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Synchrotron radiation from accelerated electrons in the magnetized cosmic string wakes.

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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 string moves through plasma the conical space around the string leads to the formation of wakes behind them.
- The magnetic field in the wake is generated by the motion of particles around cosmic strings.

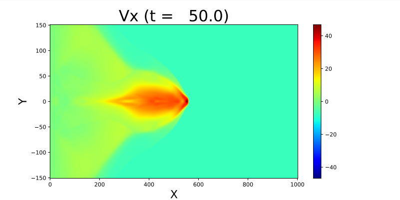


Figure 1: The wake structure due to a moving cosmic string. [S Nayak, S Sau, S Sanyal; Astroparticle Physics 146(2023) 102805]

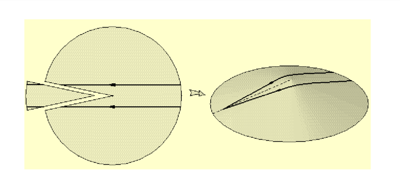


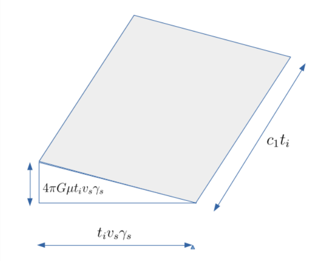
Figure 2: An illustration to show the formation of cosmic string wake. [https://guava.physics.uiuc.edu]

- The wake is formed at $t = t_i$. The dimension of the wake at t_i is

$$L_1 \times L_2 \times L_3 = c_1 t_i \times t_i v_s \gamma_s \times 4\pi G\mu t_i v_s \gamma_s \qquad (1)$$

- Dimensions of the wake will be affected by the expansion of the space.
- The width of the wake will grow by accreting matters from both sides.
- The width of the wake generated at t_i and observed at a time t in a co-moving frame of reference is given by

- $\delta\theta \simeq 8\pi G\mu$



$$L_3 = \frac{24\pi}{5} G\mu v_s \gamma_s t_0 \frac{\sqrt{1 + z(t_i)}}{1 + z(t)} \qquad (2)$$

[Da Cunha et al,Phys. Rev. D93,123501(2016)]

- The string moves with supersonic velocities, shock waves are generated behind the cosmic string.

- The velocity of the shock wave [Ponce and Vishniac, ApJ, 332:57-66, (1988)]

$$v_{sh} = \frac{1}{4}[(\Gamma_m + 1)^2 u^2 + 16c_s^2]^{1/2} - \frac{(3 - \Gamma_m)}{4} u \qquad (3)$$

  Here, $u = v_s \delta\theta (1 - v_s^2)^{-1/2}$ and $c_s^2 = \frac{\Gamma_m p_1}{\rho_1 + p_1}$

  $\delta\theta$ is the angle of deflection of the particles due to the cosmic string metric. v_s is the velocity of the string.

- The shock velocities can go as high as $0.9c$.

- Relativistic shock waves are known to generate accelerated electrons which subsequently emit synchrotron radiation.

- Electrons in the shocks behind magnetized cosmic string wakes will also emit synchrotron radiation.

Synchrotron Radiation from electrons in the wake.

- The magnetic field B is considered to be homogeneous all over the wake of the string.
- The electrons are accelerated by the motion of the shock generated in the string's wake, they will lose energy as synchrotron radiation.
- The average power that is radiated by the electrons is given by,

$$\langle P^{syn}(\nu)\rangle = \frac{\sqrt{3}e^3 B}{m_e c^2}\int_1^\infty d\gamma N_e(\gamma) R(\alpha) \qquad (4)$$

$\gamma \longrightarrow$ Relativistic Lorentz factor,
$N_e(\gamma) \longrightarrow$ Electron distribution in cosmic string wake,
$R(\alpha) \longrightarrow$ Combination of Bessel functions.

Where, $\alpha = \frac{\nu}{\nu_c}$, and peak frequency $\nu_c \sim \frac{eB\gamma^2}{2\pi mc}$

[C. D. Dermer and G. Menon (2009).]

One zone model

One Zone model is generally used for a spherical region of plasma but this model has also been adapted to model streaming jets.

The physical quantities to define the model are

- **The Doppler factor :** For the relativistic outflow δ_D defined by,

$$\delta_D = \frac{1}{\gamma(1 - \beta cos\theta)} \tag{5}$$

  Here $\beta = \frac{v_s}{c}$ and θ is the viewing angle which is very small. Strings are assumed to move with relativistic velocities, so δ_D depends only on the Lorentz factor.

