Cosmological Consequences of Superconducting String Networks

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Abstract

We consider the cosmological consequences of a network of superconducting cosmic strings. For strong enough current the period of friction domination never ends. Instead a plasma scaling solution is reached. We demonstrate that this gives rise to a very different cosmology than the usual horizon scaling solution. In particular the string network gives rise to a distinct imprint on the microwave sky, giving non-Gaussian features on much smaller angular scales. It also gives rise to a filament structure in string wakes. Because of the presence of the string magnetocylinder, the string magnetic field cannot create a primordial magnetic field. Similarly, it evades nucleosynthesis constraints. We also show that strings formed at the supersymmetry breaking scale can create the required baryon asymmetry of the universe.

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1. Introduction

The microphysics of cosmic strings has received considerable attention. In particular, Witten [1] showed that cosmic strings become superconducting as a result of boson condensates or fermion zero modes in the string core. Such strings are capable of carrying a sizeable current, with the maximum current being about $10^{20} A$ for a grand unified scale string. Inevitably, such currents have cosmological and astrophysical [2] consequences. The consequences for emission of synchrotron radiation [3] and for high energy $\gamma$-rays [4] have been explored. However, all these studies have assumed that the evolution of a network of superconducting strings is similar to that of ordinary strings.

Early studies using both analytic [5] and numerical techniques [6] showed that the string evolution was indeed similar to that of ordinary cosmic strings. However, these studies neglected the very early times when the string is interacting strongly with the surrounding plasma. As shown recently in [7], for strong enough currents, this friction dominated period may never end. In this case the network reaches the so-called plasma–scaling solution, where the density of strings may be much larger than that of the usual horizon–scaling string networks. In this case the strings are highly tangled and move rather slowly. Also considering the attractive gravitational fields generated by superconducting strings [8], it is evident that, compared with ordinary cosmic strings, a network of superconducting strings could have very different cosmological implications on the matter and radiation content of the early universe.

In this letter we briefly explore some of the most important cosmological consequences of a plasma–scaling superconducting string network. Assuming a constant string current, we first discuss the characteristics of the plasma–scaling solution. We then describe the string spacetime and its implications on the surrounding particles and radiation. Afterwards, we explore the implications of the network regarding the Cosmic Microwave Background Radiation (CMBR) anisotropies and the formation of the Large Scale Structure (LSS) of the Universe. We also discuss any effects a plasma–scaling string network may have on Big Bang Nucleosynthesis (BBN) and whether it can generate a Primordial Magnetic Field (PMF) sufficient enough to account for the currently observed magnetic fields of the galaxies.

Finally, we apply our results to a recently proposed baryogenesis mechanism with superconducting cosmic strings [9]. This mechanism uses strings formed at the supersymmetry breaking scale. With our plasma scaling solution this mechanism produces a sufficiently strong baryon asymmetry to account for nucleosynthesis. This improves the result of [4], where vorton domination was needed to obtain enough baryon asymmetry. In what follows, unless stated otherwise, we use natural units ($\hbar = c = 1$).

2. Friction and plasma–scaling

After the formation of the string network, curves and wiggles on the strings tend
to untangle due to string tension, which results in oscillations of the curved string segments on scales smaller than the causal horizon and larger than their curvature radii. Friction dissipates the energy of these oscillations and leads to their gradual damping \[10\]. Thus, the strings become smooth on larger and larger scales with their curvature radius \( R \) growing accordingly.

Friction on a cosmic string is caused by the interaction of the string fields with the plasma particles. As shown in \[7\], for string currents \( J \) larger than a critical value \( J_c \), the friction force is determined by the string magnetic field generated by the current. This critical current is estimated as,

\[
J_c \sim J_{\text{max}} \sqrt{L G \mu}
\]  

where \( \mu \) is the string mass per unit length, \( G = m_P^{-2} \) is Newton’s gravitational constant (with \( m_P = 1.22 \times 10^{19} GeV \) being the Planck mass) and \( J_{\text{max}} \sim \sqrt{\mu/L} \) is the maximum acceptable string current, over which the string loses its superconducting properties \[1\], with \( L \sim \ln(\Lambda R) \) being the self-inductance of a string of radius \( \Lambda^{-1} \).

