ELECTROMAGNETIC EMISSION BURSTS FROM THE NEAR-CUSP REGIONS OF SUPERCONDUCTING COSMIC STRINGS

L.V. ZADOROZHNA,[1] B.I. HNATYK[2]

[1]Taras Shevchenko National University of Kyiv, Faculty of Physics
(2, Academician Glushkov Ave., Kyiv 03680, Ukraine; e-mail: Zadorozhna_Lida@ukr.net)

[2]Taras Shevchenko National University of Kyiv, Astronomical Observatory
(3, Observatorna Str., Kyiv 04053, Ukraine; e-mail: hnatyk@observ.univ.kiev.ua)

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The cosmic strings are relicts of the early Universe which can be formed during the phase transitions of fields with spontaneously broken symmetry. Here, the motion of the near-cusp region of a superconducting cosmic string in the cosmic plasma with a large Lorentz-factor is studied. The characteristics of nonthermal emission of electrons of the cosmic plasma which are accelerated on the front of a shock wave around of the near-cusp region are calculated. All important channels of the emission and various cooling regimes of the plasma are considered. It is shown that, due to the relativistic collimation of the emission flow and the Doppler shift of its frequency, the hard (X-ray and gamma-) emission of cosmic strings (loops) can be registered even at cosmological distances. The emission flows are periodic and narrow-directed and has character of bursts. The expected flows, which are $\nu F_\nu \sim 10^{-12} - 10^{-14}(\text{erg/cm}^2 \cdot \text{s})$ for strings on the Grand Unified Theory scale, can be registered with the help of modern cosmic X-ray and land-based Cherenkov telescopes.

1. Introduction

Cosmic strings were first proposed by Kibble in 1976 as one of the types of topological defects which were formed in the course of the phase transitions of fields with spontaneously broken symmetry [1]. The novel supersymmetric inflation theories include also the so-called fundamental cosmic strings of several kinds which can be fundamental strings stretched by the inflation up to cosmological scales [2] and one-dimensional branes formed as a result of the annihilation of branes with higher dimensionalities [3].

A significant number of astrophysical manifestations can be from superconducting cosmic strings [4, 5], whose interior contains massless carriers of charge which behave themselves as a current along a string and move without resistance. In addition to the gravitational action (the gravitational lensing and the generation of gravitational waves), the superconducting strings generate various electromagnetic emission flows and fluxes of elementary particles. Such processes will run especially efficiently in the vicinity of cusps. They are the segments of a string which are deformed due to the motion and have form of a fold. The top of a fold reaches instantaneously the motion velocity equal to the light speed c (in the idealized model), and the near-cusp regions at an initial distance dl from the top are accelerated to a Lorentz-factor $\gamma_c \sim (dl/l)^{-1}$, where l is the characteristic scale of the curvature of a string (or the size of a loop). For example, the self-crossing of or the formation of a cusp on a superconducting string creates the conditions for the emission of high-energy particles (including neutrinos and protons) which can be responsible for cosmic rays with superhigh energies [6]. The bright millisecond extra-galactic radio-burst [7] was explained by the electromagnetic emission from a cusp of a superconducting string with its energy on the Grand Unified Theory scale $\sim 10^5$ GeV [8]. Works [9, 10] studied the low-frequency electromagnetic emission of near-cusp regions of superconducting strings and its transformation in a hard electromagnetic emission of the type of cosmological gamma-bursts.

One more characteristic astrophysical manifestation appears at the motion of a superconducting string relative to the cosmic plasma. Around the magnetosphere generated by its current in the cosmic plasma, there appears the typical regime of circumfluence with a shock wave. On its front, particles of the cosmic plasma will be accelerated to high energies. By moving in a magnetic field behind the front of the shock wave, the particles (electrons) will generate the nonthermal synchrotron, synchrotron self-Compton (inverse Compton scattering on "own" synchrotron photons), and external (on external photons, in particular, relict ones) inverse Compton emissions. The nonrelativistic motion of a string was studied in [11], and the motion of a string (or a loop) with a typical moderately relativistic Lorentz-factor $\gamma_s \sim 2$ was considered in [12]. However, as was mentioned above, the near-cusp regions move with velocities close to the light speed ($\gamma_s \sim 10^2 - 10^6$). Therefore, their emission characterized by both a significant Doppler shift and the relativistic collimation requires a separate analysis which is presented in what follows.

2. Near-Cusp Regions of Cosmic Strings

The cosmic strings form entangled networks in the Universe which evolve in the scale-invariant way. That is, the Hubble volume contains several infinite segments of strings and a collection of loops, whose concentration changes with the time as

$$n = \frac{1}{\alpha(ct)^3}. \qquad (1)$$

Moreover, the typical length of a loop l is determined by the relation $l \approx \alpha ct$, where t is the cosmological time moment. For analytic estimations, we consider the Friedman cosmological model with the critical density of matter (without the Λ term), take the Hubble constant $H_0 = 72$ km $\cdot$ s/Mpc, and set $t = t_0(1+z)^{-3/2}$, where $t_0 = (2/3)H_0^{-1}$ is the Universe lifetime [6] and z is the red shift. The parameter α determines the loss rate of energy by a string due to the gravitational emission and depends on the energy scale of a phase transition, during which a string was formed:

