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Electromagnetic radiation of superconducting cosmic strings

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Cosmic strings are relics of the early Universe which can be formed during the phase transitions of fields with spontaneously broken symmetry in the early Universe. Their existence finds support in modern superstrings theories, both in compactification models and in theories with extended additional dimensions. Strings can hold currents, effectively become electrically superconducting wires of astrophysical dimensions. Superconducting cosmic strings can serve as powerful sources of non-thermal radiation in wide energy range. Mechanisms of radiation are synchrotron, synchrotron self-Compton and inverse-Compton on CMB photons radiation of electrons accelerated by bow shock wave, created by magnetosphere of relativistically moving string in intergalactic medium (IGM). Expected fluxes of radiation from the shocked plasma around superconducting cosmic strings are calculated for strings with various tensions and for different cases of their location. Possibilities of strings detection by existing facilities are estimated.

Key words: superconducting cosmic strings, cosmic plasma, electromagnetic radiation

INTRODUCTION

Cosmic strings as one-dimensional topological defects in gauge fields theory could arise as a result of spontaneous symmetry breaking by Kibble mechanism in the cooling down early Universe, or in non-equilibrium conditions after inflation [7]. Strings have formed entangled networks during their existence, which are composed of loops and infinite strings [4, 14], strings oscillate and move with relativistic velocities.

As if the cosmic strings arise at the end of the inflation period, they contribute insignificantly to the total spectrum of fluctuations of the density [17]. However, no direct observations of strings in fluctuations of the microwave emission are available till now, which imposes some restrictions on the parameters of strings. The existence of strings with tension $G\mu/c^2 \lesssim 10^{-7}$, where μ is the tension of a string, G is the gravitational constant [6], which follows from the testing of the power spectrum of the CMB temperature, is still possible, so these strings may be a subject of studies and observations.

According to some SUSY particle-physics models, cosmic strings can possess a properties of developing tremendous electric currents, thus they effectively become electrically superconducting wires of astrophysical dimensions [5, 11]. We study the electrodynamic properties of such strings and their interaction with the cosmic plasma. It was shown that moving through the cosmic plasma with relativistic velocity superconducting cosmic strings become sources of electromagnetic radiation.

CHARACTERISTICS OF COSMIC STRINGS

The energy scale of a phase transition is characterized by parameter η related to the tension (mass per unit length) μ of a string by $\mu \sim \eta^2/(\hbar c^3)$, where $\hbar$ is the Planck constant. Dimensionless parameter that characterizes the gravitational action of cosmic string (i. e. its energy loss rate) α, connected with tension μ, is:

$$\alpha = \frac{\Gamma G\mu}{c^2} \sim \frac{\eta^2}{m_{Pl}^2 c^4},$$

where $\Gamma \approx 50$ is the dimensionless parameter, m_{Pl} is the Planck mass [13]. The typical length of the loops of cosmic strings is $l = \alpha ct$, where t is the cosmological moment of time [3]. Since we consider a close region of the Universe $t = t_0 = 13.6 \cdot 10^9$ yrs.

Distribution function of loops concentration with time is $n = \left[\alpha(ct)^3\right]^{-1}$ [3]. For a given α, the average distance on which the loops can be positioned (or distance from a loop to an observer) is $d_s = n^{-1/3} = \alpha^{1/3}ct$. The middle angle, at which loop can be observed on the Earth: $\theta \sim l/d_s = \alpha^{2/3}$ depends only on tension of string (see Table 1) [10].

Table 1: Characteristics of cosmic strings with various tensions

	parameters of string		
α	l, pc	d_s, pc	$\theta,''$
$5 \cdot 10^{-6}$	$2.1 \cdot 10^4$	$7.1 \cdot 10^7$	60.3
10^{-6}	$4.2 \cdot 10^3$	$4.2 \cdot 10^7$	20.6
10^{-8}	41.7	$9.0 \cdot 10^6$	1
10^{-11}	0.042	$9.0 \cdot 10^5$	0.01

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INTERACTION OF SUPERCONDUCTING STRINGS WITH INTERGALACTIC PLASMA

Let strings move with Lorentz factor γ_s in the intergalactic medium with typical parameters: concentration of protons and electrons $n_e \sim n_p = n_1 = 10^{-7} n_{-7}\,\mathrm{cm}^{-3}$, where $B_1 = B_{IGM} = 10^{-7} B_{-7}\,\mathrm{G}$ is the magnetic field (hereinafter $B_{-7} = B/10^{-7}$, $n_{-7} = n/10^{-7}$ etc.).

