Magnetic Reconnection in the Wakes of Cosmic Strings

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Abstract
The motion of cosmic strings in the universe leads to the generation of wakes behind them. We study magnetized wakes of cosmic strings moving in the postrecombination plasma. We show that magnetic reconnection can occur in the postshock region. Since the width of the cosmic-string wake is very small, the reconnection occurs over a very short length scale. The reconnection leads to a large amount of kinetic energy being released in the postshock region of the cosmic-string wake. This enhances the kinetic energy released during the reconnection. We make a rudimentary estimate of the kinetic energy released by the magnetic reconnection in cosmic-string wakes and show that it can account for low-energy gamma-ray bursts in the postrecombination era.

Unified Astronomy Thesaurus concepts: Cosmic magnetic fields theory (321); Gamma-ray bursts (629)

1. Introduction
The generation and evolution of magnetic fields have been studied quite extensively in the literature. There are many well-established sources for the generation of these magnetic fields. One of the methods of generation of these fields involves the motion of cosmic strings. Cosmic strings are topological defects which are formed due to symmetry-breaking phase transitions in the early universe (Vilenkin & Shellard 2000). The motion of these strings through the cosmic plasma leads to a wake-like structure behind them. Primordial magnetic fields in the early universe can be generated by these cosmic-string wakes due to the Harrison mechanism as well as the Biermann mechanism. In most cases, the seed magnetic field generated in the early universe then grows due to the dynamo mechanism.

Various signatures of topological defects, especially cosmic strings, have been predicted in the literature (Kaiser & Stebbins 1984; Brandenberger et al. 2010; Dvorkin et al. 2011; Lizarraga et al. 2016). Recently, the interaction of the shocks in the wakes of cosmic strings are being studied in detail to look for signatures of cosmic-string wakes in the 21 cm redshift surveys (Hernández 2011; McDonough & Brandenberger 2013). There are many different kinds of strings based on the nature of the phase transition that leads to their formation. Some of the cosmological signals are specific to the kind of cosmic string being considered. For example, it has been shown that fast radio bursts (FRB) can be generated by cusps of superconducting strings (SCSs; Vachaspati 2008; Yu et al. 2014; Zadorozhna 2015). Apart from this, cusps of SCSs can also serve as engines for generating gamma-ray bursts (GRBs; Berezinsky et al. 2001). These are all shown to be signatures of an SCS network in the early universe.

In this work, we show that GRBs can result from magnetic reconnection in the wake of an Abelian Higgs string. The GRBs occur when the magnetic field lines come close together in the cosmic-string wake and release a large amount of energy through magnetic reconnection. In this case, the cosmic string need not be a superconducting cosmic string. Magnetic fields can be generated in the wake of an Abelian Higgs string during the radiation epoch by the Biermann battery mechanism (Sau & Sanyal 2020). The Biermann mechanism generates the field when there are density inhomogeneities in the wake due to the motion of neutrinos around the cosmic string. The neutrinos and the electrons interact through the weak ponderomotive force, and an inhomogeneity is generated in the electron distribution in the wake of the cosmic string. It is well known that there is a temperature difference across the wake due to the shock structure (Layek et al. 2001). The electron inhomogeneity generated by the neutrinos, however, is not aligned with the temperature gradient. This misalignment of the electron density fluctuation and the temperature gradient results in the generation of a magnetic field. If these fields are enhanced due to turbulence in the plasma, they will survive until the matter epoch. Our previous work (Nayak et al. 2023) has indicated that there is a possibility of magnetic reconnection in cosmic-string wakes; in this work we show how magnetic reconnection occurs in the wake of cosmic strings and discuss the possibility that they may lead to GRBs in the postrecombination era.

Magnetic reconnection occurs in highly conducting plasmas. In this process, the field lines of oppositely directed magnetic fields come close together and rearrange their topology by breaking and reconnecting. In this process, energy in the magnetic field is released to the surrounding plasma. Depending upon the magnitude of the magnetic field and the length of the reconnection region, the energy released can be very large. The process of magnetic reconnection is a complex process that involves the motion of charged particles and the fields generated by these charged particles over a short length scale and timescale. The first model to describe the process of reconnection in detail was the Sweet–Parker model (Parker 1957). The model gave an estimate of the energy released during the magnetic reconnection process. Later, several other models were developed to understand the process in more detail (Yamada et al. 2010). In this work, we have used the Sweet–Parker model to make an initial estimate of the energy that can be released by magnetic reconnection in cosmic-string wakes. Though the energy released depends on the magnetic field, we find that a conservative estimate shows that the energy released may lead to GRBs.