For \( J \geq J_c \) friction prevents the network from reaching horizon-scaling \[7\]. Instead the strings are found to move with a more or less constant terminal velocity,

\[
v \sim \sqrt{\frac{J_c}{J}} \sim \left[ \frac{G \mu}{\sqrt{G J^2}} \right]^{1/2} \ll 1
\]  

In this case the string network does satisfy a scaling solution (so-called plasma-scaling), which, however, may differ substantially from the usual horizon-scaling of ordinary strings. Indeed, a plasma-scaling network consists of slowly moving, highly tangled strings, with curvature radius and inter-string distance much smaller than the horizon, since \( R \sim vt \ll H^{-1} \), where \( H \sim t^{-1} \) is the Hubble parameter \[4\]. Still, although denser, a plasma-scaling network is not in danger of dominating the overall energy density of the universe because, \( \rho_s/\rho \sim \sqrt{G J^2} \ll 1 \), where \( \rho_s \sim \mu/R^2 \) is the energy density of the strings and \( \rho \sim 1/Gt^2 \) is the energy density of the universe with \( t \) being the cosmic time.

It should be noted here that \( J \) is the value of the local, coherent current on the string, which generates the string magnetocylinder and determines the frictional cross-section between the string and the plasma. \( J \) should be thought as a free parameter, which, however, is expected to assume large values \[1\] either directly at current generation or through subsequent interactions with weak primordial magnetic fields \[11\]. On large scales the orientation of the string current is expected to be the stochastic, or Kibble current \[12\]. The string current is dynamically conserved,

\[1\] In \[4\], the factors of \( L \) were omitted for simplicity. However, it is important to maintain them for quantitative calculations. Indeed, it can be easily shown that, for strings formed at the breaking of the Grand Unified Theory (GUT-strings) \( L \sim 100 \).

\[2\] Note that in the one-scale model the curvature radius and the inter-string distance of the string network are of similar magnitude.
which, in view of the growth in the curvature radius during string network evolution and causal interaction of different current patches on the string, results in the local value $J$ remaining approximately constant \cite{7}. We note that superconducting strings in the friction dominated era have also been considered in \cite{13}. However, the much smaller rms current was used rather than the local, coherent current. As a consequence the effect of the magnetocylinder, and thus the string interaction with the plasma, was not included. This resulted in ref \cite{13} concluding that frictional effects would be small in contrast to our results \cite{7}.

### 3. The string gravitational field

The exact metric of the spacetime around a current carrying string was first calculated by Moss and Poletti \cite{14}. The implications of this spacetime on test particles and light rays was also investigated \cite{15}, reaching similar conclusions as ref \cite{14}. However, it was Linet \cite{16} who first attempted to explore the gravitational properties of a superconducting string system in a more realistic way, by considering only first order terms in $G$. Linet demonstrated that this was fully consistent with the original, exact solution. A more thorough study of the linearised spacetime of a superconducting string \cite{17} arrived at similar conclusions. Finally, these results were extended \cite{18} by also considering higher order terms in the gauge coupling. However, in all the above work the importance of self-inductance effects on the string spacetime has not been fully appreciated. Taking these into account \cite{8} has shown that the perpendicular to the string geometry is described by,

$$ ds^2_{\perp} = (1 + 2\Phi)[-dt^2 + dr^2 + (1 - \delta/\pi)r^2d\theta^2] $$

where $\Phi \sim L(GJ^2)\ln(Ar)$ is the attractive gravitational potential and $\delta$ is the deficit angle estimated as \cite{8},

$$ \delta \simeq 8\pi G(\mu + LJ^2) $$

Therefore, the existence of a current on the string generates an attractive gravitational field. This field along with the conical form of the spacetime affects the surrounding particles while the string moves in the plasma. In \cite{8} it is shown that the velocity boost felt by the particles towards the perpendicular direction to the string motion is,