During oscillations of a loop in the intergalactic magnetic field, an electric current is generated in it with the mean amplitude $i = k_i q_e^2 B_{IGM} l/\hbar$, where q_e is the electron charge, $k_i \sim 1$ is a constant. The current generates the proper magnetic field around the string $B_{mag}(r) = 2i/(cr)$, where r is a distance from the string [16].

The ionized cosmic plasma cannot penetrate into the region of a strong magnetic field near the string, that is why the shock wave is formed at some distance r_s from it. Behind its front, the flow of the plasma in the reference system of the string is decelerated and flows around the "magnetosphere" of the string which is a region with the high pressure of the magnetic field balancing the dynamical pressure of a plasma in the after-shock region on the string. Therefore, the radius of a shock wave can be determined. With the accepted notations we get [18]:

$$r_s = \frac{k_i q_e^2 B_{IGM} l}{2\hbar c^2 \gamma_{sh}\sqrt{\pi n_1 m_p}} = 3.1 \cdot 10^{15} k_i \gamma_{sh}^{-1} B_{-7} \alpha_{-8} n_{-7}^{-1/2}\ \mathrm{cm}, \quad (1)$$

where m_p is the proton mass, $\gamma_{sh} = \gamma_s$ is the Lorentz-factor of the shock wave.

The characteristic of a shock wave is its Lorentz factor γ_{sh} and Lorentz factor of plasma behind wave front γ_2 (both are in lab reference system) [2]:

$$\gamma_2 \simeq \sqrt{(\gamma_{sh}^2 + 1)/2}.$$

Particle concentration n_2 and energy density e_2 behind the front of a shock wave are [18, 19]:

$$n_2 \approx 4\gamma_2 n_1,$$

$$e_2 = e_{tot} \simeq e_p = \gamma_2 n_2 m_p c^2 \approx 4\gamma_2^2 n_1 m_p c^2.$$

Relativistic protons give the main contribution to the energy density behind relativistic shock wave $e_p \simeq e_2$. Magneto-hydrodynamic processes behind the front of a shock wave lead to the transfer of some part of the thermal energy of protons to electrons $e_e = \epsilon_e e_2$, $\epsilon_e < 1$ and to the generation of a turbulent magnetic field $e_B = \epsilon_B e_2$, $\epsilon_B < 1$. Its value is [19]:

$$B_2 = 2\gamma_2\sqrt{8\pi c^2 \epsilon_B m_p n_1} = 3.9 \cdot 10^{-5} \gamma_2 n_{-7}^{1/2} \epsilon_{B,-1}^{1/2}\ \mathrm{G}.$$

We assume that electrons develop a power-law distribution in the after-shock region with exponential cutoff at the high energies:

$$N(\gamma_e) = K' \gamma_e^{-p} e^{-\frac{\gamma_e}{\gamma_{e,max}}},$$
$$N(E_e) = K E_e^{-p} e^{-\frac{E_e}{E_{e,max}}}, \quad (2)$$

where K and K' are the proportionality coefficients, $\gamma_{e,max}$, $E_{e,max}$ is a maximal Lorentz factor and a maximal energy of electrons, respectively, and $p = 2.2$ ($p \approx 2.25$ from the analysis of data for gamma-ray bursts).

