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Strings in the Sun?

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If light superconducting strings were formed in the early Universe, then it is very likely that now they exist in abundance in the interstellar plasma and in stars. The dynamics of such strings can be dominated by friction, so that they are "frozen" into the plasma. Turbulence of the plasma twists and stretches the strings, forming a stochastic string network. Such networks must generate particles and magnetic fields, and may play an important role in the physics of stars and of the Galaxy.

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Cosmic strings could arise as a random network of linelike vacuum defects at a phase transition in the early Universe. According to the "standard" scenario, the network evolves by chopping off horizon-size loops which then gradually radiate away their energy and finally disappear.[1] This scenario is based on the assumption that friction due to the interaction of strings with surrounding matter becomes negligible, compared to the string tension, well before the present time. Here we argue that the cosmological evolution of light superconducting strings[2] is drastically different from the "standard" scenario. As such strings move through magnetized cosmic plasmas, they develop large electric currents, and the friction is greatly increased. As a result, the strings can be "frozen" into the plasma. If a small amount of such strings existed in the Galaxy, then the turbulence of the plasma had to stretch them, filling the interstellar space (and perhaps even the stars) by a random network of superconducting strings.

We shall first review the basic physics of superconducting strings. The mass per unit length of string is

$$\mu \sim \eta^2 \hbar c^3, \tag{1}$$

where η is the energy scale of symmetry breaking; $\mu \simeq 10^{22}$ g/cm for the grand-unification scale ($\eta \simeq 10^{16}$ GeV) and $\mu \simeq 10^{-6}$ g/cm for the electroweak scale ($\eta \simeq 10^2$ GeV). If a superconducting string moves with velocity v in a magnetic field B, then the current in the string grows at the rate[2]

$$di/dt \sim \alpha c v B, \tag{2}$$

where α is the fine-structure constant. The current builds up until it reaches the critical value

$$i_c = \kappa c^2 (\alpha\mu)^{1/2}, \tag{3}$$

where $\kappa \lesssim 1$ is the model-dependent numerical factor. For electroweak strings with $\kappa \simeq 1$ the critical current is $i_c \simeq 10^8$ A. When i_c is reached, the growth of the current terminates and the string starts producing particles of mass $m \sim \kappa\eta/c^2$ at the rate (per unit length of string)

$$dN/dt \sim evB/\hbar c. \tag{4}$$

Let us now consider the interaction of a current-carrying string with plasma.[3] The force of friction acting on a string moving with velocity v is comparable to that on a cylinder whose radius r_s is determined by the balance between the dynamical pressure ρv^2 and the magnetic pressure $B^2/8\pi$. Substituting $B \sim i/cr_s$, we find $r_s \sim i/cv\sqrt{\rho}$. The force of friction per unit length of string is $F_f \sim \rho v^2 r_s \sim i\sqrt{\rho}v/c$. In this paper we shall be mainly interested in the case when the strings have critical currents; then

$$F_f \sim \kappa v c (\alpha\mu\rho)^{1/2}. \tag{5}$$

Tension in a string of curvature radius R produces a force per unit length $F_t \sim \mu/R$, and the velocity of the string relative to the plasma is determined by $F_t \sim F_f$. This gives

$$Rv/c \sim \kappa^{-1}(\mu/\alpha\rho)^{1/2}. \qquad (6)$$

From the expression for r_s and Eq. (6), it follows that $r_s \sim \kappa^2 \alpha R \ll R$.

Observations show[4] that the interstellar plasma in our Galaxy is in a state of turbulent motion with a characteristic scale $L \simeq 10^{20}$ cm. The typical velocity on that scale is $v_L \simeq 10^6$ cm/s and the magnetic field is $B_L \simeq 10^{-6}$ G. On scales $R > L$, the motion of the plasma is well approximated by the Kolomogorov spectrum, $v_R \sim v_L(R/L)^{1/3}$, while for $R < L$ the spectrum is roughly that of magnetohydrodynamic turbulence.[4] In the latter case, $B_R^2/8\pi \sim \rho v_R^2/2$ and

$$v_R \sim v_L(R/L)^{1/4}. \qquad (7)$$

Comparing the turbulent velocity v_R with the string velocity from Eq. (6), we find the scale R_* at which $v \sim v_R$:

$$R_* \sim 10^{16}\kappa^{-4/5}\mu_{-6}^{2/5}\,\text{cm}. \qquad (8)$$

Here, μ_{-6} is μ in units of 10^{-6} g/cm and we have used $\rho \simeq 10^{-25}$ g/cm^3 for the density of interstellar plasma. (Here we disregard the neutral component; see below.) Strings with curvature radii $R \ll R_*$ are unaffected by turbulence, while strings with $R \gg R_*$ are dragged along by the plasma. In fact, the large-scale behavior of the strings is similar to that of the magnetic field lines which are "frozen" into the plasma.