GRBs are large explosions of energy over a finite period of time. These may be short-duration bursts of very high energy or
longer-duration bursts of lower energies. The energy emission mechanism for a GRB is still not well understood. Most of the GRBs are attributed to the merger of two neutron stars or to the collapse of a star. Some of the GRBs are also attributed to the process of magnetic reconnection in the plasma. GRBs from magnetic reconnection have previously been studied in the context of a turbulent magnetic plasma with a high magnetization parameter (Granot 2016). Detailed numerical simulations are currently being done to investigate the possibility of generating GRBs due to magnetic reconnection around jets and collapsing neutron stars. In this work, we show that GRBs can also be emitted from magnetic reconnection in cosmic-string wakes.

In Section 2 we review the formation of shocks in cosmic-string wakes and the generation of magnetic fields in the shock. In Section 3, we discuss the possibility of magnetic reconnection occurring in these wakes. In Section 4, we present the cosmological consequences of the magnetic reconnection occurring in these wakes and predict the possibility of observational signals arising from these reconnections. Finally we present our conclusions in Section 5.

2. Shocks and Magnetic Fields in Cosmic-string Wakes

As mentioned in Section 1, cosmic strings generated from symmetry-breaking phase transitions in the early universe produce a wake-like structure behind them. The wake-like structure is due to the conical spacetime of the cosmic string. Shocks are generated in the wakes of these strings as they move through the plasma. A detailed analysis of the shock structure can be obtained from Ponce & Vishniac (1988) and Trojan & Vlasov (2012). In a recent work, it was shown that a magnetic field can be generated in the shock of a cosmic string due to the Biermann mechanism (Sau & Sanyal 2020). We briefly review the generation of the magnetic field in the shock in this section and show in Section 3 why such magnetic fields will lead to magnetic reconnections in the wake of a cosmic string.

Massive particles moving around cosmic strings often form closed orbits around the string (Saha & Sanyal 2018). If these particles happen to be neutrinos, then they generate a neutral current close to the string. The neutrinos interact with the electrons in the plasma by the weak force and cause electron currents in the plasma. These currents lead to oscillatory density fluctuations of the electron density in the wake of the cosmic string. It was shown in Sau & Sanyal (2020) that these density fluctuations can lead to the generation of a magnetic field in the cosmic-string wake through the Biermann mechanism.

The evolution of the magnetic field by the Biermann battery mechanism is given by

\[
\frac{\partial B}{\partial t} = \nabla \times (v_e \times B) + \frac{\eta_{\text{res}}}{4\pi} \nabla^2 B - \frac{1}{eN_e} \nabla \times (j \times B) - \frac{1}{N_e e} \nabla N_e \times \nabla T. \tag{1}
\]

Here, \( B \) is the magnetic field generated by the electron current, \( v_e \) is the velocity of the electrons in the plasma, \( \eta_{\text{res}} \) is the resistivity of the plasma, \( e \) is the electric charge, \( N_e \) is the electron number density, and \( T \) is the temperature of the plasma. In the absence of a magnetic field in the plasma, it is the last term that generates the magnetic field.

We will now establish that, due to the temperature difference across the shock wave, the Biermann term (last term) will generate opposite magnetic fields on the two sides of the shock. The density gradient in the cosmic-string wake is nonuniform, and the gradient of the electron number density is given by

\[
\nabla N_e = \frac{\partial N_e}{\partial x} + j \frac{\partial N_e}{\partial y} + \dot{k} \frac{\partial N_e}{\partial z}. \tag{2}
\]