$$\alpha = \frac{\Gamma G \mu}{c^2}, \qquad (2)$$

where $\Gamma \sim 50$ is a dimensionless parameter [13], G is gravitational constant, and μ is the mass per unit length of a string [14]. Loops of strings oscillate periodically. In this case, different segments of a string move with different relativistic velocities, so that sharp bends-folds (cusps) are formed on them each period. A section of a near-cusp region at a characteristic proper (in the immovable state) distance Δl from the cusp top will be accelerated to the Lorentz-factor $\gamma_s \sim l/\Delta l$ at the oscillatory formations of a cusp and will be reduced, in this case, by γ_s times (in the reference system of a string). That is, in the reference system of a string, the near-cusp segment with a Lorentz-factor γ_s has a length

$$\Delta l' = l/\gamma_s^2. \qquad (3)$$

Moreover, $\gamma_s = 1/\sqrt{1-\beta^2}$, and $\beta = v_s/c$, where v_s is the velocity of a cusp. Of course, the connection between the size and the velocity for a near-cusp segment of a string depends on the specific dynamics of a loop and can be determined by the numerical modeling. In [9,10], this connection in the analytic approximation was described as inversely proportional, which corresponds to the case of loops with dominant low-frequency perturbations. In the given work, we consider the more conservative case of inversely squared dependence.

3. Ultrarelativistic Shock Wave Around a Near-Cusp Region

Let us consider the motion of a segment of a loop in the cosmic plasma with the following parameters: the concentrations of protons and electrons

$$n_e \sim n_p = n_1 = 10^{-7}(1+z)^3 n_{-7} \text{ cm}^{-3},$$

and the magnetic field

$$B_1 = B_{\rm IGM} = 10^{-7}(1+z)^2 B_{-7} \text{ Gs}.$$

(Hereafter, we use the notation $B_{-7} = B/10^{-7}$ Hz, $n_{-7} = n/10^{-7}$ cm^{-3}, *etc.*, and IGM means the intergalactic magnetic field). Oscillations of a loop in the intergalactic magnetic field are accompanied by the generation of an electric current in it with a certain mean value i_0 averaged over the whole length [9–12]. During the formation of a cusp, the current in a near-cusp segment increases due to the compression (a reduction of the segment length) of a string up to the value

$$\Delta i = i_0 \gamma_s = k_i q_e^2 B_{\rm IGM} l \gamma_s/\hbar, \qquad (4)$$

and generates the own magnetic field around this part of a string:

$$\Delta B_{\rm mag}(r) = 2\Delta i/cr, \qquad (5)$$

where r is the distance from the string, q_e is the electron charge, $\hbar$ is the Planck constant, and $k_i \sim 1$ is a constant.

The maximum Lorentz-factor of a cusp is determined by the reverse reaction of the increasing current in the near-cusp region. The critical value $i_{\max}$ is reached, when the energy of charge carriers becomes comparable with the eigenenergy of a string (its tension). For the maximum current [9]

$$i_{\max} = q_e \eta/\hbar,$$

where η is the energy scale of a phase transition, during which the loop was formed, we obtain

$$\gamma_{s,\max} = i_{\max}/i_0 = q_e\eta/\hbar i_0 = \frac{1}{k_i q_e B_{\rm IGM} l}\left(\frac{\alpha\hbar c^5}{\Gamma G}\right)^{1/2} =$$

$$= 7\times10^7(1+z)^{-1/2}\alpha_{-8}^{1/2}B_{-7}^{-1}. \quad (6)$$

Thus, the narrow near-cusp segments of a string will move with a very large Lorentz-factor.

As was discussed in [12] in detail, a relativistic shock wave with the Lorentz-factor equal to that of the given segment of a loop $\gamma_{sh} = \gamma_s$ and with the radius

$$r_s = \frac{k_i q_e^2 B_{\rm IGM} l}{2(\pi n_1 m_p)^{1/2}\hbar c^2} =$$

$$= 2.2\times10^{15}(1+z)^{-1}k_i B_{-7}\alpha_{-8}n_{-7}^{-1/2}\ \text{cm} \quad (7)$$

will be formed at some distance from a relativistic segment of the string around it, where the dynamical pressure of an incident plasma becomes equal to the magnetic pressure in the magnetosphere of a string. It is worth noting that, for the considered ultrarelativistic segments of a loop, the shock wave radius (in the reference system of a string) is independent of the Lorentz-factor of a segment of the loop (due to the growth of a current in the segment of the loop with increase of its Lorentz-factor).

4. Acceleration of Relativistic Electrons by a Shock Wave

We now consider an ultrarelativistic shock wave around a near-cusp region of a string. The concentration of particles n_2 and the heat energy density e_2 behind its front in the ultrarelativistic approximation are [12]

$$n_2 \simeq 2.8\gamma_s n_1, \quad (8)$$

$$e_2 \simeq 2\gamma_s^2 n_1 m_p c^2. \quad (9)$$

A part ϵ_e of the total heat energy (the energy of protons) is transferred to electrons,

$$e_e = \epsilon_e e_2,$$

and a part ϵ_B is spent for the generation of a turbulent magnetic field behind the front [15]

$$e_B = \epsilon_B e_2,$$

($\epsilon_e < 1$, $\epsilon_B < 1$), so that the magnetic field behind the front is equal to

$$B_2 \simeq 1.4\gamma_s\sqrt{8\pi c^2\epsilon_B m_p n_1} =$$

$$= 2.8\times10^{-5}\gamma_s(1+z)^{3/2}n_{-7}^{1/2}\epsilon_{B,-1}^{1/2}\ \text{Gs}. \quad (10)$$

Let electrons in the after-shock-wave region be distributed by the power law [16]

$$N(\gamma_e) = K'\gamma_e^{-p}, \quad (11)$$

where K' is the coefficient of proportionality which is determined by the total concentration of electrons [12]. We set $p > 2$ ($p \approx 2.2$ for gamma-bursts).