Long strings are stretched and twisted by turbulent vortices and develop fractal shapes with a characteristic scale R_*. The length of string is most efficiently increased by vortices of size $\sim R_*$. Every such vortex interacting with the string stretches the string by $\sim R_*$ on a time scale $t_* \sim R_*/v_*$, where v_* is the turbulent velocity on scale R_*. This process continues until a random network of strings permeates the entire volume occupied by the plasma. Individual strings in the network have fractal shapes with a minimum scale $\sim R_*$, and the distance between the nearest string segments is also $\sim R_*$. Closed loops of size $\lesssim R_*$ will be constantly formed by string intersections at the rate of about one loop per volume R_*^3 per time t_*. Such loops shrink under the action of tension and lose their energy to heat and particle production. The efficiency of this dissipation mechanism is sufficient to balance the stretching of strings by the turbulence. It is clear that the number of string segments per volume R_*^3 cannot become much greater than 1, since then strings would disappear because of loop formation faster then they are produced by turbulent motion of the plasma.

Besides the string tension and the frictional force, the strings are acted upon by the magnetic force F_B. If we disregard plasma effects, $F_B \sim iB/c \sim (B^2/\rho v^2)^{1/2} F_f \sim F_f$. Note, however, that plasma effects lead to the screening of the superconducting current at the distance r_s from the string, and so the effect of F_B becomes less important. On scales $\lesssim R_*$ tension causes the strings to cross the magnetic field lines. As a result, electric currents are constantly induced in the strings. By use of Eqs. (2) and (3) and the equipartition of kinetic and magnetic energies of the plasma, it is easily verified that the current on scale R_* reaches the critical value on a time scale $\sim t_*$. This justifies our assumption that $i \sim i_c$.

The string energy dissipated by friction and transformed into heat per volume R_*^3 per time t_* is $\mathcal{E}_f \sim \mu c^2 R_*$ and the energy of the magnetic field dissipated in the form of relativistic particles is $\mathcal{E}_p \sim \kappa\eta(eBR_*/hc)R_*$. Using Eq. (6) we find $\mathcal{E}_p/\mathcal{E}_f \sim (B^2/\rho v_*^2)^{1/2} \sim 1$.

The whole random network of strings can be generated from a single "seed" loop of size $R > R_*$. The largest loop formed per galaxy in the early Universe has size comparable to that of a galaxy at horizon crossing,[1] $R \simeq 10^{20}$ cm. The condition $R > R_*$ is satisfied if $\mu_{-6} < 10^{10}\kappa^2$ or $\eta < 10^7\kappa$ GeV. For the electroweak scale $\eta \simeq 10^2$ GeV and with $\kappa \simeq 1$, the distance to the nearest string is $\simeq 10^{16}$ cm. Although this is much smaller than the distance to the nearest star, a direct observation of the string is hardly possible. An estimate of the synchrotron radiation of plasma in the magnetic field of the string[3] shows that this effect is hopelessly small. The energy output of a string of length R_* in the form of relativistic particles is

$$d\mathcal{E}/dt \sim \mu c^2 v_* \sim 10^{20}\kappa^{-1/5}\mu_{-6}^{11/10}\text{erg/s}.$$

Assuming that γ rays of energy $\epsilon \sim \kappa\eta$ carry away a fraction f of this energy, we find that the flux of such γ rays on Earth is $\sim 10^{-11} f\kappa^{2/5}\mu_{-6}^{-1/5}$ cm^{-2} s^{-1}, which is much smaller than the observed background flux.

Although individual strings are very difficult to detect, their cumulative effect can be quite significant. The energy output in the form of high-energy particles due to all strings in the Galaxy is

$$\frac{d\mathcal{E}}{dt} \sim \frac{\mu c^2 v_*}{R_*^3} V \sim 10^{40}\kappa^{11/5}\mu_{-6}^{-1/10}\text{erg/s}, \qquad (9)$$

where $V \simeq 10^{67}$ cm^3 is the galactic volume. Remarkably, the value 10^{40} erg/s coincides with the estimates of the energy input necessary to sustain the observed concentration of cosmic rays in the Galaxy.[5] Note that the μ dependence in Eq. (9) is extremely weak. The cumulative γ-ray flux from the strings is $10^{-5} f\kappa^{6/5}\mu_{-6}^{-3/5}$ cm^{-2} s^{-1}. For $\kappa \simeq 1$, $\mu \simeq 10^{-6}$ g/cm, this is consistent with observations[6] if $f < 10^{-3}$. In general, f depends on the elementary-particle model, and models predicting high values at f may be ruled out.

Besides particle production, some part of the energy of strings can be transformed into small relativistic loops.