$$ u = 8\pi G\mu v\gamma + 8\pi GJ^2L\left(v\gamma + \frac{1}{v\gamma}\right) $$

where $\gamma^{-1} = \sqrt{1 - v^2}$ is the Lorentz factor. In the above the first two terms are due to the deficit angle whereas the last term is due to the attractive gravitational field. The gravitational field dominates for $J \geq J_G$ where\footnote{In can be easily verified that, for realistic values of the parameters, $J_G > J_c$.}
\[ J_G \sim J_{\text{max}}(LG\mu)^{1/6} \tag{6} \]

The effect of the existence of strong string currents on the string spacetime morphology and on the characteristics of the string network scaling solution is expected to reflect itself on the numerous cosmological implications of strings, in particular the CMBR anisotropies and the formation of the LSS of the universe.

4. Anisotropies on the microwave sky

The root mean square (rms) CMBR temperature anisotropies generated by cosmic strings may be estimated as \[19\],

\[ \left( \frac{\Delta T}{T} \right)_{\text{rms}} \simeq \sqrt{N} \left( \frac{\Delta T}{T} \right)_S \tag{7} \]

where \( N \sim (HR)^{-2} \) is the number of strings inside a horizon volume (see \[7\]) and

\[ \left( \frac{\Delta T}{T} \right)_S \simeq \delta v\gamma \tag{8} \]

is the anisotropy generated by a single string \[20\]. Thus, from \([4]\) and the above, the rms anisotropy generated by a network of superconducting strings is \([7]\),

\[ \left( \frac{\Delta T}{T} \right)_{\text{rms}} \simeq \delta \simeq 8\pi G(\mu + LJ^2) \tag{9} \]

The above suggests that the rms effect of the string spacetime on radiation does not depend on the gravitational field of the strings. This is to be expected since, for radiation, \( ds_{\perp} = 0 \) and \([3]\) suggests that the prefactor \((1 + 2\Phi)\) cannot influence the shape of the null geodesics. Moreover, because \( LJ^2 \leq \mu \) the magnitude of the rms temperature anisotropies is little affected by the string current. However, in terms of the stochastic nature of the anisotropy distribution, a plasma–scaling string network may produce a distinct imprint on the microwave sky, due to the larger number of strings per horizon. Since the string network is denser one possible effect is to shift the position of the Doppler peak to smaller values of \( l \).

Indeed, the distribution of CMBR temperature anisotropies generated by a horizon–scaling network of ordinary strings is expected to be non-Gaussian over angular scales smaller than \((\Delta \vartheta)_0 \sim 1^\circ\), which corresponds to the angular scale of the horizon at the time of last scattering \([21]\). However, as the inter-string distance is much smaller in a plasma-scaling string network, one would expect to discover non-Gaussian signatures only on angular scales smaller than,

\[ \Delta \vartheta \sim \frac{R}{H^{-1}}(\Delta \vartheta)_0 \sim v(\circ) \ll 1^\circ \tag{10} \]

For GUT-strings the rms anisotropy is \((\Delta T/T)_{\text{rms}} \simeq 8\pi G\mu \sim 10^{-5}\), in good agreement with the observations. In this case, it is easy to see that, for maximum string
current, the Gaussianity of the distribution appears over angular scales less than 0.1° as,

\[ v(J_{\text{max}}) \sim (LG\mu)^{1/4} \]  

(11)

However, in order to ascertain the full string predictions for the CMBR anisotropies large computer simulations are necessary. Whilst early simulations produced disappointing results suggesting the lack of a Doppler peak [23] the most recent simulation suggests that local cosmic strings can account for the observed CMBR [24]. It is likely that our denser network will have more power on small scales since its scaling distance is smaller. A full scale numerical simulation is required to compute the exact scale of the peak in the power spectrum. This is the subject of a future investigation.