In the case of the cosmic-string waves, the temperature gradient is perpendicular to the flow direction. Though we can have small fluctuations in the other direction, the gradient of the temperature is dominated by \( j \frac{\partial T}{\partial y} \). If we consider the origin of the coordinate system to be at the position of the cosmic string, then the two sides of the planar shock generated by the moving cosmic string will have opposite temperature gradients. The temperature gradient in this case denotes the direction in which the hot electrons will flow (Schoeffler et al. 2016). The temperature of the shock wave will be higher than the background, so hot electrons will move out from the wake to the background plasma. As the wake is moving through the middle of the plasma, the direction of the velocity of the hot electrons would be opposite in the right-hand side and the left-hand side of the wake. Figure 1 illustrates the concept. The upper (left) half of the shock is referred to as “A,” while the lower (right) part is referred to as “R.” Therefore, if the temperature gradient at A is \( j \frac{\partial T}{\partial y} \), then at R it will be \(-j \frac{\partial T}{\partial y}\). It is difficult to depict this in a plane. The negative sign in the vector comes from the fact that the electrons in the temperature gradient are moving in opposite directions.

The number density gradient remains the same at both A and R sides. This means that the magnetic field generated by the Biermann mechanism at A and R are equal and opposite:

\[
B_A = -j \frac{\partial N_e}{\partial z} \frac{\partial T}{\partial y} + k \frac{\partial N_e}{\partial x} \frac{\partial T}{\partial y} = -B_R. \tag{3}
\]

As a special case, if the density inhomogeneities are in the “y”-direction only and the electrons move out in the “y”-direction only, then the magnetic field will be formed in the “z”-direction. Generally, for such an ideal case, the magnetic field...
on one side of the wake will be in the positive “$z$”-direction, while the magnetic field on the other side of the wake will be in the negative “$z$”-direction due to the opposite flow direction of the electrons. However, for a planar wake, we are looking at a quasi-two-dimensional process. The two dimensions considered here are the $x−y$ plane. The hot electron current is flowing in opposite directions in the two-dimensional plane, so basically for the quasi-two-dimensional plane we have approximated $B_2 = -i \frac{\partial B}{\partial y} = -B_y$ to map it on the two-dimensional plane.

Since the plasma is highly conductive, the magnetic Reynolds number is very large. This makes the magnetic diffusivity very large. The two magnetic field lines then diffuse and squeeze the fluid like two infinitely conducting sheets. We thus have a situation that was first described by Sweet and Parker (Yamada et al. 2010) in their model for magnetic reconnections in conducting plasmas. The Sweet–Parker model is also a quasi-two-dimensional model for magnetic reconnections. This means that there is a strong possibility that the magnetic reconnections will occur in the shocks generated in the wakes of cosmic strings.

In recent simulations of cosmic-string wakes, lines of magnetic reconnection have been observed as the string moves through the plasma (Nayak et al. 2023). These magnetic reconnection lines have been observed for a magnetic field in the wake of a cosmic string with some spatial variations. In Section 3, we calculate the reconnection rates and length of the charge sheets that can be generated in the wakes of cosmic strings based on the Biermann mechanism outlined previously in Sau & Sanyal (2020).

3. Magnetic Reconnection in the Wakes

According to the Sweet–Parker model of magnetic reconnection (Parker 1957), a current layer is formed between two oppositely directed magnetic fields generated in a conducting plasma. The electrical current density in these regions becomes very high. This forces the magnetic lines to break and reconnect, changing the topology of the magnetic field. The curvature force associated with the changed configuration results in the conversion of magnetic energy to kinetic energy.

Assuming steady state conditions, the length of the diffusion region between the two oppositely directed diffusing fields is given by $l = \frac{uL}{v}$, where $u$ is the velocity with which the field lines merge and $v$ is the velocity at which the fluid is expelled from the diffusion region. $L$ is the scale of the magnetic field that we are considering. In the cosmic-string wake, $L$ will be determined by the dimensions of the wake. We are looking at the motion in two dimensions. Let us assume that the string is moving along the $x$-direction. The lines of forces will be generating a strain in the wake of the string. We assume that the magnetic field changes very slowly in the $y$-direction so that we can assume the $y$-component of the magnetic field to be approximately constant. We are then left with the $x$-component of the magnetic field. The field lines push in the $y$-direction, and the pressure difference due to the stretching of the fields leads to the velocity of the diffusing fields. The velocity of the diffusing field lines will be given by $u = \frac{c^2}{4\pi\eta R} \left( \frac{\partial B}{\partial y} \right)$, where $\sigma$ is the conductivity of the fluid. The quantity $\left( \frac{\partial B}{\partial y} \right)$ is evaluated at $y = 0$; this is the Sweet–Parker model. The fluid is expelled with the characteristic velocity $v$ given by $v \sim \frac{B}{\eta R}$. This is known as the hydromagnetic velocity, and it will be henceforth denoted by $C_H$. $\rho$ is the mass density of the plasma. As can be seen from the expression, this is equivalent to the Alfvén velocity in the magnetized wake. In Figure 1, we have briefly sketched the magnetic field generated by the wakes and shown how it can be mapped onto the Sweet—Parker model.