The minimum Lorentz-factor of electrons [12]

$$\gamma_{e,\min} = 22\gamma_s\epsilon_{e,-1}. \quad (12)$$

We now calculate the maximum Lorentz-factor for accelerated electrons with regard for various limitations of our problem. One of the limitations follows from the comparison of the lifetime of a near-cusp region with the characteristic time of the acceleration of electrons

$$t_{\rm cusp} = \frac{l}{2c\gamma_s^2}, \quad (13)$$

$$t_{\rm acc} = \frac{cR_{\rm L}}{\upsilon_{\rm A}^2}, \quad (14)$$

where $R_{\rm L}$ is the Larmor radius, and $\upsilon_{\rm A}$ is the Alfvén velocity. As a result, we obtain

$$\gamma_{e,\max} = \frac{q_e\epsilon_B B_2 l}{m_e c^2\gamma_s^2} = 6\times10^{12}\gamma_s^{-1}\alpha_{-8}n_{-7}^{1/2}\epsilon_{B,-1}^{3/2}. \quad (15)$$

One more limitation follows from the comparison of the times of the acceleration and radiation of electrons. The time of the synchrotron radiation of electrons is

$$t_{\rm syn} = \frac{\gamma_e m_e c^2}{P_{\rm syn}}, \quad (16)$$

where $P_{\rm syn}$ is the emission power of an electron [11]. Therefore, we get

$$\gamma_{e,\max} = \sqrt{\frac{12\pi\epsilon_B q_e}{B_2\sigma_{\rm T}}} =$$

$$= 9.6\times10^9\gamma_s^{-1/2}(1+z)^{-3/4}n_{-7}^{-1/4}\epsilon_{B,-1}^{1/4}, \quad (17)$$

where $\sigma_{\rm T}$ is the Thompson cross-section.

In addition, it is necessary to consider the limitation on the maximum energy of electrons due to the boundedness of the sizes of the region of their acceleration:

$$\gamma_{e,\max} = q_e r_s B_2/m_e c^2 \sim$$

$$\sim 3.6\times 10^7 \gamma_s (1+z)^{1/2} k_i B_{-7}\alpha_{-8}\epsilon_{B,-1}^{1/2}. \quad (18)$$

We choose the lowest limitation for the maximum energy of electrons as the minimum of these quantities depending on the parameters α and γ_s.

By moving in the magnetic field of the after-shock-wave region, accelerated electrons radiate photons in a wide energy interval. Mechanisms of the emission are the synchrotron, synchrotron self-Compton, and inverse Compton ones.

5. Synchrotron Emission of Relativistic Electrons

For a remote observer, the synchrotron emission from a near-cusp region on the string will concentrate itself in a narrow beam with the angle between the motion direction of a cusp and the source-observer direction $\theta_s \sim 1/\gamma_s$ and with the maximum concentration of energy in the angle $\theta_{s,\min} \sim 1/\gamma_{s,\max}$ [2]. The energy of synchrotron photons for electrons with the Lorentz-factor γ_e in a local coordinate system is

$$\hbar\omega_{\rm syn} = \frac{\hbar q_e B_2}{m_e c}\gamma_e^2. \quad (19)$$

At the passage to the reference system of an external observer, the frequency shifts by the Doppler-factor [17]

$$\delta = \frac{1}{\gamma_s(1-\beta\cos\theta_s)}. \quad (20)$$

For $\theta_s \le 1/\gamma_s$, $\delta \approx \gamma_s$.

The synchrotron cooling regime is determined by the parameter $\gamma_{e,c}$ which is the Lorentz-factor of electrons radiating for the hydrodynamic time interval [12]

$$\gamma_{e,c} = \frac{3m_e c}{4\sigma_T e_B t_{\rm hyd}} \approx$$

$$\approx 1.4\times 10^{13}\gamma_s^{-2}(1+z)^{-2}k_i^{-1}\alpha_{-8}^{-1}B_{-7}^{-1}n_{-7}^{-1/2}\epsilon_{B,-1}^{-1}. \quad (21)$$

Let us compare $\gamma_{e,c}$ and $\gamma_{e,\min}$. The fast cooling is realized, if $\gamma_{e,c} < \gamma_{e,\min}$, and all electrons rapidly lose the energy for the emission. But if $\gamma_{e,c} > \gamma_{e,\min}$, then only the electrons with energies higher than $\gamma_{e,c}$ are efficiently cooled, and the main amount of electrons is in the regime of slow cooling.

5.1. Slow cooling regime

Synchrotron emission in the case of a power distribution is approximated by a broken energy spectrum with characteristic critical frequencies. The first break is expected to be at the self-absorption frequency ν_a, lower which the system becomes optically thick. At frequencies $\nu_a \ge \nu$, the self-absorption is essential, and the emission flow is proportional to ν^2. Two other frequencies at breaks are the characteristic frequencies ν_m and ν_c of the emission of electrons with the Lorentz-factors $\gamma_{e,\min}$ and $\gamma_{e,c}$, respectively [17]. For slow cooling, $\nu_a < \nu_m < \nu_c$.

