Generation of magnetic fields in cosmic string wakes

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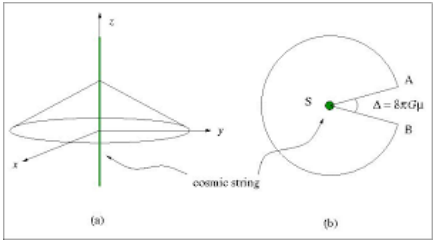
Outline

Introduction

- Neutrinos rotating around Abelian-Higgs strings generate a neutral current close to the string.
- The neutrino current density depends on its distance from the string.
- A neutrino gradient as well as an electron gradient is generated in the plasma due to the neutral current.
- Current acts like a cross perturbation across the cosmic string wake.
- The high Reynolds number of the plasma and the cross perturbation generates a magnetic field in the cosmic string wake.

Cosmic string

- Cosmic strings are 1 D topological defects, formed due to the axial or cylindrical symmetry breaking.
- Mathematically they are solutions of certain field theories, whose energy is concentrated along an infinite line.
- They were first introduced by Tom Kibble.



Cosmic string

[1] *Kibble T W B, 1976, J. Phys. A: Math. Gen. 9, 1387*
[2] *https : //aether.lbl.gov/eunhwa$_w$ebpage$_2$/stringdynamics.html*

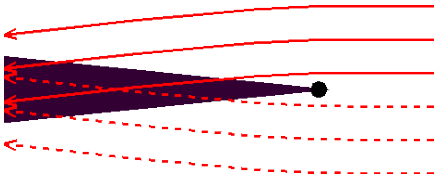
Cosmic string

- The underlying field theoretical model that we have taken is Abelian–Higgs model which has string–like solutions. This is Abelian–Higgs string.
- If we have massive partcle distributed in static cosmic string space time they will diffuse to cluster around cosmic string.
- For specific set of linear momentun, angular momentum value massive particle will form closed orbit near the cosmic string.

[3] *Nielsen H B and Olesen P, 1973, Nucl. Phys. B, 61, 45*
[4] *A. Saha and S. Sanyal, JCAP 2018.03 (2018) 022*

Wakes due to Cosmic strings

- When a string moves towards a direction it sweeps a surface. Nearby matters will move towards that area.
- Matter accretion happens at that surface and form a 2 D structure. This is cosmic string wake.
- Cosmic string wakes arise due to the conical nature of space time around a cosmic string.



Cosmic string wake

[5] *http : //www.hpcc.ecs.soton.ac.uk/hpci/collaborations/cosmology/about.html*

[6] *A. Stebbins, S. Veeraraghavan, R. H. Brandenberger, J. Silk, and N. Turok, Astrophys. J.322,1 (1987)*

Wakes due to Cosmic strings

- If the string moves with a velocity v_s, the particles moving along that plane get a velocity perturbation Δv due to the deficit angle of the string.
- Cosmic string has a deficit angle $\Delta = 8\pi G\mu$.
- Magnitude of the velocity kick towards the center of the plane behind the string.

$$\delta v \approx \Delta v_s \gamma_s = 4\pi G \mu v_s \gamma_s$$

- As more and more particles are kicked towards the string, an overdensity or wake is generated behind the string.

[7] *J. Silk and A. Vilenkin, Phys. Rev. Lett.53, 1700 (1984)*
[8] *T. Vachaspati, Phys.Rev. Lett.57, 1655 (1986)*

Neutrino motion around cosmic strings

- We have taken neutrino as our massive particle among many other massive particles in the wake.
- We have taken the following set of value :

  Energy $(E) = 1.083$,
  Linear momentum $(l_z) = 0.025$,
  Angular momentum $(p_z) = 0.02$.
- Co-variant Dirac equation for neutrino :

$$i\gamma^{\mu}(\partial_{\mu} - \Gamma_{\mu})\psi = m\psi$$

[9] *A. Vilenkin , Physical Review D 20, 1807 (1979)*

Neutrino motion around cosmic strings

- General line element for cylindrical co-ordinate is given by

$$ds^2 = N^2(r)dt^2 - dr^2 - L^2(r)d\phi^2 - N^2(r)dz^2$$

- Neutrino wave function :

$$\psi = \frac{1}{4\pi} = \begin{bmatrix} i(E+m-p)^{1/2} J_{l_z+1/2}(\alpha r) \\ \beta(E+m+p)^{1/2} J_{l_z-1/2}(\alpha r) \end{bmatrix} e^{(ip_z z - iEt - il_z\phi)}$$

where $\alpha = [(E+m)^2 - {p_z}^2]^{1/2}$, E = Energy of the particle , p_z= Linear momentum , l_z= Projection of total angular momentum

Neutral current generated by the neutrinos

- Neutrino current density along z direction is :

$$j(r) = \psi^{\dagger}\gamma^{t}\gamma^{z}\psi$$

- Total neutral current :

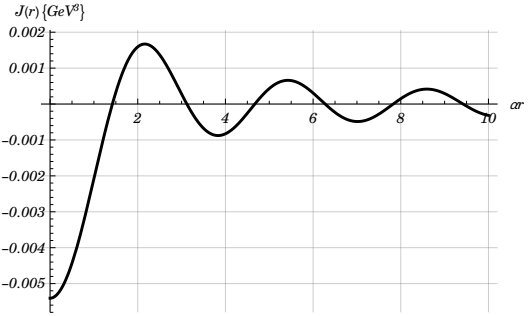
$$J(r) = \int_{0}^{\infty} dE \int_{-E}^{E} dp \sum_{m} f(E,m) j(r)$$

$f(E,m)$ is the Fermi distribution function for neutrino in a rotating system

$$\implies f(E,m) = \left[exp\left(\frac{E - l_z\Omega - \mu\beta}{T} \right) + 1 \right]^{-1}$$

Generation of density perturbations in the Wakes

- Neutrino current is maximum around 2.3 . Its value is near 0.002 GeV^3.
- This plot represent neutrino /anti-neutrino density in the plasma. Negative density signifies electron over-density in those region.