The concentration of electrons $n_{e,2}$ and the density of their thermal energy $e_{e,2}$ can be calculated as:

$$n_{e,2} = \frac{K}{p-1}\left(\frac{1}{E_{min}^{p-1}} - \frac{1}{E_{max}^{p-1}}\right),$$

$$e_{e,2} = \epsilon_e \gamma_2 n m_p c^2 = \frac{K}{p-2}\left(\frac{1}{E_{min}^{p-2}} - \frac{1}{E_{max}^{p-2}}\right). \quad (3)$$

Now, in the assumption of a very high maximal electrons energy (in comparison with their minimal energy), K can be found from formula (3) (where $p = 2.2$, $\gamma_{sh} = 2$):

$$K \simeq 4(p-2)\epsilon_e n_1 \gamma_2^2 m_p c^2 (m_e c^2 \gamma_{e,min})^{p-2} = 1.5 \cdot 10^{-12} \gamma_2^{2.2} n_{-7} \epsilon_{e,-1}^{1.2}\ \mathrm{erg}^{1.2}\mathrm{cm}^{-3},$$

while K' equals:

$$K' = \frac{K}{(m_e c^2)^{p-1}} = 3 \cdot 10^{-5} \gamma_2^{2.2} n_{-7} \epsilon_{e,-1}^{1.2}\ \mathrm{cm}^{-3}. \quad (4)$$

The minimal Lorentz-factor of electrons can be expressed as:

$$\gamma_{e,min} = \frac{m_p}{m_e}\frac{p-2}{p-1}\gamma_2 \epsilon_e = 31\gamma_2 \epsilon_{e,-1}. \quad (5)$$

The maximal Lorentz-factor of electrons is estimated from the equality of acceleration time t_{acc} and time of synchrotron cooling t_{syn} [12, 18]:

$$t_{acc} = \frac{cR_L}{v_a^2},$$

$$t_{syn} = \frac{\gamma_e m_e c^2}{P_{syn}},$$

where $R_L = \gamma_e m_e c^2/(q_e B_2)$ is the Larmor radius of electron, v_a is the Alfvén velocity ($v_a^2/c^2 \simeq 2\epsilon_B$), $P_{syn} = 4/3\sigma_T c e_B \gamma_e^2$ is the emission power of one electron in the local system of coordinates (the after-shock plasma), σ_T is the Thompson cross-section. As a result $\gamma_{e,max}$ is as follows:

$$\gamma_{e,max} = \sqrt{\frac{12\pi\epsilon_B q_e}{B_2\sigma_T}} = 8.1\cdot 10^9 \gamma_2^{-1/2} n_{-7}^{-1/4} \epsilon_{B,-1}^{1/4}. \qquad (6)$$

Another restriction for $\gamma_{e,max}$ can be found considering the geometric boundedness of the acceleration region ($\sim r_s$): $E_{e,max} = q_e r_s B_2$. Previous expression can be rewritten as [18]:

$$\gamma_{e,max} = \frac{q_e r_s B_2}{m_e c^2} \approx 7.1\cdot 10^7 \gamma_2 \gamma_{sh}^{-1} k_i B_{-7} \alpha_{-8} \epsilon_{B,-1}^{1/2}. \qquad (7)$$

Hence, on account of passing plasma through the front of a shock-wave, behind the front a power energetic spectra of relativistic electrons are being formed with characteristics (2), (4), minimal energy (5) and maximal energy (6) or (7). These electrons will appear themselves because of non-thermal (synchrotron, inverse Compton and synchrotron self-Compton) radiation from the after-shock region. Such radiation is one of the main manifestations of the superconducting cosmic strings in the IGM.

SYNCHROTRON RADIATION OF SUPERCONDUCTING COSMIC STRINGS

Spectral emissive ability of the electrons due to synchrotron radiation is as follows [8]:

$$j(\nu) = \int_{E_e} J(\nu, E_e) N(E_e) \mathrm{d}E_e,$$

where $N(E_e)$ is energetic distribution of electrons and $J(\nu, E_e)$ is spectral emissive ability of one electron. In the present paper we use approximation for this function, which was proposed in [1]:

$$J(\nu, E_e) = \frac{\sqrt{2}e^3 B}{m_e c^2} x \int_x^\infty K_{5/3}(\eta)\mathrm{d}\eta = \frac{\sqrt{2}e^3 B}{m_e c^2} C x^{1/3} e^{-x}.$$

Here $x = \frac{\nu}{\nu_c} = \frac{2\nu}{3\gamma_e^2\nu_g} = \frac{4\pi m_e c\nu}{3eB\gamma_e^2} = b\frac{\nu}{\gamma_e^2}$, where $b = \frac{4\pi m_e c}{3eB}$, $C \approx 1.85$, m_e is the electron mass and B is the magnetic field.