5. Large scale structure overdensities

The angular deficit of the string spacetime and the attractive gravitational field generate two overlapping streams of matter behind a moving string. This is because of the relative boost, \( u \), felt by the plasma particles towards the string trail. Thus, the matter overdensity generated by a moving string may be estimated as, \( \delta \rho = \beta \rho \), where \( 0 < \beta \leq 1 \) is determined by the fraction of the matter streams that remain inside the string wake, rather than dissipating into the inter-string space. The \( \beta \) factor is strongly related to the nature of the dark matter of the universe. For baryonic or Cold Dark Matter (CDM) \( \beta \simeq 1 \) as almost all the overdensity is contained inside the string wake. For Hot Dark Matter (HDM) though, \( \beta \) can be substantially smaller as an important fraction of the overdensity diffuses away due to free streaming effects [22].

The length of a string wake is \( l(t) \sim vt \) and its thickness is \( d(t) \sim ut \), where \( u \) is given by (5). Thus, the linear mass overdensity of the wake is \( \delta \mu = (\delta \rho) dt \simeq \beta \rho u vt^2 \). Therefore, the total overdensity of a string wake is,

\[ \left( \frac{\delta \rho}{\rho} \right) \simeq \frac{1}{\rho R^2} \beta \frac{u}{v} \]  

(12)

For currents smaller than \( J_G \) the boost \( u \) is determined by the deficit angle terms in (5). In this case it easy to see that,

\[ \left( \frac{\delta \rho}{\rho} \right)_{J<J_G} \simeq \beta \delta \]  

(13)

where we have taken \( \gamma \simeq 1 \) since the coherent motion of the strings is never expected to be ultrarelativistic [7].

The above estimate is not very different from the case of ordinary strings, which again is due to the fact that the deficit angle is largely insensitive to the string current. However, when the gravitational field becomes important, the situation is drastically changed.
For very strong currents the gravitational attraction term dominates in (5). In this case, using also (2) one finds,

\[
\left( \frac{\delta \rho}{\rho} \right)_{J \geq J_G} \simeq \beta (8\pi L) \frac{(GJ^2)^{3/2}}{G\mu}
\]

(14)

For maximum current the above becomes,

\[
\left( \frac{\delta \rho}{\rho} \right)_{J = J_{max}} \simeq \beta \left( \frac{8\pi}{\sqrt{L}} \right) \sqrt{G\mu}
\]

(15)

Observations of the galaxy correlation function of the LSS suggest that \((\frac{\delta \rho}{\rho})_{obs} \sim 10^{-5}\) [22]. Therefore, for GUT-strings with weak currents there is reasonable agreement for CDM models with \(\beta \simeq 1\). However, for strong currents HDM or MDM (Mixed Dark Matter) models are preferable. Indeed, for maximum current (15) suggests that \(\beta \leq 0.1\). In general, from the comparison with observation it can be shown that, for GUT-strings with \(J \geq J_G\) one requires,

\[
J \leq \beta^{-1/3} J_G
\]

(16)

The above constraints may be somewhat strengthened if the distribution of dark matter is smoother than the distribution of the galaxies. Indeed, it is believed that the observed galactic distribution, which is used in order to estimate the density perturbations in the universe today, represents only the peaks in the actual density distribution of the dark matter. It is, thus, believed that the overall density perturbation of the universe relates to that observed as, \((\frac{\delta \rho}{\rho})_{obs} = b(\frac{\delta \rho}{\rho})\), where \(b \geq 1\) is the so-called bias factor [22]. From the above it is evident that this factor may be included in \(\beta\) and so the form of our results remains unaffected. Also, since \(b\) is expected to be of order unity, the quantitative estimates remain reliable.

