HIGH ENERGY PARTICLE PRODUCTION FROM CONDUCTING COSMIC STRINGS

S. Sivaram

Indian Institute of Astrophysics, Bangalore 560034, India

Abstract

Cosmic strings are of current interest as they could provide the density fluctuations to trigger galaxy formation. However, if the string loops are conducting and have relatively low tension then their electromagnetic interactions with the ambient cosmic plasma would be significant. A current carrying cosmic string moving at relativistic speeds will have a shock front connected with its motion and electrons as well as ions in equipartition would be accelerated by the relativistic shock to typical energies of well over a 100 MeV. Moreover particles may be accelerated by plasma instabilities in the string wake to several hundred GeV depending on the string loop length and ambient magnetic field. The resulting differential energy spectrum follows a power law distribution with a spectral index close to the observed value for cosmic rays. Apart from shock acceleration of charged particles another manifestation of such strings is synchrotron radiation at typical radio wavelengths.

1. Introduction. Recently there has been much interest in cosmological effects of strings which could have been produced at a phase transition in the early universe and could provide the density fluctuations needed to start the formation of galaxies. The gravitational interactions of strings are characterized by a dimensionless parameter $\eta = G\mu/c^2 \sim (M/M_{pl})^2$; where the string tension μ is related to the mass scale M at which the early universe phase transition occurs as $\mu \sim M^2$; M_{pl} is the planck mass. For $M=M_{pl}$; $\eta = 1$, $\mu = c^2/G$ which is the maximum value for μ. For grand unification strings, $\mu = 2\times10^{-7}\ c^2/G$ corresponding to $M \approx 10^{15}$GeV, while for supersymmetric GUT strings, $\mu = 10^{-4}\ c^2/G$ ($M=10^{16}$ GeV). For strings appearing in the breaking of So (10) symmetry at $M_x = 10^{17}$ GeV, $\mu \approx 10^{-3}\ c^2/G$ and for heterotic superstrings $\mu \approx 5\ 10^{-4}\ c^2/G$. The angular momentum mass relation $J \sim kM^2$ for a wide range of astronomical objects with a near universal $k = 10^{-15}$ is consistent with a similar relation for rotating strings if $\mu = 4\times10^{-4}\ c^2/G$; $k = c(2\pi\mu)^{-1}$. Accretion onto cosmic strings can lead to formation of galactic halos with density distributions required for flat rotation curve if $\mu = 10^{-6}\ c^2/G$. However string loops lose energy chiefly by gravitational relation at a rate $p \approx \beta G u^2 c$ ($\beta \approx 10$), resulting in a lifetime of $t = RC/\beta G\mu$ for a loop of length R. The requirement that the loops should last for an age of the order of the Hubble time $\sim 1/H$ constraints $\mu < 10^{-6}\ c^2/G$ or $M < 10^{15}$ GeV. More stringent limit on u comes from the requirement that the strings should not produce so much gravitational radiation as to interfere with the primordial nucleosynthesis yields. Models where galaxies accrete around loops obtain $\mu = 10^{-6}\ c^2/G$. Again effects associated with the gravitational

lensing of distant objects by strings (typical separation of the images of the object lensed is $\sim 4\pi G\mu$) enables constraints to be put on string parameters. $\mu = 6\times10^{-5}\ c^2/G$ corresponds to 2.5 arc min separation. As earlier values of $\mu = 10^{-3}$ to 10^{-5}, thought to be useful for galaxy formation now seem too high and the constraint $\mu < 10^{-6}\ c^2/G$ would imply separation of images lensed by strings to be less than 0.1 arc min ruling out wide separation quasar pairs. Another problem with larger values of μ is that the corresponding M is higher, i.e. $> 10^{16}$ GeV, and in the context of inflationary universe scenarios would imply (along with other unwanted relics like monopoles) that the strings are now diluted to negligible low number density levels to serve for galaxy formation purposes.

2. Conducting strings and their interactions. In some models the strings can behave as conducting wires and it is possible for them to be light (small μ). They can then have dominant electromagnetic interactions with a current in a loop of length R moving with velocity V in a magnetic field B, given by $i \sim e^2 B_1 R$, the magnetic field produced by this current near the string being $B = 2i/cR$, $V \ll R$. The motion of such a string being very supersonic, a shock front is formed at a distance d_s from the string as it moves through interstellar plasma. $d_s \approx \alpha R B_1 (4\pi nm)^{-1/2}$, $\alpha = e^2/\hbar c$, m = mass of charge carriers on string. String moving through the plasma with velocity V has a damping force per unit length of $f_d \sim nmV^2 d_s$ and the rate of energy loss (loop length R) is $\sim f_d RV$ and this energy dissipated by shock heating gives lifetime $\sim \mu Rc^2/f_d RV$ which is to be compared with the lifetime for gravitational radiation emission given earlier. For $\mu > 10^{-11} c^2/G$, gravitational radiation is the dominant energy loss mechanism; and for $R_t \approx 30$ pc (typical loop length), no. of loops with $R < R_t$ is $(\sim (R_t/R)^{3/2})$, $B \approx 10^{-6}$ G, $d_s = 10^{13}$ cm$n^{-1/2}$, $f_d RV \sim 10^{40}$ $(R/R_t)^2 \sqrt{n}$ erg/s).