Finally, spectral emissive ability of the electrons with power-law energetic distribution can be written as:

$$j(\nu) = \int_{E_e} J(\nu, E_e) N(E_e)\mathrm{d}E_e = A \int_{\gamma_{e,min}}^{\gamma_{e,max}} \left(\frac{\nu}{\gamma_e^2}\right)^{1/3} e^{-b\frac{\nu}{\gamma_e{}^2}} \gamma_e^{-p} e^{-\frac{\gamma_e}{\gamma_{e,max}}} \mathrm{d}\gamma_e, \qquad (8)$$

where $A = CK'\sqrt{2}e^3 B b^{1/3}/(m_e c^2)^2$.

Now let us consider which spectral fluxes (fluxes per unit of frequency) we can observe from the superconducting cosmic strings located in the intergalactic medium. They easily are expressed through the spectral emissive ability of the electrons $j(\nu)$, the emission region V_{em} and through the average distance from the terrestrial observer to the string d_s:

$$F_\nu = \frac{V_{em} j(\nu)}{4\pi d_s^2}. \qquad (9)$$

At the same time emission region can be expressed through the radius of the emission region and its length:

$$V_{em} = \frac{3}{2}\pi r_s^2 l \approx 2\cdot 10^{-4} \gamma_{sh}^{-2} k_i^2 B_{-7}^2 \alpha_{-8}^3 n_{-7}^{-1}\ \mathrm{pc}^3.$$

INVERSE COMPTON RADIATION OF SUPERCONDUCTING COSMIC STRINGS

Spectral emissive ability of the isotropically distributed electrons in the case of inverse Compton radiation is [9]:

$$j(E_\gamma) = cE_\gamma \int \mathrm{d}\gamma N(\gamma) \int \mathrm{d}\epsilon n_{ph}(\epsilon)\sigma_{KN}(E_\gamma, \epsilon; \gamma), \qquad (10)$$

where γ is the Lorenz factor of electron, $N(\gamma)$ is the energetic distribution of electrons, ϵ and E_γ are the energies of photon before and after interaction, respectively, $n_{ph}(\epsilon)$ is the isotropic initial photon energy distribution,

$$\sigma_{KN}(E_\gamma, \epsilon; \gamma) = \frac{3\sigma_T}{4\epsilon\gamma^2} G(q, \eta)$$

is the angle-integrated cross-section of inverse Compton radiation, σ_T is the Thomson cross-section,

$$G(q, \eta) = 2q\ln\eta + (1+2q)(1-q) + 2\eta q(1-q),$$

$$q = \frac{E_\gamma}{\Gamma(\gamma m_e c^2 - E_\gamma)},\ \Gamma = \frac{4\epsilon\gamma}{m_e c^2},\ \eta = \frac{\epsilon E_\gamma}{(m_e c^2)^2}.$$

In a lot of astrophysical environments, the initial photon energy field may be represented by the isotropic black-body radiation:

$$n_{ph}(\epsilon) = \frac{1}{\pi^2\hbar^3 c^3} \frac{\epsilon^2}{\exp(\epsilon/\epsilon_c) - 1},$$

where $\epsilon_c = kT$. In our case we consider cosmic microwave background radiation with a typical temperature $T = 2.73\,\mathrm{K}$.