Apart from the magnitude of the overdensities a plasma–scaling string network may generate LSS morphologically different from the one due to ordinary strings. Indeed, the slow moving strings of a friction dominated network would produce filaments, rather than thin wakes. It is possible that these filaments are thickened by gravitational effects. The distribution of these filaments would be denser due to the smaller inter-string distance of the network. This is rather unfortunate as the spectrum of density distributions would lose power on large scales, a problem already present for ordinary strings. Thus, one could argue that plasma–scaling superconducting string networks are not sufficient to explain the overall LSS, and some other density perturbation mechanism is required to seed the structure on very large scales. If such a mechanism exists then the smaller filamentary structure generated by the strings could be swept inside the ‘pancakes’ of the larger, horizon–sized density perturbations. Such structures, i.e. embedded filaments on large walls are indeed observed [25]. However, a full numerical simulation is required to investigate this and is the subject of future investigation. If the numerical simulations confirm
these tentative conclusions then possible mechanism to generate both cosmic strings and large scale density perturbations could be Hybrid Inflation [26].

6. Nucleosynthesis and galactic magnetic fields

In an early work of Butler and Malaney [5] it was suggested that the existence of a network of electrically charged current carrying strings may seriously disturb Big Bang Nucleosynthesis (BBN). Their argument was based on the fact that a current carrying string generates a Biot-Savart magnetic field which results in the creation of a magnetocylinder around the string core [3][22][7]. This magnetocylinder is impenetrable to charged plasma particles but not to single neutrons. Thus, in [5] it was argued that inside the trail of the moving strings an overdensity of neutrons would be generated that may affect the rate of BBN’s reactions and the abundance of the resulting elements.

However, it can be easily shown that this is not actually the case. Firstly, the charged plasma particles that are pushed away on the border of the magnetocylinder follow the magnetic field lines in a similar way that the solar wind is directed towards the Earth’s magnetic poles by the Earth’s Magnetosphere. Thus, the orbits of the charged plasma particles trace the surface of the magnetocylinder and, therefore, are expected to be sucked back into the trail of the string after the string has passed. Moreover, not only does the charged plasma close behind the string magnetocylinder but some of it may even penetrate it from the back as discussed in [22].

Another argument against the disastrous implications of [5] is due to purely geometrical facts. The dimensions of the string magnetocylinder are determined by the pressure balance between the plasma and the string magnetic field as [3][7],

\[ r_s \sim \frac{J}{\sqrt{\rho v}} \] (17)

where \( v \) is the string velocity. The plasma–scaling solution suggests that, inside a volume \( \sim R^3 \) one would expect only about one string segment of length \( \sim R \). This segment is expected to sweep, while moving, a volume \( \Delta V \sim r_s \times R \times v \Delta t \). Thus, using \( R \sim vt \), the fraction of volume traced by string magnetocylinders per Hubble time \( t \) is,

\[ \frac{\Delta V}{R^3} \sim \frac{r_s}{R} \sim \frac{J^2}{\mu} \leq L^{-1} \sim 10^{-2} \] (18)

Therefore, since the duration \( \Delta t_{BBN} \) of BBN is no more than about a hundred Hubble times [25], an arbitrary point in space may be swept by a string magnetocylinder at most once or twice. Such an encounter would last about \( \Delta t \sim r_s/v \sim L^{-1}t \ll \Delta t_{BBN} \) Thus, one would expect that any effect that such an event may have on BBN’s processes would be insignificant.

It would be misleading to believe that BBN’s processes could be disturbed by the long–range Biot-Savart string magnetic field. Indeed, the field is, in fact, not
expected to extend beyond the border of the string magnetocylinder because the charged plasma particles, while travelling on the magnetocylinder’s border, generate a surface current of opposite orientation to the string current \[7\]. As a result, the string magnetic field is cancelled outside the magnetocylinder.

For the same reason the string magnetic field cannot be involved in any astrophysical processes, since, being contained inside the magnetocylinders of the strings, it never really comes into contact with the cosmic plasma. Thus, such a field cannot freeze into the plasma and be in any way directly responsible for seeding the galactic magnetic fields. However, as shown in \[8\], superconducting cosmic strings may efficiently generate a primordial magnetic field indirectly, through dynamical friction. Such a field may be strong and coherent enough to easily trigger the galactic dynamo and generate the observed galactic magnetic fields. Also, it can be shown that the the plasma vorticity generated by the string motion and gravitational pull may be contribute to the fragmentation process of galaxy formation as the scale of the spinning plasma volumes compares to the protogalactic scale before gravitational collapse \[8\].