For an external observer, the emission power maximum is located at the frequency

$$\nu_m^{\rm obs} \approx \frac{q_e B_2}{4\pi m_e c}\gamma_{e,\min}^2\delta/(1+z) =$$

$$= 1.9\times 10^4\gamma_s^4(1+z)^{1/2}n_{-7}^{1/2}\epsilon_{e,-1}^2\epsilon_{B,-1}^{1/2}\ {\rm Hz}. \quad (22)$$

The synchrotron emission power from unit volume per unit frequency interval in a local reference system (the spectral emissive ability; hereafter, we take $p = 2.2$ like for gamma-bursts) is

$$j_{\nu,\max} = AK'\nu_m^{\frac{-(p-1)}{2}} =$$

$$= 1.2\times 10^{-31}\gamma_s^{3.2}(1+z)^{3/2}n_{-7}^{3/2}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{1.2}\ {\rm erg/cm^3\cdot Hz\cdot s}, \quad (23)$$

where A and K' can be found in [12, 19]. The spectral flow of the synchrotron radiation for an external observer is as follows:

$$F_\nu^{\rm obs} = \frac{V_{em}j_\nu}{4\pi d_{\rm L}^2}\delta^3(1+z). \quad (24)$$

Here, V_{em} is the radiating region volume (so that $L_\nu = V_{em}j_\nu$ is the spectral luminosity), and $d_{\rm L} = 3t_0c(1+z)^{1/2}\left[(1+z)^{1/2}-1\right]$ is the photometric distance from a land-based observer to the radiating region. The diameter of the radiating region is r_s, and its length is a part of the loop length which decreases due to the oscillation of the loop from Δl down to $\Delta l/\gamma_s$. Then $V_{em} = \frac{3}{2}\pi r_s^2\Delta l/\gamma_s \approx 2\times 10^{51}(1+z)^{-7/2}\gamma_s^{-2}k_i^2B_{-7}^2\alpha_{-8}^3n_{-7}^{-1}\ {\rm cm^3}$.

The maximum of the synchrotron radiation flow ($\rm erg/cm^2\cdot Hz\cdot s$) is given by

$$F_{\nu,\max}^{\rm obs} = 2.6\times 10^{-38}\frac{\gamma_s^{4.2}k_i^2B_{-7}^2\alpha_{-8}^3n_{-7}^{1/2}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{1.2}}{(1+z)^2\left[(1+z)^{1/2}-1\right]^2}. \quad (25)$$

The results of calculations for various values of the parameters are presented in Tables 1 and 2 and in Fig. 1.

5.2. Fast cooling regime

For a power energy spectrum of electrons, the synchrotron radiation power from unit volume per unit frequency interval in the case of fast cooling can be written as

$$j_\nu \sim \begin{cases} (\nu_a/\nu_c)^{1/3}(\nu/\nu_a)^2 j_{\nu,\max} & \text{if } \nu_a \geq \nu; \\ (\nu/\nu_c)^{1/3} j_{\nu,\max} & \text{if } \nu_c \geq \nu > \nu_a; \\ (\nu/\nu_c)^{-1/2} j_{\nu,\max} & \text{if } \nu_m \geq \nu > \nu_c; \\ (\nu_m/\nu_c)^{-1/2}(\frac{\nu}{\nu_m})^{-p/2} j_{\nu,\max} & \text{if } \nu > \nu_m. \end{cases} \quad (26)$$

The radiation power maximum is located at the frequency characteristic of an electron with $\gamma_{e,c}$. For an external observer,

$$\nu_c^{\rm obs} \approx \frac{q_e B_2}{4\pi m_e c}\gamma_{e,c}^2 \delta/(1+z) =$$

$$= 7.7\times 10^{27}\gamma_s^{-2}(1+z)^{-7/2}k_i^{-2}\alpha_{-8}^{-2}B_{-7}^{-2}n_{-7}^{-1/2}\epsilon_{B,-1}^{-3/2}\ \text{Hz}. \quad (27)$$

The spectral emissive ability

$$j_{\nu,\max} = K'' A' \nu_c^{\frac{-p}{2}}, \quad (28)$$

where $A' = A(p+1)$ (see [11]). The coefficient K'' can be calculated in the following way. In the reference system of the plasma behind the front of an ultrarelativistic shock wave around a near-cusp region with the surface area $S_{ef} = 4r_s l/\gamma_s^2$, the heat energy (of protons) of the plasma increases by $L_{pl} = S_{ef} e_2 c/3$ every second (the shock wave velocity relative to the after-shock-wave plasma is $c/3$). Its share ϵ_e is transferred to electrons every second,

$$dE_e/dt = \epsilon_e L_{pl} \approx 0.3\epsilon_{e,-1} r_s l c^3 n_1 m_p =$$

$$= 2.6\times 10^{36}(1+z)^{-5/2}k_i\alpha_{-8}^2 B_{-7} n_{-7}^{1/2}\ \text{erg/s}, \quad (29)$$

and, respectively, is emitted every second:

$$dE_e/dt = \int_{\nu_a}^{\nu_{\max}} L_\nu d\nu. \quad (30)$$

From the last relation, we determine K''.