Let us re-write equation (10) in the form:

$$j(E_\gamma) = \int \mathrm{d}\gamma N(\gamma) J(\gamma, E_\gamma),$$

where the spectral emissive ability of one electron with the Lorenz factor γ is:

$$J(\gamma, E_\gamma) = \frac{3\sigma_T m_e^2 c^2 \epsilon_c}{4\pi^2 \hbar^3}\gamma^{-2} I(\eta_c, \eta_0) = \\ = \frac{2e^4 \epsilon_c}{\pi \hbar^3 c^2}\gamma^{-2} I(\eta_c, \eta_0),$$

with the function $I(\eta_c(E_\gamma), \eta_0(\gamma, E_\gamma))$:

$$I(\eta_c, \eta_0) = \int \frac{(\eta/\eta_c) G(\eta_0/\eta, \eta)}{\exp(\eta/\eta_c) - 1}\mathrm{d}\eta,$$

where

$$\eta_c = \frac{\epsilon_c E_\gamma}{(m_e c^2)^2},$$

$$\eta_0 = q\eta = \frac{E_\gamma^2}{4\gamma m_e c^2(\gamma m_e c^2 - E_\gamma)}.$$

Let us use the approximation for integral $I(\eta_c, \eta_0)$:

$$I(\eta_c, \eta_0) \approx \frac{\pi^2}{6}\eta_c \left(\exp\left[-\frac{5}{4}\left(\frac{\eta_0}{\eta_c}\right)^{1/2} \right] + \right. \\ \left. + 2\eta_0 \exp\left[-\frac{5}{7}\left(\frac{\eta_0}{\eta_c}\right)^{0.7} \right] \right) \exp\left[-\frac{2\eta_0}{3\eta_c} \right]. \quad (11)$$

This approximation accurately represents I in any mode, from Thomson to extreme Klein-Nishina. Equation (11) is correct for any η_c [9]. In the present study we used this approximation.

Now when we know how to calculate spectral emissive ability of inverse Compton radiation we can easily find its spectral flux using the formula (9).

SYNCHROTRON SELF-COMPTON RADIATION OF SUPERCONDUCTING STRINGS

Let us consider situation when photons which were born due to synchrotron radiation scatter on relativistic electrons behind the front of a shock-wave. Regarding the fact that electrons are ultra-relativistic and their energy are much bigger than energy of photons in this case we will also observe inverse Compton radiation and photons will receive the part of electron's energy. This type of radiation is called synchrotron self-Compton radiation.

We have calculated spectrum of synchrotron radiation (8) that is why now we can find spectral emissive ability of synchrotron self-Compton radiation. We just need to integrate synchrotron spectrum using (10). To find the concentration of synchrotron photons which is applied in this formula we have to use the following expression:

$$n_{ph}(\epsilon)\mathrm{d}\epsilon = \frac{\omega_{ph}(\epsilon)}{\epsilon}\mathrm{d}\epsilon = \frac{r_s}{c\epsilon} j(\epsilon)\mathrm{d}\epsilon,$$

where r_s is a radius of a shock-wave around the cosmic string (1). At the same time this is typical size of emission region.

Then again using the formula (9) we can easily find spectral flux of synchrotron self-Compton radiation.

FLUXES FROM STRINGS LOCATED IN THE IGM

In the present paper spectral fluxes of synchrotron, inverse Compton and synchrotron self-Compton radiation were calculated for strings with different tensions μ. Obtained results are presented in Figs. 1–3.

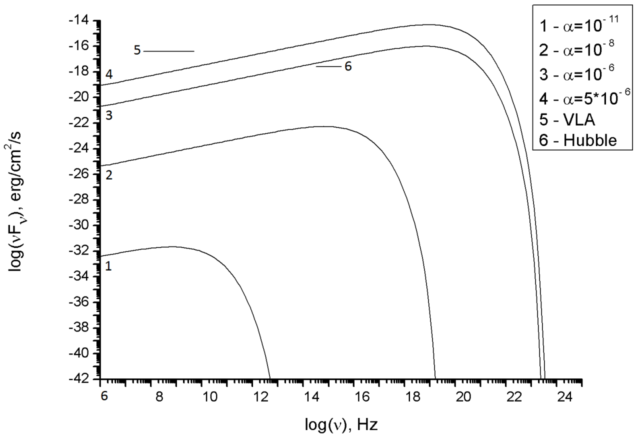

Fig. 1: Expected spectral flux of synchrotron radiation from a loop of a cosmic string in the intergalactic medium at the average distance from the terrestrial observer for strings with different tensions (for $n_1 = 10^{-7}\,\mathrm{cm}^{-3}$, $B = 10^{-7}\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