- **Distance from the observer:** The luminosity distance d_L is given by,

$$d_L = d_A(1 + z)^2 \tag{6}$$

  Where z is the red-shift and d_A is the angular size distance.

- **Electron distribution:** The non thermal relativistic electrons are assumed to be uniformly distributed throughout the region with an isotropic pitch angle distribution.

- For this model, the synchrotron radiation is given by,

$$\nu F_{\nu}^{syn} = \frac{\delta_D^4 \nu' \langle P^{syn}(\nu') \rangle}{4\pi d_L^2} \tag{7}$$

  Where, the electron distribution given by $N_e(\gamma')$ where γ' is the comoving Lorentz factor.

Numerical tools

- We have used the python module **AGNpy**. The primary inputs come from the particular source being studied and the the final output spectrum depends upon the electron distribution, the Lorentz factor, the Doppler factor, redshift etc. [https://agnpy.readthedocs.io/en/latest/index.html]
- We have modified the geometry in the AGNPY module to include the scaling due to the redshift parameter to obtain the synchrotron radiation in our case.
- We obtain these input parameters for the case of the cosmic string and use the module to obtain the final spectrum.

Electron distribution

We have assumed that there are a distribution of electrons which are moving across the cosmic string wake and these electrons have a **power law distribution**,

$$N_e(\gamma) = K_e \frac{1}{4\pi} \gamma^{-p} H(\gamma; \gamma_1, \gamma_2) \tag{8}$$

Where, power law exponent $p \sim 2$ (slightly greater than 2) and $H(\gamma; \gamma_1, \gamma_2)$ is the Heaviside function. The normalization constant

$$K_e = \frac{(p-2)u_e}{m_e^2 \left(\gamma_1^{(2-p)} - \gamma_2^{(2-p)} \right)} \tag{9}$$

Total energy density of the non thermal electrons

$$u_e = m_e c^2 \int_{\gamma_1}^{\gamma_2} \gamma d\gamma n_e(\gamma) \tag{10}$$

$\gamma_1 \simeq 1$ is the minimum Lorentz factor of the electrons and $\gamma_2 \simeq 10^7$ is the maximum possible Lorentz factor of electrons.

total energy of the electrons

$$W_e = u_e V_B \tag{11}$$

In comoving coordinates, the volume of the wake is ,

$$V_b = c_1 \frac{t_0}{\sqrt{(1+z_i)}} \times v_s \gamma_s \frac{t_0}{\sqrt{(1+z_i)}} \times \frac{24\pi}{5} (G\mu) v_s \gamma t_0 \frac{\sqrt{(1+z_i)}}{(1+z)} \tag{12}$$

If the cosmic string wake is generated at $t = t_i$ and the synchrotron radiation is being emitted at time t, then

$$n_e(t, t_i) = f \rho_B(t_i) m_p^{-1} \left(\frac{(z(t)+1)}{(z(t_i)+1)} \right)^3 \tag{13}$$

Here f is the ionization fraction and ρ_B is the energy density in the baryons. ρ_B can be calculated from the critical density of baryons.

[Da Cunha et al,Phys. Rev. D93,123501(2016)] , [Danos et al Phys.Rev.D 82: 023513,(2010)]

- We consider the wakes are formed at matter-radiation equality (t_{eq}). So, $z_i = z_{eq} = 3400$.

- The synchrotron observations are made at different z which are

$$z = 30,$$
$$z = 1,$$
$$z = 0.069.$$

- So for different values of the redshift, this total energy is different. For $z = 30$, $W_e = 3.5 \times 10^{53} erg$, for $z = 1$, $W_e = 2 \times 10^{52} erg$, for $z = 0.069$, $W_e = 10^{52} erg$.

- W_e is the input for the AGNPY module. As the W_e is different for different redshifts z, hence the spectrum is different for different values of z.

Synchrotron spectrum

We have used the python module **AGNpy** to obtain the spectrum.

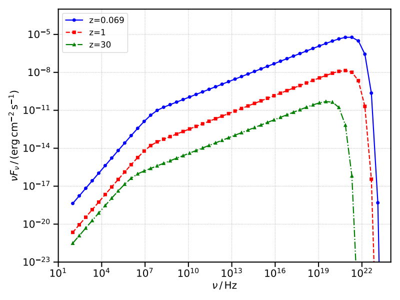


Figure 3: The synchrotron spectrum for different z values.

- **Turnover frequency**$\Rightarrow 10^7$ Hz.
- **Spectral break** $\Rightarrow 10^{20}$ Hz.
- Spectral break shifts to low frequencies as we move back in time.
- The initial low frequency **self-absorption region** has a power law exponent of ~ 1.28
- The **optically thin emission region** has a low spectral index of ~ 0.42.
- It dips very sharply in the high frequency range.