Neutrino current as a function of r. αr is dimensionless.

Neutrino and electron density perturbations

- The flow of neutrinos in a plasma medium is given by

$$\frac{\partial N_\nu}{\partial t} + \nabla . \vec{J_\nu} = 0$$

$$\frac{\partial \vec{P_\nu}}{\partial t} + (\vec{v_\nu} . \nabla)\vec{P_\nu} = \vec{F_\nu} = \sqrt{2} G_F \left(\vec{E_e} + \frac{\vec{v_\nu}}{c} \times \vec{B_e} \right)$$

- The continuity equations for the electron plasma dynamics,

$$\frac{\partial N_e}{\partial t} + \nabla . \vec{J_e} = 0$$

$$\frac{\partial \vec{P_e}}{\partial t} + (\vec{v_e} . \nabla)\vec{P_e} = \vec{F_e} = -e\vec{E_e} + \sqrt{2} G_F \left(\vec{E_\nu} + \frac{\vec{v_e}}{c} \times \vec{B_\nu} \right)$$

[10] *A. Serbeto, Physics Letters A, 296, 217 (2002)*

Neutrino and electron density perturbations

- Using perturbative approach we obtain a relation between the density perturbation of neutrino and electron.
- Relation between these two density perturbations are

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right) \delta N_e = -\frac{\sqrt{2} G_F N_e}{m_e c^2} \left(\frac{\partial^2}{\partial t^2} - c^2 \nabla^2\right) \delta N_\nu$$

  N_e= electron density of the plasma, ω_p= plasma oscillation frequency.
- Neutrino current will generate a potential ϕ_e due to the charge separation given by $\nabla^2 \phi_e = 4\pi e \delta N_e$.

[11] *L.O. Silva, R. Bingham, J.M. Dawson, J.T. Mendonca, and P.K. Shukla, Phys. Plasmas 7, 2166, (2000)*

Generation of magnetic fields in the wake

- Magnetic field evolution in the plasma is given by the equation

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

  $\vec{v_e}$= electron fluid velocity, N_e= number density of the electrons, T_e= electron temperature and η_{res}= resistivity of the plasma.

- Last term on the right hand side is the Biermann battery term. If there is no magnetic field ($\vec{B_e} = 0$), this term generates the magnetic field in the plasma.

[12] *K. M. Schoeffler, N. F. Loureiro, R. A. Fonseca, and L. O. Silva. Physics of Plasmas 23, 056304 (2016)*

The Biermann battery mechanism

- If density perturbation of neutrino is along y-axis temperature gradient will be along x axis.
- So the Biermann battery term

$$\frac{\partial B}{\partial t} \sim \frac{\sqrt{2} G_F}{m_e c^2} \frac{\partial N_\nu}{\partial y} \frac{\partial T_e}{\partial x}$$

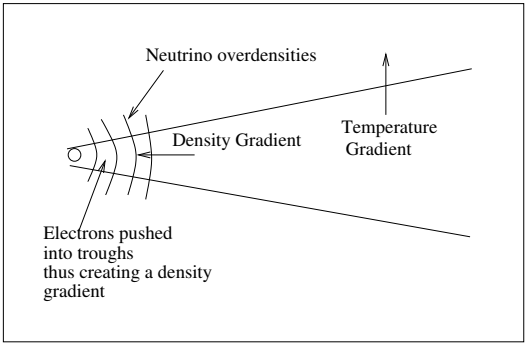


Figure: 3. Neutrino current as a function of r. αr is dimensionless.

Estimation of the magnetic Field

- Temperature gradient across a cosmic string shock (in the x-direction) is of the order of $10^{-5}T$ and $G_F = 10^{-5}GeV^{-2}$
- We have found $\frac{\partial N_\nu}{\partial y} \sim 0.02GeV^3$ and $\frac{\partial T_e}{\partial x} \sim 10^{-5} \times 200GeV$
- Approx. order of magnitude of the magnetic field is about $10^{13}G$. But the observed magnetic field value at that temperature was around $\sim 10^{24}G$.
- This small field can grow into a larger field due to turbulence and higher Reynolds no of the plasma.

[13] *B. Layek, S. Sanyal and A. M. Srivastava, Physical Review D 63, 083512, (2001)*
[14] *G. Baym, D. Bodekar and L. McLerran Physical Review D 53, 662 (1996)*

Conclusions

- So the neutrino density flux generates charge separation and electron current in the neutral plasma.
- At the electroweak scale the equipartition magnetic field is $\sim 10^{24} G$. Though the field generated is small but it is quite possible that this small field can grow into a larger field due to turbulence.
- We plan to do detailed simulations at a later stage to see the nature of these magnetic field.

Publication

’ **Neutrino currents in wakes of cosmic strings**’ , S. Sau, S. Sanyal, *Eur. Phys. J. C 80, 152 (2020)* .

Acknowledgement

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Thank You

Topological defect

- Topological defects are configurations of matter that form during symmetry breaking phase transitions.
- Defects are of various dimensions depending on the order parameter or kind of symmetry that is broken.
- Cosmic Strings : One dimensional defects formed when axial or cylindrical symmetry is broken.
- Z(3) Domain walls : Two dimensional defects that arise due to the breaking of the Z(3) symmetry.