7. Baryogenesis

In a recent work Brandenberger and Riotto \[9\] have suggested a new mechanism for explaining the baryon asymmetry in the Universe, involving superconducting cosmic strings. Their model considers a cosmic string network formed at the breaking of supersymmetry at temperatures of order \(10^2\text{TeV}\). Charged sleptons and squarks condense in the string core, resulting in bosonic superconductivity. CP-violating interactions during the string network formation period may result in the confinement of a non-zero net baryon number inside the string core, which would be preserved due to dynamical and topological current conservation until after the electroweak phase transition, when it could be released through string loop decay without being erased by sphaleron processes. In their treatment Brandenberger and Riotto have shown that the confined baryon number is released during the friction domination period of the string network. However, they did not take into account the effects of excessive friction on the string evolution due to the existence of a magnetocylinder around the string core.

As discussed in previous sections, for large currents a network of superconducting strings remains always friction dominated. Thus, such a friction–scaling string network would be more tangled and denser, which would imply that the captured baryon number density may be larger than the original considerations of Brandenberger and Riotto. Following the reasoning of \[9\] we calculate the baryon number density generated by a network of superconducting strings carrying maximum current \(J \sim 10^2\text{TeV}\).

Using the one–scale model, the number density of loops created per unit time is given by \[22\].
\[
\frac{dn}{dt} = \nu R^{-4} \frac{dR}{dt} \sim \frac{v}{R^4} \tag{19}
\]

where \( \nu \) is a numerical factor of order unity. Each of these loops contains a net baryon number trapped inside the strings at the time of their formation \( t_0 \). If \( Q \) is the baryon charge per unit length, and \( Q \sim \sqrt{\mu} \) \[9\] then the charge per correlation length at the network formation is, \( Q_0 = QR_0 \), where \( R_0 \sim (\lambda \sqrt{\mu})^{-1} \) is the initial correlation length \[27\] with \( \lambda \) being the self--coupling of the string vortex field. The baryon charge on larger string segments can be estimated using a random walk. Thus, when a loop of radius \( R(t) \) is formed one would expect it to contain baryon charge of order

\[
Q_R(t) \sim \left[ \frac{R(t)}{a(t_0) R_0} \right]^{1/2} Q_0 \tag{20}
\]

where \( a(t_0) \propto t^{1/2} \) is the scale factor of the Universe and we have included the conformal stretching of the strings. When the loop decays a fraction \( \epsilon \leq 1 \) of the captured baryon charge is released as a net baryon number, \( \Delta n_B = \epsilon Q_R \), where \( \epsilon \) is determined by the rates of CP-violating processes \[9\].

The total baryon number density generated by loop decay is easily estimated as \[9\],

\[
n_B(t) = \int_{t_i}^t dt' \epsilon Q_R(t') \frac{dn}{dt'}(t') \left( \frac{t'}{t} \right)^{3/2} \tag{21}
\]

where the final factor is due to cosmological redshift and \( t_i \) is the earliest time, when loops that contribute to the baryon number density are formed. Using (19) and (20) equation (21) gives,

\[
n_B \simeq \frac{5}{4} \nu Q_0 R_0^{-3} \left( \frac{t_0}{t} \right)^{3/2} \left( \frac{t_0}{t_i} \right)^{5/4} \tag{22}
\]

This gives,

\[
\frac{n_B}{s} \sim \epsilon \nu Q_0 \lambda^3 g_*^{-1} \left( \frac{T_i}{T_0} \right)^{5/2} \tag{23}
\]

where \( s \) is the entropy density of the Universe, \( g_* \sim 10^2 \) is the number of degrees of freedom and \( T_i = T(t_i) \).