Values of the radiation flow maximum at the radiation frequency for an external observer are given in Tables 3 and 4. The total observed flow in the fast cooling regime is presented in Fig. 2.

T a b l e 1. Estimation of the flow in unit logarithmic interval of frequencies $\nu_m F_{\nu,\max}$, $\nu_m^{\rm SSC} F_{\nu,\max}^{\rm SSC}$, $\nu_m^{\rm IC} F_{\nu,\max}^{\rm IC}$ in the slow cooling regime (for $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $\gamma_s = 10^2$, $z = 2$)

α	Flows (erg/cm^2·s)		
	$\nu_m F_{\nu,\max}$	$\nu_m^{\rm SSC} F_{\nu,\max}^{\rm SSC}$	$\nu_m^{\rm IC} F_{\nu,\max}^{\rm IC}$
10^{-6}	$4.3\cdot 10^{-12}$	$2.6\cdot 10^{-17}$	$1.5\cdot 10^{-17}$
10^{-8}	$4.3\cdot 10^{-18}$	$2.6\cdot 10^{-25}$	$1.5\cdot 10^{-23}$
10^{-11}	$4.3\cdot 10^{-27}$	$2.6\cdot 10^{-37}$	$1.5\cdot 10^{-32}$

T a b l e 2. Estimation of the flow in unit logarithmic interval of frequencies $\nu_m F_{\nu,\max}$, $\nu_m^{\rm SSC} F_{\nu,\max}^{\rm SSC}$, $\nu_m^{\rm IC} F_{\nu,\max}^{\rm IC}$ in the slow cooling regime (for $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $\gamma_s = 10^2$, $z = 0.5$)

α	Flows (erg/cm^2·s)		
	$\nu_m F_{\nu,\max}$	$\nu_m^{\rm SSC} F_{\nu,\max}^{\rm SSC}$	$\nu_m^{\rm IC} F_{\nu,\max}^{\rm IC}$
10^{-6}	$1.3\cdot 10^{-10}$	$2.1\cdot 10^{-15}$	$3.7\cdot 10^{-15}$
10^{-8}	$1.3\cdot 10^{-16}$	$2.1\cdot 10^{-23}$	$3.7\cdot 10^{-21}$
10^{-11}	$1.3\cdot 10^{-25}$	$2.1\cdot 10^{-35}$	$3.7\cdot 10^{-30}$

6. Synchrotron Self-Compton Radiation

While synchrotron radiation photons are scattered by high-energy relativistic electrons behind the front of the shock wave, one observes the inverse Compton effect, at which electrons transfer a part of their energy to photons. If the synchrotron radiation spectrum is known, we can calculate the self-Compton radiation spectrum which is composed also from several segments with breaks at the frequencies $\nu^{\rm SSC} = 4\gamma_e^2\nu_{\rm syn}x_0$, where $x_0 \approx 0.5$ [18].

In the slow cooling regime, we have:

T a b l e 3. Estimation of the flow in unit logarithmic interval of frequencies $\nu_c F_{\nu,\max}$, $\nu_c^{\rm SSC} F_{\nu,\max}^{\rm SSC}$, $\nu_c^{\rm IC} F_{\nu,\max}^{\rm IC}$ in the fast cooling regime (for $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $\gamma_s = 10^4$, $z = 2$)

α	Flows (erg/cm^2·s)		
	$\nu_c F_{\nu,\max}$	$\nu_c^{\rm SSC} F_{\nu,\max}^{\rm SSC}$	$\nu_c^{\rm IC} F_{\nu,\max}^{\rm IC}$
10^{-6}	$7.5\cdot 10^{-9}$	$1.1\cdot 10^{-18}$	$2.7\cdot 10^{-13}$
10^{-8}	$8.4\cdot 10^{-11}$	$1.3\cdot 10^{-18}$	$2.6\cdot 10^{-15}$

T a b l e 4. Estimation of the flow in unit logarithmic interval of frequencies $\nu_c F_{\nu,\max}$, $\nu_c^{\rm SSC} F_{\nu,\max}^{\rm SSC}$, $\nu_c^{\rm IC} F_{\nu,\max}^{\rm IC}$ in the fast cooling regime (for $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $\gamma_s = 10^4$, $z = 0.5$)

α	Flows (erg/cm^2·s)		
	$\nu_c F_{\nu,\max}$	$\nu_c^{\rm SSC} F_{\nu,\max}^{\rm SSC}$	$\nu_c^{\rm IC} F_{\nu,\max}^{\rm IC}$
10^{-6}	$3.3\cdot 10^{-6}$	$1.5\cdot 10^{-14}$	$3.6\cdot 10^{-9}$
10^{-8}	$3.6\cdot 10^{-8}$	$1.6\cdot 10^{-14}$	$4.2\cdot 10^{-11}$