The length of the diffusion region depends on the dimensions of the cosmic-string wake. For a long single string generated at $t_f \ll t_{eq}$, the dimensions of the wakes in terms of the redshift are given by $l_f$ and $w_f$. Here, $l_f = t_f \frac{v}{z}$, and $w_f = v_t t_f \frac{z}{v}$. Here, the suffix $f$ stands for the time at which the string is generated, and the subscript $eq$ stands for the time after which the different particles went out of equilibrium. The thickness of the wake is given by $4\pi Gm_e v_t t_f z$, where $t_f$ is the time at which the reconnection occurs. According to the Sweet–Parker model of magnetic reconnection, the magnetic energy is converted into the kinetic energy of the plasma. The sudden increase in the kinetic energy leads to the acceleration of the particles in the plasma. Thus, an estimate of the velocity of the merging fields gives us an estimate of the increase in the kinetic energy of the plasma. For this we calculate $\frac{\partial B}{\partial y}$). The details of the derivation can be obtained from Parker (1957). The final result is

$$K.E. = \frac{1}{2} \rho c^2 \frac{C_H}{\sigma L}.$$ (4)

where $c$ is the velocity of light. So, a large amount of kinetic energy is released for a dense plasma with a low electrical conductivity and a high magnetic field. For a cosmic-string wake, the density is usually 4 times the density of the background plasma. Though the magnetic field in the wake may not be very high, it may be high enough to generate a considerable amount of energy that could have prospects of detection by various methods.

As the cosmic string moves through the plasma, the emission of kinetic energy can result in a burst of electromagnetic radiation. The radiation can be in any range of the electromagnetic spectra, but because of the large kinetic energy, we expect it to be in the gamma-ray region of the spectra. Since the wake behind the cosmic string is quite narrow, it can then be detected as a burst of gamma rays. In Section 4, we calculate the kinetic energy that can be released due to the reconnection in the wakes of the cosmic strings.

4. Gamma-Ray Bursts from Magnetic Reconnection

The release of a large amount of energy in the plasma accelerates the particles in the plasma, which may lead to the generation of a significant amount of radiation. So, it is quite possible that magnetic reconnection in the shocks of cosmic strings can lead to a burst of energy that could be a gamma-ray progenitor. There exist some GRB models that show magnetic reconnection to be the progenitor of a GRB, but this is the first time that magnetic reconnections in cosmic-string wakes have been considered as the progenitor of a GRB. A detailed numerical calculation is beyond the scope of this work, so we do an order-of-magnitude estimate of the energy that is released due to magnetic reconnection in the wake.

The kinetic energy that is released due to reconnection depends inversely on the length scale of the reconnecting.
magnetic field. Since the opening angle of the cosmic-string wake is very small, this length scale is also very small. It will depend on the thickness of the wake and would be of the order of $4\pi G\mu r^2 v_{\text{A}}^2$. One of the reasons why magnetic reconnections are traditionally not considered for GRBs is because of the large length scale over which they occur. In typical astrophysical plasma, the length scale over which reconnection occurs is considerably large. However, in the case of cosmic-string wakes, only the length of the wake is large; the thickness of the wake is much smaller as it is determined by the deficit angle of the cosmic string. This depends on the symmetry-breaking scale. Since the Grand Unified Theory (GUT) symmetry-breaking phase transition happened at $10^{16}$ GeV, the deficit angle of the GUT cosmic string is typically of the order of $10^{-12} - 10^{-6}$ Abelian Higgs strings have $G\mu$ of the order of $10^{-11} - 10^{-8}$. Current observational limits from the Planck Collaboration have put the upper limit of Abelian Higgs strings at $3 \times 10^{-7}$ (Alves et al. 2014). The order of the string velocity is $(\gamma v_s) \sim 0.4$ (da Cunha 2020). The time of the wake formation can be written as $t_f = \left( \frac{3}{2} \right) H(z) \left( \frac{\gamma + 1}{\gamma + 1} \right)$ (Brandenberger et al. 2010). Assuming that the wake formation happened around the recombination epoch ($z \sim 3000$) (Brandenberger et al. 2010) and the magnetic reconnection is happening at lower values of the redshift ($z \sim 30$), the length scale turns out to be $10^{-3}$ in dimensionless units. The conductivity of the plasma in the matter-dominated epoch is given by $\sigma \sim 10^{10} \text{s}^{-1}$ (Caprini & Ferreira 2005). The kinetic energy is thus dependent primarily on the magnetic field in the wake and the plasma density. The plasma density at recombination is given by $3.8 \times 10^{-3} \text{eV}^4$. Since the value of $C_H$ depends upon the magnetic field and is generally greater than $1$ for strongly magnetized plasma, as a first approximation we consider it to be of the order of $1$. An approximate estimate will then put the kinetic energy generated due to the magnetic reconnection to be of the order of $10^{14} \text{erg cm}^{-2}$.

