Dark strings

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Recent astrophysical observations have motivated novel theoretical models of the dark matter sector. A class of such models predicts the existence of GeV scale cosmic strings that communicate with the standard model sector by Aharonov-Bohm interactions with electrically charged particles. We discuss the cosmology of these ''dark strings'' and investigate possible observational signatures. More elaborate dark sector models are argued to contain hybrid topological defects that may also have observational signatures.

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Recent observations by the PAMELA [1] and ATIC [2] experiments show anomalous positron fractions and total electron and positron (e^+e^-) fluxes in cosmic rays in the GeV to TeV energy range. The signal may be an outcome of annihilating dark matter [3,4] or have an astrophysical origin [5], and both possibilities are currently under intense investigation. If the signal is due to dark matter annihilation, model building suggests a dark sector separate from the standard model sector with a tiny interaction linking the two sectors [4]. Thus the Lagrangian has the form

$$L = L_{\rm SM} + L_{\rm DS} + L_{\rm int} \tag{1}$$

where SM stands for standard model, DS for dark sector, and ''int'' represents the interaction that bridges between the two sectors. The dark sector has its own symmetries that are *all* spontaneously broken. This has to be so for Abelian symmetries, otherwise we would also have a cosmological background of massless dark photons that, in the simplest scenarios, interfere with big bang nucleosynthesis. The issue is more subtle for non-Abelian symmetries since these can be confining. If the confinement scale is high enough, the symmetry need not be broken and dark matter may also be made of ''dark hadrons.'' However, as we shall see, to connect with the standard model at very low energies, a definite gauge field needs to be picked out and the low energy symmetry of the dark sector is effectively Abelian and broken.

To connect with observations, one of the dark sector symmetries is broken at the GeV scale, with a gauge boson that acquires mass at the GeV scale. Let us call this gauge boson, a_μ, and denote its field strength by, $a_{\mu\nu}$. Then the interaction Lagrangian is taken to be

$$L_{\rm int} = +\frac{\epsilon}{2} a_{\mu\nu} A^{\mu\nu} \tag{2}$$

where A_μ denotes the electromagnetic gauge field and $A_{\mu\nu}$ its field strength. The coupling ϵ is small and is needed to be on the order of 10^{-3} to connect with observations [4]. We shall take $\epsilon = 10^{-3}\epsilon_3$.

Although more complicated versions of the interaction Lagrangian are possible, especially in the context of large symmetries and representations in the dark matter sector, they all reduce to the form in Eq. (2) at energies below the GeV scale. The low energy dark sector Lagrangian ($L_{\rm DS}$) is therefore an Abelian-Higgs model for the single relevant gauge field a_μ. The $U(1)_{\rm DS}$ symmetry of $L_{\rm DS}$ is broken at the GeV scale and a_μ then acquires a GeV scale mass. The $U(1)_{\rm DS}$ symmetry breaking also produces cosmic strings [6] with GeV scale tension: $\mu \sim (1~{\rm GeV})^2 \sim 10^{-10}~{\rm gm/cm}$. The only way these strings can interact with the standard model sector is via the interaction in $L_{\rm int}$. (Hidden-sector topological defects have also been considered in [7].)

It is convenient to rewrite the Lagrangian for the gauge sector in the following manner

$$L_{\rm gauge} = -\frac{1}{4}\bar{A}_{\mu\nu}\bar{A}^{\mu\nu} - \frac{1}{4}(1-\epsilon^2)a_{\mu\nu}a^{\mu\nu} \tag{3}$$

where we have absorbed the interaction term into a redefined gauge field $\bar{A}_\mu = A_\mu - \epsilon a_\mu$. This means that a particle with electromagnetic charge q interacts with a_μ with an effective dark sector charge of ϵq.

A dark string with unit topological winding contains $2\pi/e'$ quanta of magnetic flux where e' is the dark sector unit charge. Hence the Aharonov-Bohm (AB) phase around a unit winding string is $\phi_{\rm AB} = 2\pi\epsilon q/e'$. If ϵq is an integer multiple of e', there will be no AB interaction. However, there is no reason for such a relation to hold, since the value of ϵ is set by integrating out heavy degrees of freedom. To be specific, we shall assume $q = e'$ and hence that the AB phase is $2\pi\epsilon$.