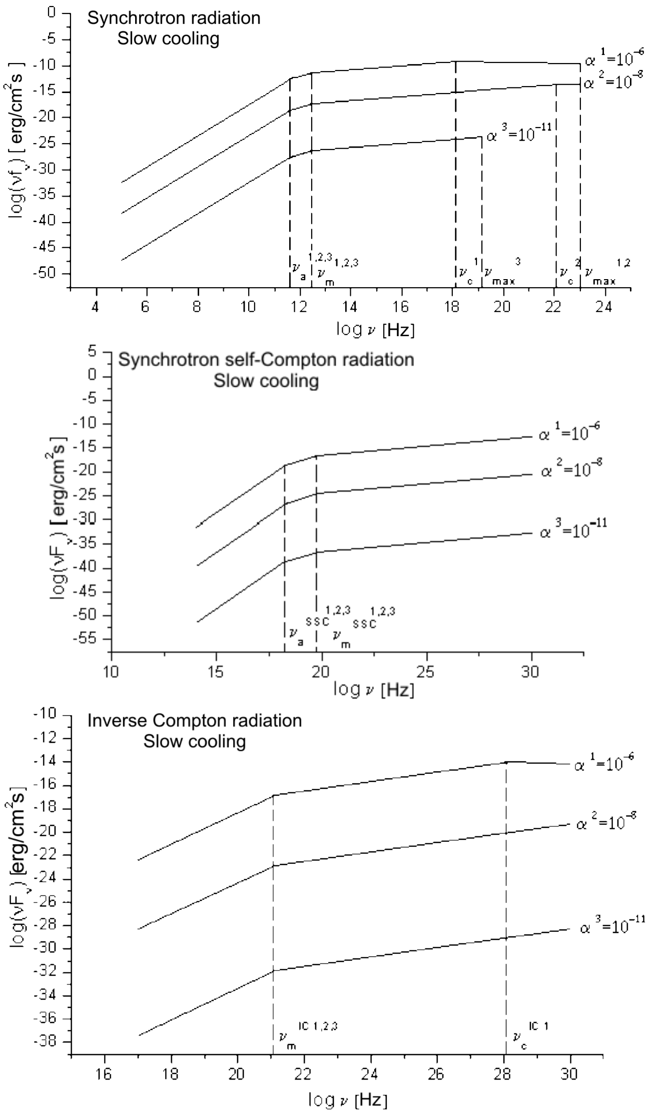

Fig. 1. Observed flows of the synchrotron, synchrotron self-Compton, and inverse Compton emissions under the slow cooling of relativistic electrons behind the front of a shock wave for cusps of loops with various tensions (at $\gamma_s = 100$, $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $z = 2$)

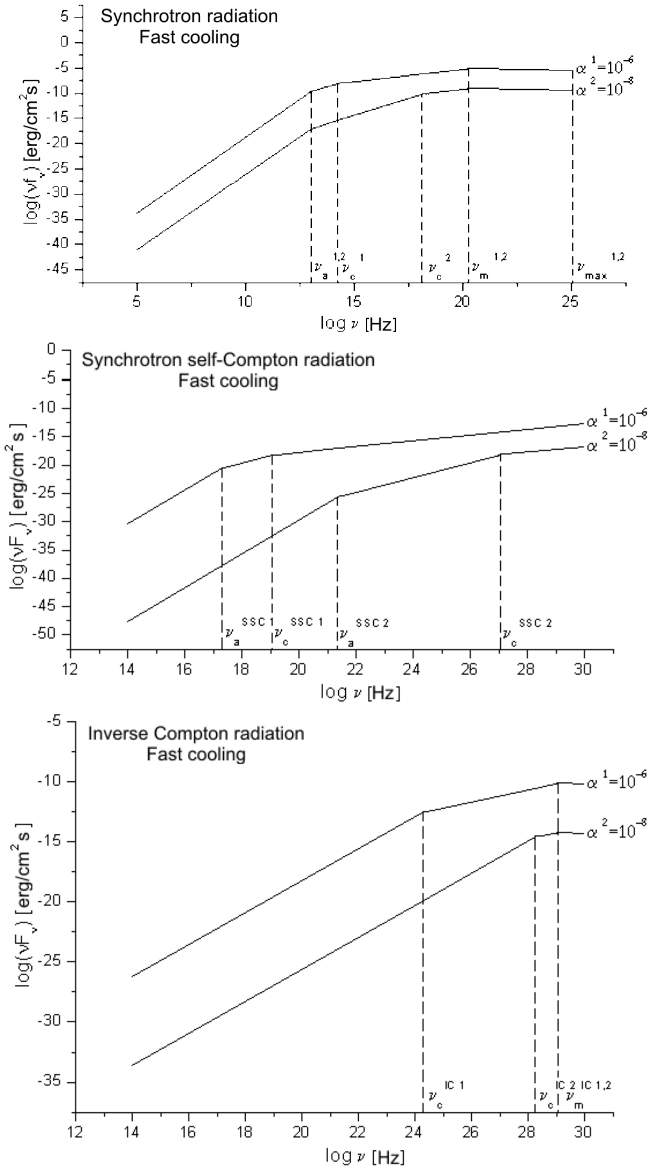

Fig. 2. Observed flows of the synchrotron, synchrotron self-Compton, and inverse Compton emissions under the fast cooling of relativistic electrons behind the front of the shock wave for cusps of loops with various tensions (at $\gamma_s = 10^4$, $n_1 = 10^{-7}$ cm^{-3}, $B_1 = 10^{-7}$ Gs, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$, $z = 2$)