Synchrotron spectrum with observed data

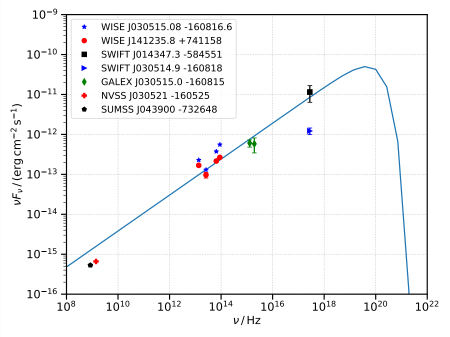


Figure 4: The synchrotron spectrum with data points from different catalogues.

Observed fluxes from the unidentified sources from the WISE, SWIFT ,GALEX, NVSS and SUMSS catalogue on the obtained spectrum for $z = 30$.

- **WISE** $\Rightarrow$ Infra-Red region. [isra.ipac.caltech.edu/frontpage/WISE]
- **SWIFT** $\Rightarrow$ X-ray region. [Hannes, Zechlin and Horns, JCAP II(2012)050]
- **GALEX** $\Rightarrow$ Ultra Violet region. [galex.stsci.edu/GR6]
- **NVSS, SUMSS** $\Rightarrow$ Radio emission region. [heasarc.gsfc.nasa.gov]

Summary and conclusions

- We have studied the synchrotron radiation emitted by relativistic electrons moving in a cosmic string wake.
- We have assumed that the overall magnetic field is homogeneous over the width of the wake. Though it is possible that the magnetic field will have some small scale fluctuations due to turbulence in the plasma, for the current work we have not looked at such details.
- We have found that the frequency spectrum obtained from the relativistic non-thermal electrons moving in the wake of a cosmic string will be over a wide range of frequencies.
- We do find that several of the surveys (NVMS, SUMSS, WISE, SWIFT and GALEX) have unidentified sources of radiations with similar flux in the range of frequencies that are covered by the cosmic string wake.

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- IoE, University of Hyderabad.

THANK YOU.

Cosmic String metric

- 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)]

Modified Bessel function

- $R(\alpha)$ can be written as

$$R(\alpha) = \frac{\alpha}{2}\int_0^{\pi} d\theta sin\theta \int_{\frac{\alpha}{sin\theta}}^{\infty} dt K_{\frac{5}{3}}(t) \tag{14}$$

  where, $\alpha = \frac{\nu}{\nu_c}$

- Modified Bessel function R satisfy the differential equation

$$x^2\frac{d^2R}{dx^2} + x\frac{dR}{dx} - (x^2+n^2)R = 0$$

  It has two linearly independent solutions $I_n(x)$ and $K_n(x)$.
  The Bessel function of the second kind of order n,

$$K_n(x) = \frac{\Gamma(n+1/2)(2x)^n}{\sqrt{\pi}}\int_0^{\infty}\frac{costdt}{(t^2+x^2)^{n+1/2}}$$

γ_{min} and γ_{max}

- we consider a power law distribution of the electrons in the post-shock region with electron Lorentz factors $\gamma_{min} < \gamma < \gamma_{max}$.
- The range of the Lorentz factor comes due to the fact that the energy is continuously injected into the electron distribution in the comoving reference frame.
- γ_{min} would be given by the minimum velocity with which the electrons are swept inside the wake of the cosmic string.
- If the electrons are not reflected or accelerated by the ions reflected from shocks, they would have the same γ as the Lorentz factor of the cosmic string.
- For $v_s = 0.5c$, $\gamma_{min} \simeq 1$

- For γ_{max}, we need to take care of not only the energy being injected in the electron distribution but also the energy being taken away by various processes.
- The energy loss can be studied taking into consideration the γ factor of the decelerating electrons given by

$$\gamma_c = \frac{9m_e(1+z)}{128m_p\sigma_T\epsilon_B n_0 c\Gamma^3 t} \tag{15}$$

. Here ϵ_B is a fixed fraction of the magnetic energy density and the downstream energy density of the fluid.

- we find that the $\gamma_c << 1$. This means that dominant mechanism for the energy loss of the electrons in the shocked fluid will be due to the synchrotron radiation.

$$\gamma_{max} = \frac{1.2 \times 10^8 \tilde{\epsilon}}{\sqrt{B}} \tag{16}$$

Here $\tilde{\epsilon} \simeq 1$ is the fractional amount of energy gained by the electron due to the Fermi processes.