Such loops may occasionally annihilate in the Earth's atmosphere. However, an estimate based on the total energy balance of strings indicates that a collision of a macroscopic loop with the Earth is an extremely rare event.

Now we turn to the intriguing possibility that strings could exist in the interiors of stars. It is clear that to be stretched by the plasma turbulence in a star, the string must be sufficiently long (see below). The possibility of a long string being captured by a star appears unlikely, since the plasma wind from the star would not allow the string to approach it. More plausible is the scenario in which the string is captured during the star formation. Stars are formed in weakly ionized clouds of density $\rho \sim 10^{-22}$–10^{-18} g/cm^3. For such clouds our estimation of R_* must be reconsidered. Let ρ_i be the density of the ionized matter and $\lambda \sim m_p/\sigma\rho$ the mean free path of a particle of the gas (m_p being the proton mass, σ being the collision cross section). If $r_s > \lambda$ (which is verified for $\rho > 10^{-22}$ g/cm^3), then it is easy to show that the pressure on the moving string is defined by $\rho_{\text{eff}} = \rho_i r_s/\lambda$. The ion mass density ρ_i in the cloud depends on the neutral mass density ρ according to the law[6] $\rho_i = C\sqrt{\rho}$, where $C \sim 3\times 10^{-16}$ g$^{1/2}$ cm$^{-3/2}$. A self-consistent calculation of R_* in the same manner as before gives

$$R_* \sim 10^{14} \kappa^{-4/3} \mu_{-6}^{1/3} v_6^{-2/3} \rho_{-20}^{-1/2}\ \text{cm}, \qquad (10)$$

which corresponds to $R_* \sim 10^{13}$–10^{15} cm for typical clouds at $\kappa \simeq 1$, $\mu \simeq 10^{-6}$ g/cm. Star formation occurs as a result of slow gravitational condensation of matter in the high-density regions of the cloud. During the early stages of this process, neutral matter contracts together with plasma and with the magnetic field and strings frozen into it. As the density increases, the degree of ionization falls and the neutral matter decouples from the plasma.[4,7] At this stage strings can be left out from the protostar if its radius is smaller than R_*. In the course of further contraction, the protostar becomes thermally ionized and recaptures its coupling to the magnetic field and to the strings. This typically happens when its radius is $R_i \simeq 10^{13}$ cm. The fraction of stars that get contaminated with strings, therefore, can be estimated as $\langle (R_i/R_*)^2 \rangle \sim 10^{-4}$–$10^0$. In fact, it is quite possible that a turbulent network of string exists in the Sun.

Little is known about the inner parts of the Sun, and so we shall concentrate on the solar convection zone.[4] Its depth is $L \simeq 10^{10}$ cm, and the velocity on that scale is $v_L \simeq 10^5$ cm/s. The density of plasma changes by several orders of magnitude across the convection zone. If there are strings in the Sun, then the typical scale of the string network R_* can be estimated along the same lines as before. For electroweak strings with $\kappa \simeq 1$, R_* varies from 10^5 cm at the bottom of the convection zone ($\rho \simeq 0.1$ g/cm^3) to 10^8 cm near the visible surface of the Sun ($\rho \simeq 10^{-7}$ g/cm^3). An estimate of the total energy output of strings shows that it can be comparable to the total solar luminosity, indicating that strings could play an important role in the energy balance of the Sun. The energy dissipated by strings is transformed partly into heat and partly into relativistic particles. All particles except neutrinos are quickly thermalized and their energy is also turned into heat. Neutrinos escape from the Sun, and their expected flux on Earth should be compared with experimental data. This flux and the typical energy of neutrinos are sensitive to the details of the elementary-particle model, as well as to the details of the inner structure of the Sun. Preliminary estimates suggest that the flux of high-energy neutrinos predicted in some models is greater than the observed flux. A comprehensive analysis of string dynamics in stars and its comparison with observations is a challenging problem which we do not attempt to address in this paper.

Even more intriguing than the presence of strings in the Sun is the possibility that strings exist in the turbulent cores of planets. Parameters of the turbulence in the core of the Earth are[4] $L \simeq 10^8$ cm, $v_L \simeq 10^{-2}$ cm/s, $\rho \simeq 10$ g/cm^3. Using these numbers we obtain from Eqs. (6) and (7) $R_* \sim 10^9 \kappa^{-4/5} \mu_{-6}^{2/5}$ which is larger than the radius of the Earth at least by an order of magnitude. Hence, the existence of a string network in the Earth appears unlikely, although it cannot be excluded, considering the very crude character of our estimate. The presence of strings in the turbulent cores of large planets seems more plausible.

To conclude, we have shown that if light superconducting strings existed in the early Universe, it is very likely that now they exist in abundance in the interstellar plasma and stars. If they do, they generate relativistic particles and magnetic fields and play an important role in the physics of stars and of the Galaxy.

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