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Evolution of magnetic fields in cosmic string wakes.

[S Nayak, S Sau, S Sanyal; Astroparticle Physics 146(2023) 102805]

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Outline

Introduction

Cosmic string and it's wake

- Cosmic strings are one dimensional topological defects produced by the symmetry breaking phase transitions in the early universe.
- When cosmic strings move through plasma, it generates wakes behind due to space-time geometry of cosmic strings.
- The initial magnetic field in the wake is generated by the motion of particles around cosmic strings.

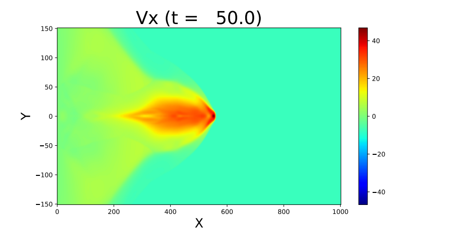

Figure 1: The wake structure due to a moving cosmic string

Generation of magnetic field

The magnetic field is generated in the cosmic string wake by the Biermann-battery mechanism.

$$\frac{\partial \vec{B_e}}{\partial t} = \nabla \times (\vec{v_e} \times \vec{B_e}) + \frac{\eta_{res}}{4\pi} \nabla^2 \vec{B_e} - \frac{1}{eN_e} \nabla \times (\vec{j} \times \vec{B_e}) - \frac{1}{N_e e} \nabla N_e \times \nabla T_e$$

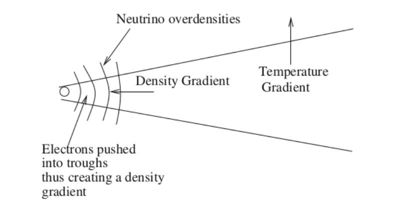

Figure 2: An illustration to show the generation of magnetic field in the wakes of cosmic strings

- $\vec{v_e}$ is the electron fluid velocity.
- N_e is the number density of the electrons.
- T_e is the electron temperature .
- η_{res} is the resistivity of the plasma.
- The last term on the right hand side is the Biermann battery term

[S. Sau, S. Sanyal, Eur. Phys. J. C 80 (2020) 152]

- The seed magnetic field generated by the Biermann-Battery mechanism is usually small.
- For the magnetic fields to survive it is assumed that these fields get amplified in the cosmic string wakes.

- There has been no detailed study of the evolution of magnetic fields in the wakes of cosmic strings.
- We are therefore interested to see how a magnetic field generated close to the cosmic string will evolve as the cosmic string moves through the plasma.

Numerical method used to simulate the cosmic string wake

Initial condition

- The space time around the cosmic string is locally flat and globally conical. We model the inflow velocity as a flow around a cone centered around the cosmic string.
- The plasma particles streaming past the cosmic string would be deflected by an angle θ .

$$v_x = v_0 cos\theta$$
$$v_y = v_0 sin\theta$$

Where, v_0 is the initial velocity and deficit angle $\theta = 8\pi G\tilde{\mu}$

- The initial velocity is combination of the string velocity and the random velocity of the particles in the plasma.

- The magnetic field is non zero at the start of the simulation. Since the nature of the magnetic field in the wakes is not known we consider the magnetic field is oscillatory in nature.

$$B(y) = B_0 \exp(-Ay) cos(\omega y)\hat{y}$$

  Where, B_0 is the initial magnetic field, A and ω are constants.

- In the early universe , at high temperature, magnetic pressure is much much lower than the thermal pressure as the plasma density is much higher. So,in the early universe plasma has high β value.
- We took the plasma density and plasma pressure in the order of β. Where, β is the ratio of the thermal pressure and the magnetic pressure.
- When the cosmic string passes through the plasma, the equilibrium is disturbed. So, A weak perturbation is imposed to the magnetic field.

Resistive MHD Equations

In the early universe we assume the plasma was inhomogeneous and resistive. For that, we solve the resistive Magneto-hydrodynamics (MHD) equations numerically.

- Continuity equation

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}.(\rho \boldsymbol{v}) = 0 \tag{1}$$

  Where, ρ is plasma density.