A dark string moving through a medium will encounter friction due to particle scattering off the string core [8] as well as due to AB scattering [9]. The transport cross section, i.e. the cross section that determines momentum transfer, due to AB scattering is (see [10])

$$\sigma_{t,{\rm AB}} = \frac{2}{p}\sin^2(\pi\epsilon), \tag{4}$$

while the transport cross section due to conventional scattering of particles interacting with the string core is

$$\sigma_{t,\mathrm{con}} = \frac{\pi^2}{p[\ln(p\delta)]^2}, \quad (5)$$

where $\delta \sim 1/\sqrt{\mu}$ is the thickness of the string and p is the magnitude of the momentum of the incoming particle. Hence the friction exerted by AB scattering is larger than the conventional drag by the factor

$$\frac{F_{\mathrm{AB}}}{F_{\mathrm{con}}} = \frac{2}{\pi^2}\sin^2(\pi\epsilon)\ln^2(p\delta) \times \frac{n_{\mathrm{elec}}}{n_{\mathrm{DM}}} \quad (6)$$

where we have also included the last factor that accounts for the different number densities of electrically charged particles to dark matter. The cosmic ratio of baryon to dark matter energy density is $\sim 1/6$ while the mass of the dark matter particle to nucleon mass is $\sim 10^3$. Putting these factors together $F_{\mathrm{AB}}/F_{\mathrm{con}} \sim \epsilon_3^2$, where we have taken $\ln^2(q\delta) \sim 10^3$. So the two drag forces are similar in magnitude if $\epsilon_3 \sim 1$.

In the cosmological setting, dark strings form when the cosmic temperature drops to $\sim$GeV, at time $t_f \sim 10^{-5}$ s. The string network contains a distribution of loops and infinite strings [11]. In the period following formation, the ambient cosmological medium scatters off the strings and damps their motion. The frictional damping force (per unit length) is $F_d \sim \epsilon^2 n\gamma v$ where n is the number density of (electrically charged) particles, v is the string speed, and γ the Lorentz factor. The rate of work done by the damping force is $\sim F_d v$ and this is also the rate at which the string loses kinetic energy $\sim \mu v^2$. Therefore the frictional damping time scale is

$$\tau \sim \frac{\mu}{\epsilon^2 n_{\mathrm{elec}}}. \quad (7)$$

The number density of particles, n_{elec} is found by taking the present number density in protons (and electrons) and evolving it back in time

$$n_{\mathrm{elec}}(t) \sim \frac{\rho_b(t_0)}{m_n}\left(\frac{a_0}{a_{(t)}}\right)^3 \sim 10^{-6}\left(\frac{T}{T_0}\right)^3 \ \mathrm{cm}^{-3}, \quad (8)$$

where we have used that the density in baryons is $\sim 5\%$ of the critical density (10^{-29} gms/cm^3), the mass of the nucleon is $m_n \sim 10^{-24}$ gms, and the fact that cosmic temperature scales inversely as the scale factor. Inserting the expression for n_{elec} in Eq. (7), with $\mu = (1\ \mathrm{GeV})^2$, we find that the damping time coincides with the Hubble time at $t_d \sim 1$ s, i.e. at a temperature $T_d \sim 1$ MeV. Hence the strings are friction dominated until t_d, and subsequently, friction damping drops rapidly (as T^3) and can be neglected. Note that the MeV scale coincides with the time at which the electrons are becoming nonrelativistic and so we are justified in using the nonrelativistic number density in Eq. (8).

Loops of dark string can dissipate their energy into gravitational radiation, e^+e^- pairs, or photons. The power emitted in gravitational radiation is $\sim \Gamma G\mu^2$ where $\Gamma \sim 100$. Since $G\mu \sim 10^{-38}$ for us, loops of length $l > l_{\mathrm{grav}} = 10^{-9}$ cm emit a negligible fraction of their energy into gravitational radiation in the current age of the Universe ($\sim 10^{17}$ s). In addition to gravitational radiation, we can expect string loops to emit charged particles due to the AB interaction [9]. For a massless charged particle, dimensional arguments imply a rate of energy loss $\sim\epsilon^2/l^2$ since the length of the loop is the only dimensional scale in the problem. (The string width and tension are not expected to play a role in the AB interaction.) We expect AB radiation to be suppressed due to the mass of the electron and only to be important for loops with a length less than the Compton wavelength of the electron, $m_e^{-1} \sim 10^{-11}$ cm. A higher order interaction, where the string produces a virtual e^+e^- pair that then annihilates to produce a photon, is also possible. The power emitted in photons is estimated as

$$\frac{dE_\gamma}{dt} \sim \frac{\epsilon^2}{l^2}\frac{\alpha}{(m_e l)^4} \quad (9)$$

where the first factor is the AB production of massless charged particles, the second factor is due to the electron propagators in the fermion loop, and the fine structure constant is due to the photon vertex. The power radiated in photons falls off rapidly with loop length, and we find that loops larger than $l_\gamma \sim 10^{-8}$ cm will survive longer than the current age of the Universe.