[1] http://www.vla.nrao.edu
[2] http://www.nasa.gov

In Fig. 1 one can also see the sensitivities of VLA[1] (Very Large Array) and HST[2] (Hubble Space Telescope) which work in the radio and optical regions, respectively. NRAO VLA Sky Survey was finished and it consists of objects which have spectral fluxes F_ν in radio region more than $3 \cdot 10^{-3}$ Jy $= 4 \cdot 10^{-17}\,\mathrm{erg\,cm^{-2}\,c}$. Hubble Space Telescope can observe objects with spectral fluxes F_ν in V-filter more than $2.5 \cdot 10^{-18}\,\mathrm{erg\,cm^{-2}\,c}$. It is obvious from the plot that synchrotron radiation from the cosmic strings with parameter $\alpha \geq 10^{-6}$ can be detected with facilities of existing telescopes.

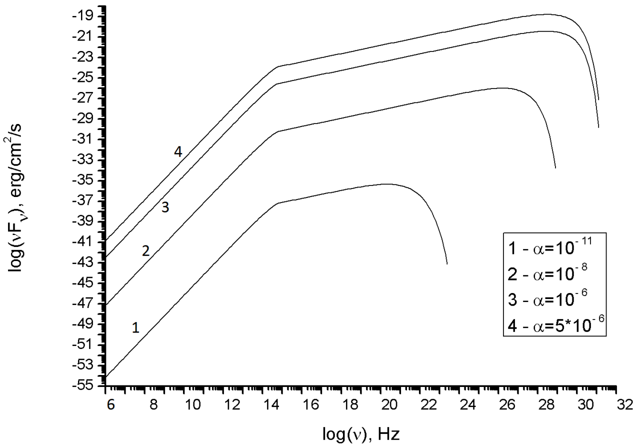

Fig. 2: Expected spectral flux of inverse Compton radiation from a loop of a cosmic string in the intergalactic medium at the average distance from the terrestrial observer for strings with different tensions (for $n_1 = 10^{-7}\,\mathrm{cm^{-3}}$, $B = 10^{-7}\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

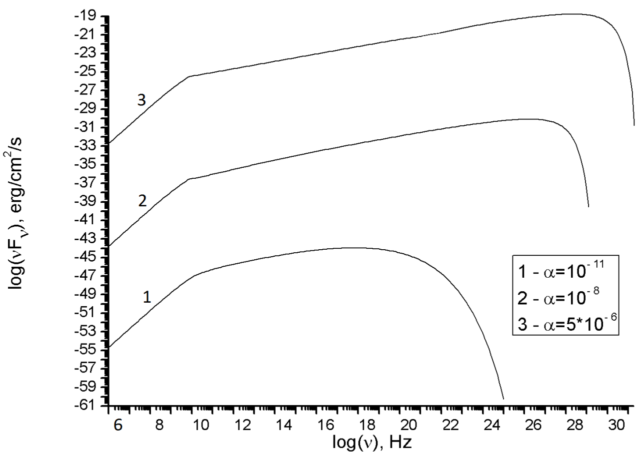

Fig. 3: Expected spectral flux of synchrotron self-Compton radiation from a loop of a cosmic string in the intergalactic medium at the average distance from the terrestrial observer for strings with different tensions (for $n_1 = 10^{-7}\,\mathrm{cm^{-3}}$, $B = 10^{-7}\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

We do not present sensitivities of any telescopes which work in the X-ray or γ-band on the plots for inverse Compton and synchrotron self-Compton radiation because they are much less than maximal fluxes of these types of radiation from the superconducting cosmic strings. So we can make a conclusion that inverse Compton and synchrotron self-Compton radiation from the strings are not available for observations by current cosmic and ground-based telescopes.