- Momentum equation

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \boldsymbol{\nabla}.(\rho \boldsymbol{v} \boldsymbol{v} + p_T \boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}) = 0 \tag{2}$$

  Where, total pressure $P_T = P + \frac{B^2}{2}$

- Energy equation

$$\frac{\partial e}{\partial t} + \nabla.[(e + p_T)\boldsymbol{v} - (\boldsymbol{v}.\boldsymbol{B})\boldsymbol{B}] + \eta \boldsymbol{j} \times \boldsymbol{B} = 0 \qquad (3)$$

Where, total energy density $e = \frac{P}{\Gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{2}$

- Induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla.(\boldsymbol{vB} - \boldsymbol{Bv}) + \nabla \times (\eta \boldsymbol{j}) = 0 \qquad (4)$$

Where η is the resistivity of plasma

[S. Zenitani, T. Miyoshi, Phys. Plasmas 18 (2011) 022105]

Numerical Setup

- These MHD equations are solved by Godunov type MHD code **OpenMHD** (https://sci.nao.ac.jp/MEMBER/zenitani/openmhd-e.html)
- **Runge-Kutta** method is used for calculating the time evolution.
- Numerical fluxes are calculated by finite volume method (Godunov type scheme-HLL method). This takes care of the evolution of the spatial part of MHD equations.

- The simulations are carried out in the x-y two-dimensional plane.
- One quadrant($x \geq 0$ and $y \geq 0$) is solved considering the symmetry of the system.
- Maximum lattice size on the x direction as 1000 and in the y direction as $y = 150$.
- Plasma β value sufficiently high up to 10^5.
- We took

$$
\begin{aligned}
B_0 = 100, &\qquad v_0 = 10, \\
A = 0.2, &\qquad \omega = 0.8, \\
\theta = 15^\circ, &\qquad \eta_0 = \frac{1}{1000}
\end{aligned}
$$

Length and time scales

For the cosmic string wakes in the recombination era.

- The horizon length is of the order of 200 Mpc and width of the cosmic string wake is of the order of 10^{-3} Mpc.
- Opening angle in our simulations is large. To scale it to the recombination era, one unit of the grid cell will correspond to $\approx 10^{-5}$ Mpc.
- The plasma β value is dimensionless. For convenience, the different quantities in the equations are also made dimensionless.
- Initial velocity is scaled by the Alfven velocity. For our simulation the Alfven velocity $v_A \sim 0.32$.
- Alfven transit time $\frac{l}{v_A}$ is used to normalize the time.

Results

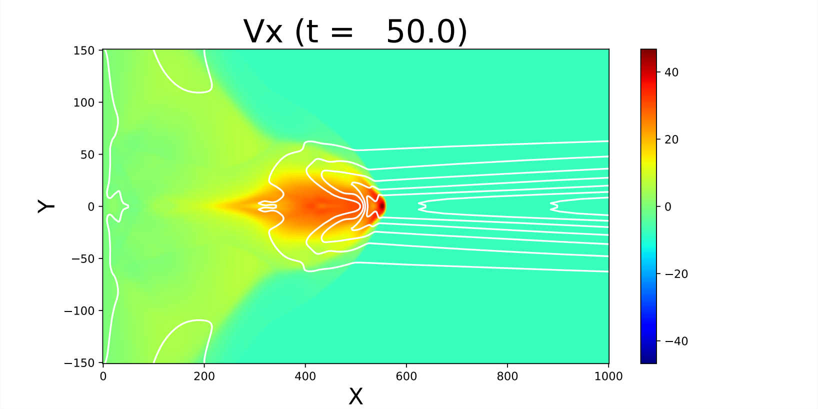

Figure 3: The wake structure due to a moving cosmic string with the magnetic field lines at $t = 50$

Formation of shocks

The sharp rise in both the density and pressure and sudden drop of velocity around $x = 550$ simultaneously indicates the formation of a shock behind the string.