We now discuss the cosmology of dark strings. The string network properties are not known in detail but we can arrive at a picture of the network by considering the effects of various physical processes. Unless this picture underestimates the string network density, we will find that there are too few strings to give an interesting observational signature.

The effect of friction on string dynamics is similar to that of Hubble damping [12] with a "friction horizon" size given by $\tau(t)$ in Eq. (7). In the friction dominated regime, string loops larger than $\tau(t)$ will stretch and become longer. This is because the strings tend to be at rest with respect to the ambient fluid which is expanding together with the Hubble expansion. In this way, friction *adds* to the energy in the network of strings whose radius of curvature is larger than $\tau(t)$. String loops smaller than the friction horizon will go through under-damped oscillations and gradually dissipate their energy. Infinite strings will smooth out on the damping length scale $\sim t_d$. For $t > t_d$, frictional damping becomes unimportant compared to Hubble damping and can be ignored. (The evolution of long strings with friction has been considered in [13].) In the undamped regime, it is generally believed that strings evolve into a network that has "universal" scaling properties and there is minimal radiation into massive modes. We will also proceed under this assumption. (See, however, Ref. [14].)

At $t = t_d$ we expect only strings whose curvature is comparable to the horizon scale. These can be in the shape of loops that are larger than the horizon or infinite strings that are straight on the horizon scale. Let us define $N_s = L_d/t_d$ where L_d is the total length of string within the horizon at $t = t_d$. Simulations of the string network suggest $N_s \sim 10$ at late times and in the absence of friction. With friction, however, this number may be different since friction causes additional stretching on scales larger than the friction horizon, and the strings move more slowly on smaller scales. By the end of the friction dominated epoch, strings on the friction horizon scale, which coincides with the causal horizon scale at $t = t_d$, would be stretched by a factor $a(t_d)/a(t_f) \sim 10^3$. Hence L_d can be larger by this factor and we can place the upper bound $N_s < 10^4$.

At $t \sim 1$ s, the smallest loop surviving the friction dominated epoch has size $t_d \sim 10^{10}$ cm. Radiation is insignificant for such loops. Therefore all (non-self-intersecting) loops from $t \sim 1$ s will survive until the present epoch. In the meantime, the loops will come to rest in the fluid frame because Hubble expansion will damp out any peculiar velocities that the loops may have had initially. This means that loops will participate in structure formation, just like any other dark matter candidate. They will accrete into galaxies and get embedded into stars and other astronomical bodies.

The ratio of loop number density to baryon number density at t_d is $n_l(t_d)/n_b(t_d) \sim 10^{-54} N_s$ where we have taken the loop density to be $\sim N_s/t_d^3$. Since the loop number density scales like dust, the number of loops in the Milky Way ($\sim 10^{12}$ solar masses or 10^{45} gms) is the number of protons in the Milky Way (10^{69}) times $10^{-54} N_s$. From here we estimate that gravitational accretion provides the Milky Way with $\sim 10^{15} N_s$ loops of size $\sim 10^{10}$ cm and mass ~ 1 gm.

Now we turn to observational signatures of dark strings. The scenario is somewhat different from that of superconducting strings [15] because those strings are frozen into the galactic plasma and get dragged and stretched due to fluid flow. This leads to a much higher density of superconducting strings in turbulent regions, such as in the galaxy. On the other hand, the plasma forces on dark strings are not strong enough to stretch them. This leads to a lower density of dark strings, and makes them harder to detect. We now discuss a few scenarios for dark strings within our galaxy.

(i) From Eq. (7) we find that the damping time in the galaxy (density 10^{-24} gms/cm^3) is 10^{24} s, i.e. longer than the age of the Universe. However, random perturbations due to density inhomogeneities in the Milky Way may cause loops to fragment into many smaller loops which are small enough to be insensitive to the medium. These loops then survive, occasionally collapsing to give off a burst of e^+e^-. A loop would be very hard to detect unless there is a close encounter. Loops that enter the Earth's atmosphere (density 10^{-3} gms/cm^3) have a dissipation time 10^3 s and propagate right through the atmosphere within this time if they are moving with velocities typical in the galaxy, $v \sim 10^{-3} = 10^2$ km/s. On arriving at the Earth's surface (ocean/ground/ice), the loop encounters a larger density ~ 1 gm/cm^3 and the dissipation time is correspondingly smaller ~ 1 s. In this time, a loop will propagate ~ 100 km and dissipate its energy. The average energy deposited in the track through the Earth's surface is the loop energy divided by the path length, i.e. $\sim 10^{-4}$ ergs/cm $\sim 10^{-2}$ eV/cm for a loop of length 10^{-8} cm. Along the way, the loop can also (partially) collapse and produce ~ 1 GeV positrons that would then annihilate to give gamma rays in the ocean or ice.

