq}}{1+z}\int_{l_{\rm min}} n(l,t) l dl = 2\frac{\mathcal{N}\mu}{t_{\rm eq}^{3/2} l_{\rm min}^{1/2}}\left(\frac{1+z}{1+z_{\rm eq}}\right)^2 = 2\frac{\mathcal{N}\mu^{3/2}}{t_{\rm eq}^{3/2} M_{\rm min}^{1/2}}\left(\frac{1+z}{1+z_{\rm eq}}\right)^{3/2}. \quad (13)$$

The total mass density of the matter-dominated universe is $1/(6\pi G t^2)$, so the fraction of collapsed matter in halos larger than $M_{\rm min}$ is

$$f_{\rm coll} = 12\pi \frac{\mathcal{N} G\mu^{3/2} t_{\rm eq}^{1/2}}{M_{\rm min}^{1/2}}\left(\frac{1+z_{\rm eq}}{1+z}\right)^{3/2}. \quad (14)$$

With $z_{\rm eq} = 5000$ and $t_{\rm eq} = 10^{12}$s, we get

$$f_{\rm coll} \approx 6\times 10^{15}\frac{\mathcal{N}(G\mu)^{3/2}}{(1+z)^{3/2}}\left(\frac{M_{\rm min}}{M_\odot}\right)^{-1/2} \quad (15)$$

Now, the gas in a halo can only collapse to form stars if it can cool. Because molecular hydrogen is easily dissociated by a few early stars, efficient star formation requires atomic hydrogen cooling, which requires a virial temperature above 10^4 K. Thus a significant fraction of a halo will be incorporated into stars only if[2]

$$M_{\rm min} \sim 10^9 (1+z)^{-3/2} M_\odot, \quad (16)$$

so

$$f_{\rm coll} \approx 2\times 10^{11}\frac{\mathcal{N}(G\mu)^{3/2}}{(1+z)^{3/4}}. \quad (17)$$

Of those baryons in halos, some fraction

$$f_{\rm star} \sim 0.1 \quad (18)$$

will participate in star formation. The number of ionizing photons produced per baryon is about

$$4\times 10^3 - 10^5 \quad (19)$$

where the higher number corresponds to metal-free stars. (For an up-to-date review of the physics of reionization, see [16].) The metallicity is likely to grow rather quickly as the first stars explode as supernovae, hence we are going to use the more conservative estimate corresponding to the lower number in (19). Some fraction

$$f_{\rm esc} \sim 0.1 \quad (20)$$

of the ionizing photons escape from their galaxies. The total ratio of intergalactic ionizing photons to baryons is thus about

$$4\times 10^3 f_{\rm coll} f_{\rm star} f_{\rm esc} \quad (21)$$

The characteristic recombination time for ionized hydrogen is

$$\tau_{\rm rec} \sim \frac{50}{(1+z)^{3/2} C} t \quad (22)$$

where $C = \langle n_H^2\rangle/\bar{n}_H^2 \sim 10$ is the "clumpiness factor". (This follows From Eq. (120) of [16].) Thus at redshifts $z \sim 15$ of interest here the universe will not be completely reionized until we have emitted some number

$$n_i \sim 10 \quad (23)$$

of photons per baryon. Thus reionization takes place when

$$4\times 10^3 f_{\rm coll} f_{\rm star} f_{\rm esc} = n_i. \quad (24)$$

Complete reionization is ruled out by the third-year WMAP data for $z > 13.6$ (one sigma) [4]. Thus we must have $f_{\rm coll} \lesssim 3\times 10^{-4} n_i f_{\rm star}^{-1} f_{\rm esc}^{-1}$ at this redshift, which means that

$$G\mu \lesssim 4\times 10^{-10}(\mathcal{N} f_{\rm star} f_{\rm esc}/n_i)^{-2/3}. \quad (25)$$

With the estimates of Eqs. (9), (18), (20), and (23), the bound is $G\mu \lesssim 3\times 10^{-8}$.

IV. DISCUSSION

A cosmic string network can produce loops that act as seeds for the formation of some small galaxies at early times. These galaxies will lead to reionization at larger redshifts than allowed by WMAP data, unless the string energy scale obeys the bound of Eq. (25). This bound relies mostly on the general argument, confirmed by simulations [13], that strings are formed at a substantial fraction of the horizon size, rather than tiny scales set by gravitational back reaction.

The bound (25) is to be compared with constraints on $G\mu$ coming from other phenomena. As we already mentioned, the current bound from CMB observations is 2×10^{-7} [3]. The bounds from millisecond pulsar timing [17] and from nucleosynthesis considerations [13] are both $G\mu \lesssim 10^{-7}$. If the parameter $\mathcal{N}$ in Eq. (25) is in the assumed range (9), and given the assumptions of Eqs. (18) and (20), the reionization bound is

$$G\mu \lesssim 3\times 10^{-8}, \quad (26)$$

somewhat stronger than presently available bounds. We emphasize, however, that precise values of $\mathcal{N}$, $f_{\rm star}$, $f_{\rm esc}$, and n_i are presently unknown and the bound (26) should be regarded as preliminary. Since Eq. (25) depends on $\mathcal{N}^{-2/3} \sim \alpha^{1/3}$, if the loops are smaller than assumed above, Eq. (26) should be scaled by $(\alpha/0.25)^{-1/3}$.

If we consider a small intercommutation probability p, as appears in cosmic superstring models [18], the density of strings will be increased for a given $G\mu$, and so the bound will become more stringent. A reasonable conjecture is that p does not affect the loop sizes, but the overall

[2]This is derived by setting $T_{\rm vir}$ in Eq. (86) of [16] to 10^4 K, with mean molecular weight 1.2 (atomic gas).

density is increased by a factor $1/p$ [17,19]. Then $\mathcal{N} \propto 1/p$, and the limit on $G\mu$ is proportional to $p^{2/3}$.

We note finally that a value of $G\mu$ near the reionization bound (26) may explain the apparent discrepancy [20,21] between the three-year WMAP data suggesting reionization at $z \sim 11$ and the star formation theory indicating that the formation of a sufficient number of stars at such early redshift is unlikely in the standard scenario. Strings with $G\mu \sim 3 \times 10^{-8}$ may account for early star formation, although such strings will play little role in structure formation at later epochs.

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