– the radiation flow maximum for an external observer (erg/cm$^2\cdot$Hz$\cdot$s) (see Tables 1 and 2)

$$F^{\mathrm{obs,SSC}}_{\nu,\max}(\nu_m^{\mathrm{SSC}}) \simeq 4\sigma_T r_s n_2 x_0 \frac{(p-1)(p+1/3)}{(p-1/3)(p+1)^2}\times$$

$$\times F_\nu^{\mathrm{obs}}(\nu_{\mathrm{syn}}(\gamma_{e,\min})) =$$

$$= 2.3\times 10^{-54}\frac{\gamma_s^{5.2}k_i^3 B_{-7}^3\alpha_{-8}^4 n_{-7}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{1.2}}{(1+z)^3\left[(1+z)^{1/2}-1\right]^2} \qquad (31)$$

in the case where $\nu_a^{\mathrm{SSC}} < \nu_m^{\mathrm{SSC}} < \nu_c^{\mathrm{SSC}}$;

– the radiation frequency for an external observer at the flow maximum

$$\nu_m^{\mathrm{obs,SSC}} = 4\gamma_{e,\min}^2\nu_m^{\mathrm{obs}} =$$

$$= 3.7\times 10^7\gamma_s^6(1+z)^{1/2}n_{-7}^{1/2}\epsilon_{e,-1}^4\epsilon_{B,-1}^{1/2}\ \mathrm{Hz}. \qquad (32)$$

In the fast cooling regime, we have:

$$F_\nu^{\rm SSC} = x_0 r_s \sigma_T n_2 F_\nu(\nu_{\rm syn}(\gamma_{e,c}))\times \tag{33}$$

$$\times \begin{cases} \frac{5}{6}\left(\frac{\nu_a}{\nu_c}\right)^{\frac{1}{3}}\left(\frac{\nu}{\nu_a^{\rm SSC}}\right), \text{ if } \nu \le \nu_a^{\rm SSC}; \\ \frac{9}{10}\left(\frac{\nu}{\nu_c^{\rm SSC}}\right)^{\frac{1}{3}}, \text{ if } \nu_a^{\rm SSC} < \nu \le \nu_c^{\rm SSC}; \\ \frac{1}{3}\left(\frac{\nu}{\nu_c^{\rm SSC}}\right)^{\frac{-1}{2}}\Big[\frac{28}{15} - \\ -\ln\left(\frac{\nu}{\nu_c^{\rm SSC}}\right)\Big], \text{ if } \nu_c^{\rm SSC} < \nu \le \sqrt{\nu_c^{\rm SSC}\nu_m^{\rm SSC}}; \\ \frac{1}{3}\left(\frac{\nu}{\nu_c^{\rm SSC}}\right)^{\frac{-1}{2}}\Big[2\frac{(2p+5)}{(p+2)(p-1)} - \frac{2(p-1)}{3(p+2)} + \\ +\ln\left(\frac{\nu_m^{\rm SSC}}{\nu}\right)\Big], \text{ if } \sqrt{\nu_c^{\rm SSC}\nu_m^{\rm SSC}} < \nu \le \nu_m^{\rm SSC}; \\ \frac{1}{(p+2)}\left(\frac{\nu}{\nu_m^{\rm SSC}}\right)^{\frac{-p}{2}}\left(\frac{\nu_c}{\nu_m}\right)\Big[\frac{2(p+5)}{3(p-1)} - \frac{2(p-1)}{3(p+2)} + \\ +\ln\left(\frac{\nu}{\nu_m^{\rm SSC}}\right)\Big], \text{ if } \nu > \nu_m^{\rm SSC}. \end{cases}$$

The observed radiation flow maximum (erg/cm$^2\cdot$Hz$\cdot$s) (see Tables 3 and 4)

$$F_{\nu,\max}^{\rm obs,SSC}(\nu_c^{\rm SSC}) \simeq \frac{28}{45}\sigma_T r_s n_2 x_0 F_\nu^{\rm obs}(\nu_{\rm syn}(\gamma_{e,c})),$$

in the case where $\nu_a^{\rm SSC} < \nu_c^{\rm SSC} < \nu_m^{\rm SSC}$;
– the radiation frequency for an external observer

$$\nu_c^{\rm obs,SSC} = 4\gamma_{e,c}^2\nu_c^{\rm obs} =$$

$$= 6\times 10^{54}\gamma_s^{-6}(1+z)^{-15/2}k_i^{-4}\alpha_{-8}^{-4}B_{-7}^{-4}n_{-7}^{-3/2}\epsilon_{B,-1}^{-9/2}\ \text{Hz}. \tag{34}$$

The total emission flows in the slow and fast regimes are given in Figs. 1 and 2.

7. Inverse Compton Effect on Cosmic Microwave Background

Electrons accelerated behind the front of a shock wave can be scattered on photons of the cosmic microwave background and can transfer a part of the energy to them. The spectrum of Compton photons has also breaks analogously to the spectrum of the synchrotron emission [20]. The break frequencies are $\nu_m^{\rm IC}$ and $\nu_c^{\rm IC}$ for electrons with the Lorentz-factors $\gamma_{e,\min}$ and $\gamma_{e,c}$, respectively.