In order to evaluate the above one needs to decide on the choice of \( T_i \). If the loops decay promptly they do so in less than a Hubble time due to the efficient radiation emission \[9\]. In this case, at earlier times than the electroweak phase transition, any baryon number released is expected to be ‘washed-out’ by sphaleron processes. Thus, only loops formed later than the time \( t_{ew} \) of the transition may contribute to the net baryon number density. Therefore, \( T_i \simeq T_{ew} = T(t_{ew}) \sim 10^2 GeV \) and equation (23) becomes,
\[
\frac{n_B}{s} \sim \epsilon \nu Q_0 \lambda^3 g_*^{-1} \left( \frac{T_{ew}}{T_0} \right)^{5/2}
\]  

(24)

The above result differs substantially from the findings of Brandenberger and Riotto (equation (30) in [9]), by a factor \( (T_{ew}/T_0)^{-2} \sim 10^6 \). Thus, the result of [9] underestimates the generated baryon asymmetry by a million times! Taking \( Q \sim \sqrt{\mu} \) (i.e. \( Q_0 \sim 1 \)) it can be easily seen that the desired asymmetry \( n_B/s \sim 10^{-10} \) can be achieved with rather natural values of the parameters: \( \epsilon \sim 10^{-1} \) and \( \lambda, \nu \sim 1 \).

However, if instead of collapsing the string loops form stable vortons, i.e. string rings stabilised by the angular momentum of the current carriers [28], the above situation is modified. Vortons may release their baryon number if they ever become unstable and decay [29]. In this case, vortons manage to preserve their baryon number throughout the period prior to the electroweak transition. Thus, the resulting net baryon number density may receive contributions even from the time of network formation, i.e. \( T_i \simeq T_0 \). Consequently, (23) would give,

\[
\frac{n_B}{s} \sim \epsilon \nu Q_0 \lambda^3 g_*^{-1}
\]  

(25)

which is identical with equation (31) of [9]. This is not surprising since, in this case, the integral of (21) is dominated by the initial contribution at the time \( t_0 \) of formation of the string network, so that the subsequent frictional evolution of the strings does not affect the results.

8. Conclusions

In conclusion, we have investigated the cosmological and astrophysical consequences of a plasma–scaling, charged-current carrying, open string network.

We have shown that such a network would generate large scale structure with very different features than the one produced by a horizon scaling network. Indeed, the slow moving strings would create filaments instead of thin wakes, whose separation distances would be much smaller than the horizon. This compounds the existing problem of structure formation with ordinary strings, due to the lack of power on large scales. One way to overcome this is by considering hybrid models, which incorporate inflation with cosmic strings (see for example [26]). In such models the large scale fluctuations could be generated by inflation and the string–produced filaments swept into the horizon-sized ‘pancake’ structures. As we have shown, the magnitude of such filamentary overdensities depends on the type of dark matter assumed, which gives upper bounds on the parameters, and may provide a link between the bias factor and the string current.

We have also found that the imprint of the strings on the microwave sky would be Gaussian on smaller angular scales than the horizon scale at decoupling. The scale of the non-Gaussian features depends on the string current and is related to the terminal velocity of the friction dominated strings.
Furthermore, we discussed possible effects of a plasma-scaling network on nucleosynthesis and showed that the latter is not seriously disturbed even for maximum string currents. We briefly considered the possibility of direct generation of primordial magnetic fields by the string magnetic fields. Since such fields are shielded by the string magnetocylinder they are unable to freeze into the cosmic plasma and have any astrophysical effect.

We have shown that, regardless of the existence of stable vortons, superconducting cosmic strings that are formed at the breaking of supersymmetry are able to generate the observed baryon asymmetry in the Universe. We showed that, in contrast to the claim in [9], a friction-scaling string network can create the required baryon number density even without the production of stable vortons, for rather natural values of the model parameters. This is due to the fact that a friction-scaling network is much denser that a horizon-scaling one, producing substantially more string loops, whose decay eject sufficient baryon charge when decaying to account for the observed anisotropy.

In overall, the plasma-scaling solution of electrically charged current carrying superconducting strings may result in a modified cosmic string cosmology. Comparing this scenario with observations could provide insight into the microphysics of strings and the effect of cosmic string superconductivity.

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