This estimate is only for a generic case. Here we have not specifically mapped any of the GRBs with the magnetic reconnection in the wake. We have only used standard values of cosmic-string wakes (da Cunha 2020) to illustrate that it is possible to generate a GRB in a cosmic-string wake. We can have these wakes of cosmic strings at any value of the redshift. We plan to do a more detailed study involving specific GRBs at a later stage.

Since there have been GRBs detected in the lower energy range ($10$–$10,000$) keV that have fluxes in the order of $10^{-8} \text{erg cm}^{-2}$, it is quite possible that the magnetic reconnection in magnetized wakes of cosmic strings can be detected as a GRB. Our rudimentary method unfortunately does not allow us to determine the timescale of the GRB, which would have been helpful in identifying an observational signal in a better way. The standard way to proceed would be to find the viscous timescale of the merging field lines (Janiuk et al. 2021) in the cosmic-string wake. This will depend on the plasma resistivity, kinematic viscosity, and other properties of the plasma. However, a large number of GRBs have been reported with flux densities ranging from $10^{-5}$ to $10^{-4} \text{erg cm}^{-2}$, with burst durations ranging from less than $0.1$ to $30$ s (Klebesadel et al. 1973). As the time duration is also similar to the timescales observed in magnetic reconnections, we plan to look into these GRBs in greater detail to see if they can be signatures of magnetized cosmic-string wakes. There are also possibilities of repeated bursts as the cosmic string moves through the plasma. The periodicity of this repetition will depend upon the motion of the cosmic string.

5. Conclusions

In this paper, we have shown that it is possible to generate GRBs from magnetic reconnection in the wakes of Abelian Higgs cosmic strings. Magnetic reconnections are currently being studied in both laboratory and astrophysical plasmas. They are manifested in solar flares, coronal mass ejection, and other solar phenomena. The search for signatures of cosmic strings and their wakes is also continuing through both direct detection methods as well as statistical methods. Cosmic-string networks are known to generate both gravitational and nongravitational signatures. The signatures related to magnetic fields and electromagnetic phenomena have, however, been limited to superconducting cosmic strings. Our work shows that in any cosmic-string wake, if the magnetic field evolves by the Biermann mechanism, it is possible to have magnetic reconnections. All it requires is a density inhomogeneity that is not aligned to the temperature gradient of the cosmic-string wake. Though in this work we have used a specific method to show the phenomenon analytically, it may be extended to many other cases where magnetic fields occur in cosmic-string wakes. We have only done a preliminary calculation for the energy of the GRB. An important parameter that distinguishes a GRB is the duration of the burst. This helps in the classification of the observed GRBs. In this current work, we have not estimated the duration of the emitted GRB in our model. We are currently working on obtaining the viscous timescale of the plasma, which will help us in determining the timescale of the GRB generated in the plasma wake.

Since this is a preliminary work, we have not been able to obtain an exact match to the observed GRBs. We have used the Sweet–Parker model and found that the energy generated by the reconnection is quite significant. There are various improvements on the Sweet–Parker model. We are currently working on a more detailed model that will tell us more about the reconnection phenomenon in the magnetized wakes of cosmic strings.

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