In the slow cooling regime, we have:
– the emission flow maximum (erg/cm$^2\cdot$Hz$\cdot$s) (see Tables 1 and 2)

$$F_{\nu,\max}^{\rm obs,IC}(\nu_m^{\rm IC}) =$$

$$= 2.8\times 10^{-51}\frac{\gamma_s^4 k_i^2 B_{-7}^2\alpha_{-8}^3}{(1+z)^{7/2}\left[(1+z)^{1/2}-1\right]^2}; \tag{35}$$

– the frequency corresponding to the flow maximum for an external observer

$$\nu_m^{\rm obs,IC} = \gamma_{e,\min}^2\frac{3kT}{2h}\delta^2/(1+z) =$$

$$= 4\times 10^{13}\gamma_s^4(1+z)^{-1}\epsilon_{e,-1}^2\ \text{Hz}, \tag{36}$$

where $h = 2\pi\hbar$, k is the Boltzmann constant, and T is the temperature of relict photons.

In the fast cooling regime, we have:
– the spectral emissive ability

$$j_\nu^{\rm IC} = K''\frac{8\pi^2 r_e^2}{h^2c^2}(kT)^{(p+6)/2}F(p+1)(h\nu)^{-p/2}, \tag{37}$$

where the function $F(p+1)$ is given in [12];
– the flow maximum of the emission from a cusp for an external observer (see Tables 3 and 4) is

$$F_{\nu,\max}^{\rm obs,IC} = \frac{V_{em}j_\nu^{\rm IC}(\nu_c^{\rm IC})}{4\pi d_{\rm L}^2}\delta^5(1+z), \tag{38}$$

which corresponds to the frequency

$$\nu_c^{\rm obs,IC} = \gamma_{e,c}^2\frac{3kT}{2h}\delta^2/(1+z) =$$

$$= 1.6\times 10^{37}\gamma_s^{-2}(1+z)^{-5}k_i^{-2}\alpha_{-8}^{-2}B_{-7}^{-2}n_{-7}^{-1}\epsilon_{B,-1}^{-2}\ \text{Hz}. \tag{39}$$

The observed flows for the slow and fast cooling regimes are presented in Figs. 1 and 2.

8. Discussion and Conclusions

We have studied the characteristics of nonthermal electromagnetic emission of electrons of the cosmic plasma which are accelerated on the front of a shock wave around a near-cusp region of the loop of a cosmic string moving with a large Lorentz-factor. We have considered all essential emission channels: synchrotron, synchrotron self-Compton (inverse Compton effect on own synchrotron photons), and external inverse Compton (on external, in particular relict, photons) emissions. Various cooling regimes, fast and slow ones, are considered. It is shown that, due to the relativistic collimation of an emission flow and the Doppler shift of its frequency, the hard (X-ray and gamma-) emission of cosmic strings (loops) can be registered at cosmological distances. The emission flows are periodic and narrow-directed and have character of bursts. The significant collimation decreases the probability to observe separate cusp-involved phenomena on the Earth; however, the collimation effects are compensated for a number of parameters by a great number of loops in a region accessible for observations. For the sake of illustration, we present the data on the expected characteristics of emission pulses for two values of the Lorentz-factors of a near-cusp region, $\gamma_s = 10^2$ and $\gamma_s = 10^4$. In the first case, the regime of slow cooling of the plasma is realized. That is, all electrons have no time to be cooled for the hydrodynamic time interval characteristic of the system, and most electrons lose an insignificant amount of energy for the emission. In the second case, the regime of fast cooling is realized, and all electrons lost rapidly (for a time interval less than the hydrodynamic one) the main share of their energy. In the tables, we present the values of emission flows from a loop which can be observed on the Earth at $z = 2$ and $z = 0.5$. In the figures, we draw the full spectra of the emission from loops which were formed at various stages of the evolution of the Universe and are positioned at the distance with $z = 2$. The synchrotron emission spectrum has maximum in the hard X-ray region, and the Compton spectrum extends up to the TeV range. The expected flows $\nu F_\nu \sim 10^{-12} - 10^{-14}$ (erg/cm$^2 \cdot$s), in particular for strings of the Grand Unified Theory scale, can be registered at cosmological distances with the help of modern cosmic X-ray and land-based Cherenkov telescopes (Chandra, XMM Newton, FERMI, H.E.S.S., *etc*).

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СПАЛАХИ ЕЛЕКТРОМАГНІТНОГО ВИПРОМІНЮВАННЯ ВІД ПРИКАСПОВИХ ОБЛАСТЕЙ НАДПРОВІДНИХ КОСМІЧНИХ СТРУН

Л.В. Задорожна, Б.І. Гнатик

Р е з ю м е

Космічні струни – релікти раннього Всесвіту, що могли утворюватися під час фазових переходів полів зі спонтанно порушеною симетрією. В роботі досліджено рух прикаспової області надпровідної космічної струни у космічній плазмі з великим лоренц-фактором. Пораховано характеристики нетеплового випромінювання електронів космічної плазми, прискорених на фронті ударної хвилі навколо прикаспової області. Розглянуто всі важливі канали випромінювання та різні режими охолодження плазми. Показано, що внаслідок релятивістської колімації потоку випромінювання та доплерівського зміщення його частоти, жорстке (рентгенівське та гама-) випромінювання космічних струн (петель) можливо зареєструвати навіть із космологічних відстаней. Потоки випромінювання періодичні та вузьконапрямлені, мають характер спалахів. Очікувані потоки, що для струн масштабу Великого Об'єднання мають значення $\nu F_\nu \sim 10^{-12} - 10^{-14}$(ерг/см$^2 \cdot$ с), можуть бути зареєстровані за допомогою сучасних космічних рентгенівських та наземних черенковських телескопів.