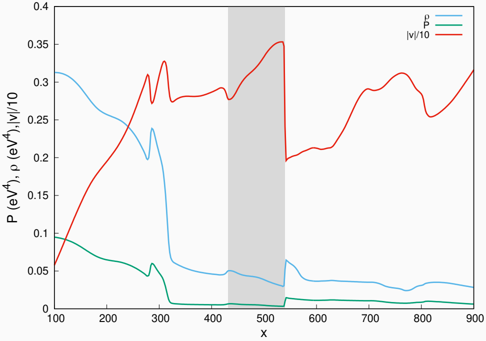

Figure 4: Plot of the pressure and density and velocity along the x-axis at $t = 140$ steps. The velocity is measured in terms of the Alfven velocity and is therefore dimensionless.

- For a cosmic string, the ratio of the post-shock temperature (T_2) to the preshock temperature (T_1) at recombination is given by,

$$\frac{T_2}{T_1} = \frac{1}{2}\Gamma(\Gamma - 1)(4\pi G\tilde{\mu}M)^2$$

  Where, M is the Mach number.
- We consider the system is supersonic and $M \simeq 1$ in these simulations.
- As the value of $4\pi G\tilde{\mu}$ is small, the temperature fluctuations from such strings will be important for high Mach numbers. For $M \simeq 1$, the temperature fluctuations will be smaller.

[A. Beresnyak, Astrophys. J. 804 (2015) 121.]

- There are multiple shocks formed in the wakes of cosmic string. And the shocks need not be steady shocks.
- Unlike steady shocks where the temperatures cool down as the shock passes by there will be consistent reheating of the plasma as multiple shocks are generated as the wakes moves forward and follow one another.
- The shocks generated are non uniform and will generate vorticity. But the vorticity generated by a single stream in not enough to generate turbulence in the plasma.

Evolution of magnetic field

- Magnetic field peaks close to the cosmic string and decreases in the post shock region.

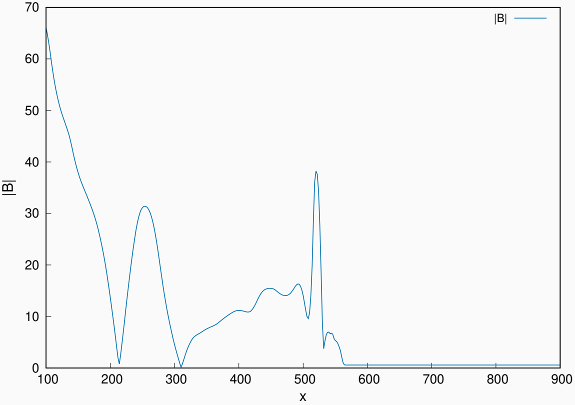

Figure 5: Plot of the magnitude of the magnetic field at $t = 50$ steps.The dimension of the field can be obtained by multiplying with a factor of $10^{-9}eV^2$

- For high β plasma, the evolution of the magnetic field does not depend on the value of β in the cosmic string wake.

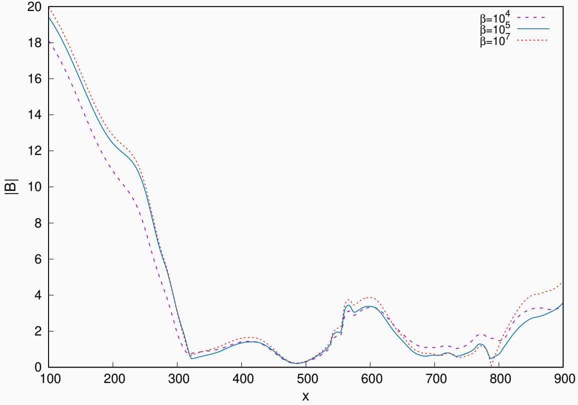

Figure 6: Plot of the magnetic field $t = 140$ steps for three different β values.

Magnetic reconnection

- Magnetic field lines do reconnect and form loops as the cosmic string moves away.

