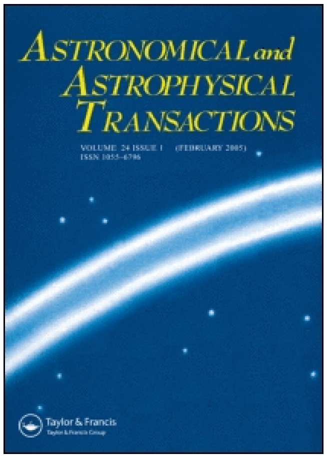

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STATIONARY COSMIC STRING LOOPS IN THE UNIVERSE

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We describe the electromagnetic and gravitational radiation from cosmic string loops with an electromagnetic current and their evolution to the stationary (vorton) state. The upper bounds on gravitational and electromagnetic radiation are found and the oscillation damping time of closed chiral strings is estimated. The analytical dependence of energy of the string with time is obtained in the case of radially oscillating ring. We found the minimal length of string that oscillates up to the present time and discuss some astrophysical applications of vortons.

Keywords: Cosmic string loops; The Universe

Cosmic strings could be created as one-dimensional topological defects at the phase transitions in the early Universe (Kibble, 1976; Zel’dovich, 1980; Vilenkin, 1980; 1985; Kibble et al., 1982). Witten (1985) has shown that strings could carry a superconducting current in certain particle physics models. The presence of a current on a string leads to the principal effect; the superconducting string loop may form a stable stationary configuration (Copeland et al., 1988; Davis and Shellard, 1988; Haws et al., 1988). Cosmic strings lose their energy on gravitational and electromagnetic radiation (if the string is superconducting). As a result, the ‘ordinary’ and not extremely long cosmic strings without a current evaporate completely during cosmological time. On the contrary the superconducting string loops could survive owing to the presence of conserved ‘charge’ and tend to the stable configuration which is called the chiral vorton (Davis and Shellard, 1988).

The study of properties of chiral cosmic string loops is necessary to understand the role of such strings in important physical processes: the mechanism of formation of galaxies, the generation of cosmic rays of ultrahigh energy and the explanation of structure and the properties of dark matter. We examine here the properties of gravitational and electromagnetic radiation and the evolution of strings due to losses of energy. Numerous studies have been devoted to calculations of the gravitational and electromagnetic radiation by cosmic strings (see reviews and references given by Shellard and Vilenkin (1994) and Hindmarsh and Kibble (1990). Similar calculations for radiation by strings with a current were performed by Blanco-Pillado and Olum (2001) and Babichev and Dokuchaev (2002). Unfortunately

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the general problem of the motion of a superconducting cosmic string coupled to the electromagnetic field is not solved analytically. The using of the Nambu–Goto equations of string motion in the general case results in the singular cusp formation and the divergence of the electromagnetic power radiated by the string. Nevertheless equations of motion can be solved precisely (Blanco-Pillado et al., 1988; Davis and Shellard, 1988; Haws et al., 1988) if, firstly, the gauge field influence on the string motion is negligible, for example, when the superconducting current is neutral, and, secondly, the string current J^a is chiral, that is $J^a J_a = 0$, where J^a is a two-dimensional current on the string world surface. The equations of motion of such a string are given by

$$x^0 = t,\ x(t, \sigma) = \frac{L}{4\pi}[a(\xi) + b(\eta)], \tag{1}$$

where $a(\xi)$ and $b(\eta)$ are the vector functions of $\xi = (2\pi/L)(\sigma - t)$ and $\eta = (2\pi/L)(\sigma + t)$ obeying the constraints:

$$a'^2 = 1, \quad b'^2 = k^2 \leqslant 1. \tag{2}$$

It turns out that the electromagnetic power radiated by the cusp of chiral cosmic strings is finite.

In this report we consider the electromagnetic and gravitational radiation by chiral strings loops which are close to the stationary vorton state (when amplitude of loop oscillations is very small). In this case the supposition that all string oscillations are faded out is physically justified. Using the general expressions for gravitational and electromagnetic radiation from the relativistic periodic source and the smallness of the parameter k we can find the upper bounds radiation of nearly stationary chiral loops:

$$|\dot{E}^{gr}| \leqslant 32\pi^4 b_3^2 G\mu^2, \quad |\dot{E}^{em}| \leqslant \tfrac{4}{3}\pi^4 b_3^2 q^2 \mu, \tag{3}$$

where μ is the energy of a string per unit length, q is the coupling constant of the fields in the string and b_3 is a maximum value $|b'''(\eta)|$ on the segment $\eta \in (0, 2\pi)$. If the current is constant along the string, then for nearly stationary loops the corresponding gravitational and electromagnetic power can be generally written in the following form:

$$\dot{E}^{gr} = K^{gr} G\mu^2 k^2, \quad \dot{E}^{em} = K^{em} q^2 \mu k^2. \tag{4}$$

For some simple configurations (Fig. 1) of the string loops we make the calculations for both types of radiation. For a radially oscillating loop with $a = (\cos\xi, -\sin\xi, 0)$, $b = k(\cos\eta, -\sin\eta, 0)$, we have $K^{gr} = 4.73$ and $K^{em} = 2.28$. The corresponding coefficients for the second example with

$$\begin{aligned} a &= \begin{cases} A\left(\xi - \dfrac{\pi}{2}\right), & 0 \leqslant \xi \leqslant \pi, \\ A\left(-\xi + \dfrac{3\pi}{2}\right), & \pi \leqslant \xi \leqslant 2\pi, \end{cases} \\ b &= \begin{cases} kB\left(\eta - \dfrac{\pi}{2}\right), & 0 \leqslant \eta \leqslant \pi, \\ kB\left(-\eta + \dfrac{3\pi}{2}\right), & \pi \leqslant \eta \leqslant 2\pi, \end{cases} \end{aligned} \tag{5}$$