FLUXES FROM THE STRINGS LOCATED IN GALAXY CLUSTERS

In the next step let us assume that superconducting cosmic string with $\alpha = 10^{-6}$ is located in a cluster of galaxies with typical parameters of magnetic field $B = 10^{-6}(1+z)^2\,\mathrm{G}$ and concentration of electrons and protons $n_1 = 10^{-3}(1+z)^3\,\mathrm{cm^{-3}}$, where z is the redshift. We obtained spectral fluxes of synchrotron, inverse Compton and synchrotron self-Compton radiation for clusters with different luminosity distances from the terrestrial observer: 20, 50, 150, 500, and 4000 Mpc. It is connected with a redshift z by the formula: $d = 3t_0c(1+ +z)^{1/2}\left[(1+z)^{1/2} - 1\right]$. Other parameters remain the same: $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$.

Our results are shown in Figs. 4–6. As one can see, in this case also only synchrotron radiation from the superconducting cosmic strings can be observed by current telescopes and only from the nearest clusters.

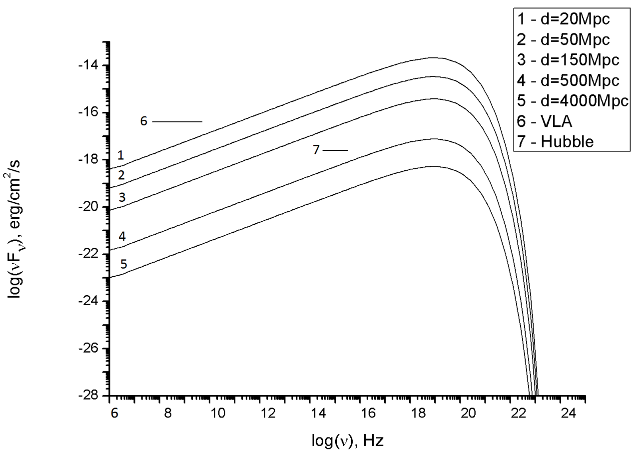

Fig. 4: Expected spectral flux of synchrotron radiation from a loop of a cosmic string in the clusters of galaxies which are located at the different luminosity distances from the terrestrial observer (for $\alpha = 10^{-6}$, $n_1 = 10^{-3}(1+z)^3\,\mathrm{cm^{-3}}$, $B = 10^{-6}(1+z)^2\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

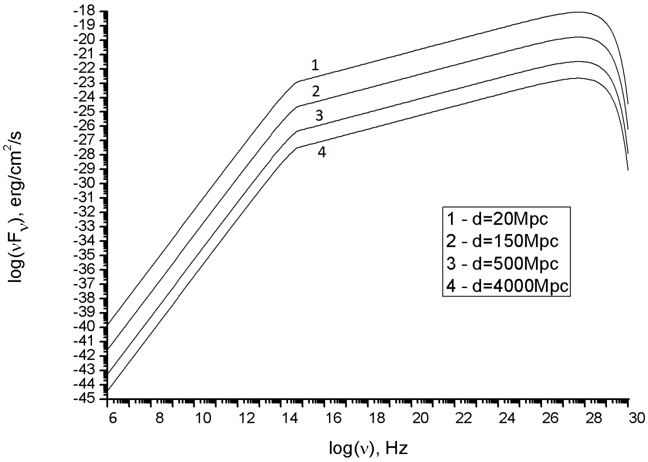

Fig. 5: Expected spectral flux of inverse Compton radiation from a loop of a cosmic string in the clusters of galaxies located at different luminosity distances from the terrestrial observer (for $\alpha = 10^{-6}$, $n_1 = 10^{-3}(1+z)^3\,\mathrm{cm}^{-3}$, $B = 10^{-6}(1+z)^2\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