The magnetic field at the stagnation point in the middle of the tangential discontinuity can be estimated from equating $nmV_s^2 = B_{st}^2/8\pi$, V_s is the supersonic velocity $\sim c/\sqrt{2}$. In the vicinity of the string $r \ll d_s$, $B = 2i/cr$ and current in a loop of length $R_t \approx 30$ pc, $B \approx 10^{-6}$ G is $i \sim 10^{22}$ (R/R_t), when the current reaches the maximum value $i_m \sim mc^2(e/\hbar)$, string starts producing particles and antiparticles at rate $\sim eE/\hbar$ per unit time per unit length, E is the electric field on axis. As $R < R_t$ for all galactic loops, particle production can occur only for $i_m < 10^{22}$ or $mc^2 < 10^8$ GeV. For equipartition between electrons and ions behind the shock, typical particle energies are $\sim 1/4\ mV_s^2 \sim 1/8\ mc^2 = 100$ MeV, which is the energy of one particles accelerated by the shock associated with the cosmic string.

3. Particle acceleration. In principle, the particles may be accelerated to energies as high as $W_{max} \approx eB_{st}d_s = 10^6\ (R/R_t)$GeV, by plasma instabilities in the string wake, limited only by requiring that their larmor radii should not be larger than d_s. Ambient magnetic field assumed is $\sim 10^{-6}$ G. This can possibly

result in a power-law non-thermal energy (W) distribution $dN \propto W^{-p} dW$. For synchrotron rad. (wavelength $\sim 1/d_s^2\ (m_e c^2/eB_{st})^3$, power radiated by these particles proportional to $W^{2-p}dW$ and if points on the string approach $v \sim c$ during each oscillation then in the vicinity of these points the motion of a small segment is ultrarelativistic with $\gamma \sim R/(\Delta r + c\Delta t)$ implying that particles can be accelerated to large γ with the fraction of particles with $\gamma = \gamma_c$ or greater being proportional to γ^{-2}. This corresponds to a spectrum (differential energy) with $p = 3$, this spectral index being close to that for cosmic rays, with $p=2.7$.

The energy density in galactic cosmic rays (~ 1 eV cm^{-3}) if uniformly distributed over a galactic disc of radius 10 kpc and thickness 200 pc, corresponds to a total energy in galactic cosmic rays of $\sim 10^{54}$ ergs and with a typical lifetime of a cosmic ray particle in the disc of 10^7 yr. $\sim 10^{14}$ sec, the required power for any replenishing source is $\sim 10^{40}$ ergs/sec. We saw in section (2) above that the energy dissipated $f_d RV$, by supersonic string motion in the interstellar ambient plasma and magnetic field is of order $\sim 10^{41}$ $ergs^{-1}$ ($n = 1$), which would provide sufficient power for replenishing the energy of the cosmic ray particles. Thus a few such string-like structures suffice to supply the background in the galaxy. The plasma temperature near the stagnation point can be obtained from the balance $\tau_{st} \sim mV_0^2/4$ and if electron and proton temperatures are the same, the electrons are accelerated to a $\gamma \sim T_{st}/m_e \sim 100$.

Owing to the diffusion of the magnetic field lines there is a thin layer of stringly magnetized plasma with $B \sim B_{st}$ at the tangential discontinuity. The thickness of this layer can be estimated as $t_e \sim (d_s d_L)^{1/2}$, where d_L is the larmor radius $\sim T_s/eB_s$ is comparable to the Debye length $\sim (T_s/4\pi ne^2)^{1/2}$. With this we can estimate the synchrotron radiation from the string, i.e. the power radiated by the strongly magnetized layer where $B \sim B_{st}$ as $P_{syn} \approx e^4 \gamma^2/m_e^2 c^3\ B_{st}^2\ n\ R\ d_s t_\ell$, $\gamma \sim 100 \gg 1$ and the typical wavelength of this radiation is $\sim \lambda \sim m_e c^2/e\gamma^2 B_{st} \sim 10/n^{1/2}$ cm. This is similar to the radio emission mechanism in a pulsar. Using the values for γ and t_ℓ we have:

$$P_{syn} \simeq 10^{33} (R/R_t)^{5/2} n^2 \text{ erg/s};$$

with a typical radio wavelength $\sim 10n^{-1/2}$ cm. Thus this could be another signature for the presence of galactic cosmic strings.

References

1. A.Vilenkin, Phys. Rep., 121, 263, 1985.
2. N.Turok, Phys. Rev. Lett., 55, 1801, 1985.
3. E.Witten, Nucl. Phys. B249, 557, 1985.
4. C.Civaram, Nature, 1987 (in press)