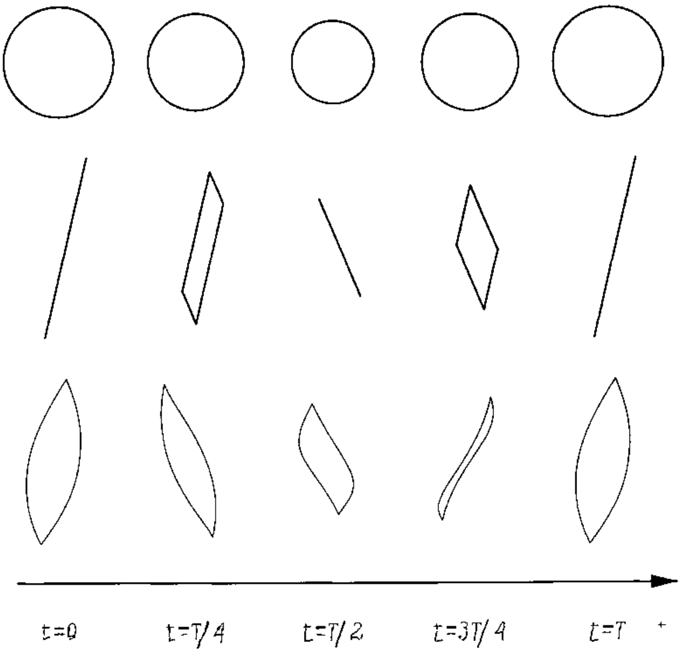

FIGURE 1 Three examples of oscillating cosmic string loops are shown: an oscillating ring, a kinky loop and a stretched loop (Babichev and Dokuchaev, 2000). When oscillating, strings are in successive sequence positions with the T/4 step, where the oscillation period $T = L/2$.

are $K^{gr} = 28.3$ and $K^{em} = 4$. For the third example of a stretched loop with

$$a = \begin{cases} A\left(\xi - \frac{\pi}{2}\right), & 0 \leqslant \xi \leqslant \pi, \\ A\left(-\xi + \frac{3\pi}{2}\right), & \pi \leqslant \xi \leqslant 2\pi, \end{cases} \tag{6}$$

$$b = k(\sin\eta, -\cos\eta, 0)$$

we have $K^{gr} = 7.63$ and $K^{em} = 3$. On the basis of these calculations we can say that for closed loops of arbitrary configuration with a small current we have $K^{gr} \approx 10$ and $K^{em} \approx 1$.

When oscillating, the string loops lose their energy but, because of the presence of conserved charge, do not evaporate completely. Based on the symmetries of the problem in the case of a radially oscillating string loop and using the conservation law we can find the analytical formulae for behaviour in time of the string loop energy and current (Babichev and Dokuchaev, 2000):

$$k^2 \approx k_0^2\, e^{-t(1/\tau_c^{gr} + 1/\tau_c^{em})}, \quad E \approx E_v\left(1 + \frac{k_0^2}{2}\, e^{-t(1/\tau_c^{gr} + 1/\tau_c^{em})}\right), \tag{7}$$

where $k_0 = k(t = 0)$, and the damping times due to gravitational and electromagnetic radiation are respectively

$$\tau_c^{gr} = \frac{L_{ph}}{K^{gr} G\mu}, \quad \tau_c^{em} = \frac{L_{ph}}{K^{em} q^2}, \tag{8}$$

where L_{ph} is the physical length of the vorton. For some other less symmetric examples of loops we can estimate the damping time of small amplitude oscillations:

$$\tau \approx \frac{L_{ph}}{K^{gr}G\mu + K^{em}q^2}. \tag{9}$$

It turns out that, in all the examples considered, the oscillation damping time of chiral strings due to gravitational radiation is an order of magnitude longer than the known lifetime estimations for the ‘ordinary’ cosmic strings without a current. It is interesting to determine what kind of radiation is stronger. To do this we estimate the ratio of damping times:

$$\frac{\tau^{gr}}{\tau^{em}} \approx \frac{q^2}{G\mu h}\frac{K^{em}}{K^{gr}} \approx 1.4 \times 10^{-4}\frac{q_e^2}{\mu_6}\frac{K^{em}}{K^{gr}}. \tag{10}$$

If $q_e^2/\mu_6 \gtrsim 1.4 \times 10^{-3}$, then electromagnetic radiation prevails in the chiral loop evolution. Therefore, for a cosmic string with the standard values of energy-per-unit-length parameter $\mu_6 \approx 1$ and charge parameter $q_e \approx 1$, the electromagnetic radiation is three orders higher than gravitational radiation. If, on the contrary, $q_e^2/\mu_6 \lesssim 1.4 \times 10^{-3}$ (e.g. if a current is neutral and there is no electromagnetic radiation at all), then pure gravitational radiation determines the evolution. From the damping time estimation it follows that only sufficiently long superconducting cosmic strings oscillate up to the present time. On the contrary the small-scale chiral loops transformed into the stationary vortons owing to the oscillation damping. That is, the minimal length of presently oscillating chiral loop varies from $L_v^{gr} \approx 10^2\mu_6$ kpc for gravitational radiation domination to $L_v^{em} \approx 70q_e^2$ Mpc for electromagnetic radiation domination depending on the relations between the parameters μ and q.

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