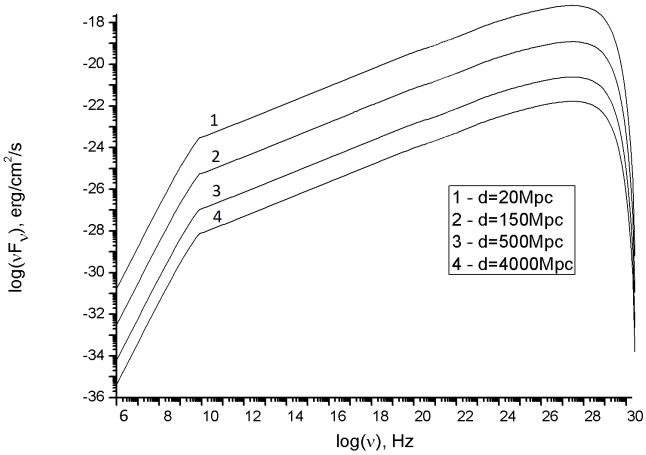

Fig. 6: Expected spectral flux of synchrotron self-Compton radiation from a loop of a cosmic string in the clusters of galaxies located at different luminosity distances from the terrestrial observer (for $\alpha = 10^{-6}$, $n_1 = 10^{-3}(1+z)^3\,\mathrm{cm}^{-3}$, $B = 10^{-6}(1+z)^2\,\mathrm{G}$, $\gamma_{sh} = 2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.1$)

RESULTS AND CONCLUSIONS

In the present paper we examined the model of motion of the superconducting cosmic string in IGM and process of interaction of its magnetosphere with an ambient intergalactic plasma. We also considered the model of generation of the relativistic shock wave around the string and acceleration mechanism of electrons on its front.

We calculated the fluxes of all types on non-thermal radiation (synchrotron, inverse Compton and synchrotron self-Compton radiation) from the loops of the superconducting cosmic strings using appropriate approximation for spectral emissive ability of one electron and assumption of exponential cutoff at the high energies in the energetic distribution of electrons. It was done for strings with different tensions which are located in the intergalactic medium and in the clusters of galaxies.

We also examined a possibility of detecting fluxes from superconducting cosmic strings by existing telescopes. It was shown that strings with the largest tensions located in the IGM are available for observation with current telescopes. Cosmic strings located in the galaxy clusters can be detected with the HST and VLA telescopes only from the nearest clusters.

REFERENCES

[1] Aharonian F. A. *Very high energy cosmic gamma radiation: a crucial window on the extreme Universe*, 2004, River Edge, World Scientific Publishing
[2] Blandford R. D. & McKee C. F. 1976, Physics of Fluids, 19, 1130
[3] Damour T. & Vilenkin A. 2005, Phys. Rev. D, 71, 063510
[4] Dubath F., Polchinski J. & Rocha J. V. 2008, Phys. Rev. D, 77, 123528
[5] Ferrer F., Mathur H., Vachaspati T. & Starkman G. 2006, Phys. Rev. D, 74, 025012
[6] Fraisse A. A. 2007, JCAP, 03, 008
[7] Kämpfer B. 2000, Annalen der Physik, 512, 605
[8] Longair M. S. *High Energy Astrophysics*, 2011, Cambridge, Cambridge University Press
[9] Petruk O. 2009, A&A, 499, 643
[10] Pogosian L., Tye S.-H. H., Wasserman I. & Wyman M. 2009, JCAP, 02, 013
[11] Ringeval C. 2001, Phys. Rev. D, 64, 123505
[12] Sari R. & Esin A. A. 2001, ApJ, 548, 787
[13] Siemens X., Creighton J., Maor I. et al. 2006, Phys. Rev. D, 73, 105001
[14] Vanchurin V. 2008, Phys. Rev. D, 77, 063532
[15] Vilenkin A. & Shellard E. P. S. *Cosmic strings and other topological defects*, 1994, Cambridge, Cambridge University Press
[16] Witten E. 1985, Nucl. Phys. A, 249, 557
[17] Wyman M., Pogosian L. & Wasserman I. 2005, Phys. Rev. D, 72, 023513
[18] Zadorozhna L. V., Hnatyk B. I. 2009, Ukrainian Journal of Physics, 54, 1041
[19] Zadorozhna L. V., Hnatyk B. I. 2009, Ukrainian Journal of Physics, 54, 1149