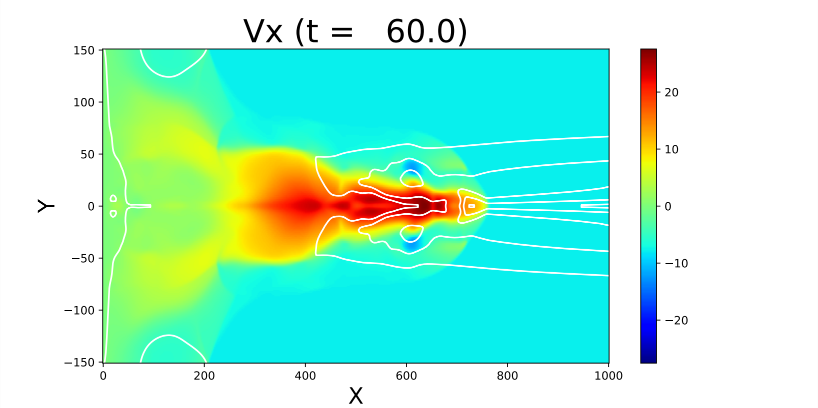

Figure 7: The wake structure due to a moving cosmic string with the magnetic field lines at $t = 60$

- As the wake evolves we see many more magnetic field lines reconnecting and forming circular loops.

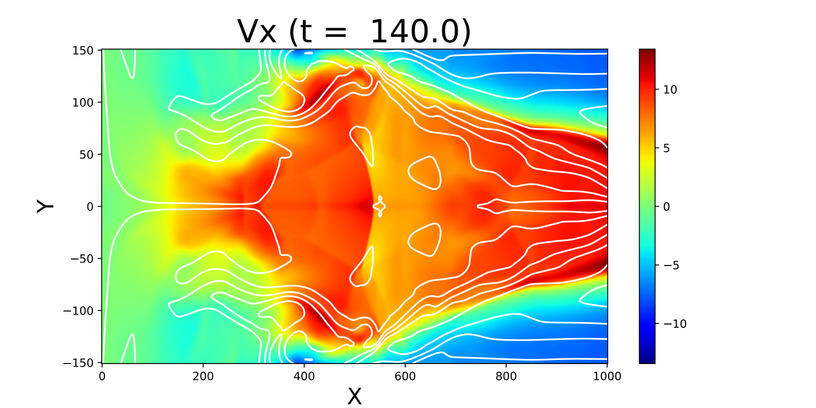

Figure 8: The wake structure due to a moving cosmic string with the magnetic field lines at $t = 140$

Summary

Summary

- The shocks generated in cosmic string wakes need not to be the steady shocks.
- Multiple shocks can be generated in the magnetized string wake. It indicates the possibility of shock collisions.
- The magnetic field lines do break, reconnect and form loops as the cosmic string moves away.
- The magnetic energy generated through reconnections in the wake leads to the acceleration of charged particles. These particles may contribute to the cosmic ray spectrum.
- Magnetic field in the shocks is not amplified unless there is an explicit dynamo mechanism involved.
- The evolution of magnetic field does not depend on the β value for such high β plasma.

Acknowledgement

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THANK YOU

Cosmic string wake

The metric around a infinitely straight Nambu-Goto string lying along the z-axis can be obtained by solving the Einstein equations. It is "conical" on the plane transverse to the string, and the line element is

$$ds^2 = dt^2 - dz^2 - d\rho^2 - \rho^2 d\theta^2 \quad ; \quad 0 \leq \theta \leq 2\pi(1 - 4G\tilde{\mu})$$

[Vilenkin, A. and Shellard, E. P. S. (jul 2000)]

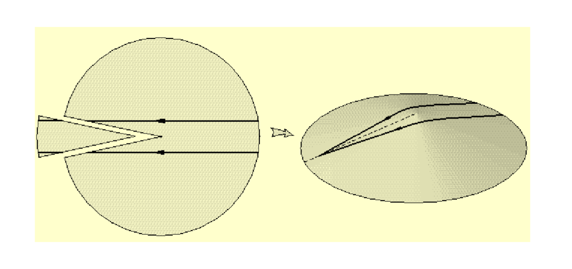

Figure 9: An illustration to show the formation of cosmic string wake

[https://guava.physics.uiuc.edu]