To calculate the flux of loops in this scenario, we assume that the number density of loops increases with decreasing length until $l \sim l_\gamma$, below which the number density decreases because the loops are evaporating. Hence loops with $l \sim l_\gamma$ are the most numerous and may be expected to contain a significant fraction of the total string length in the galaxy. A simple estimate of the number density of loops is therefore obtained by considering all the $10^{25} N_s$ cm of available string length to be in loops of $\sim 10^{-8}$ cm. Taking the loop velocity to be $\sim 10^{-3}$, this implies a galactic loop number density $\sim 10^{-33} N_s$ cm^{-3} and a flux $\sim 10^{-9} N_s$ km^{-2} yr^{-1}, which is too small to be of experimental interest even if $N_s \sim 10^4$.

(ii) The second possibility is that when loops enter dense regions of the galaxy, density perturbations cause them to collapse and annihilate. One situation in which a loop collapses is known: if any loop starts at rest and obeys the Nambu-Goto equations, then it must collapse into a double line at one instant [16]. So if some part of a loop enters a dense region and slows down due to damping, a (partial) collapse seems likely. Loop annihilation will produce dark sector bosons that will eventually decay into e^+e^-. Assuming that the e^+e^- are produced with energy ~ 1 GeV (i.e. 10^{-24} gms), a 1 gm loop injects on order 10^{24} e^+e^-. For loops of size ~ 1 s, the burst lasts for ~ 1 s, with an energy output $\sim 10^{21}$ ergs. Once injected into the galactic medium, the e^+e^- evolution is as for secondary e^+e^- production by cosmic rays.

Even if the energy output of any individual loop collapse in the galaxy is too small to be of any consequence, the cumulative effect of all loops gives rise to a population of positrons. The maximum number density of positrons produced in this way is estimated by converting the total energy in loops in the galaxy, $\sim 10^{15} N_s$ gms, in terms of ~ 1 GeV positrons. Therefore there are $10^{39} N_s$ positrons and the average number density is $10^{-27} N_s$ cm^{-3} where we have taken the volume of the galaxy to be $\sim(10 \text{ kpc})^3$. This number density corresponds to a flux $\sim 10^{-17} N_s$ cm^{-2} s^{-1} and is tiny compared to the observed flux (though at 10 GeV), which is $\sim 10^{-5}$ cm^{-2} s^{-1} GeV^{-1} [2].

We could also consider intergalactic loops that enter the Milky Way—just like cosmic rays hit the Earth's atmosphere. If the structures in the Milky Way, or the dark matter in its halo, cause the entering loop to collapse, they would produce a burst of e^+e^-, and subsequently synchrotron radiation and gamma rays. This may result in excess synchrotron radiation from the outskirts of the Milky Way and correlated gamma ray emission.

(iii) The third possibility is that loop dynamics remains largely unaffected in the galactic medium and loops simply reside and oscillate in the galaxy. This possibility implies that there is a population of loops in our Milky Way, but it is not clear how one might observe them. The only hope is if loops develop cusps—points on the string that reach the speed of light—that beam large amounts of electromagnetic radiation via the AB interaction. This may be similar to radio transients ("sparks") from superconducting strings [17]. Cusp annihilation would also produce a beam of energetic e^+e^- that might be observable, similar to the discussion in Ref. [18] but adapted for GeV scale strings within our galaxy.

In the string evolution scenario of Refs. [14], the string network maintains scaling by releasing all its energy directly to particles. In our case, this would imply that the string network loses energy by directly emitting dark sector particles that eventually convert to e^+e^-, and little radiation in electromagnetic and gravitational radiation. The e^+e^- inject energy into the cosmological medium and one might hope for an observational signature on this account. At the epoch of recombination, the e^+e^- may cause enhanced reionization and this would affect the propagation of cosmic microwave background photons [19]. If we evolve the loops at $t = t_d$ like pressureless matter, the energy density in GeV scale cosmic strings at recombination is only $10^{-30}N_s$ of the baryon energy density. Even if all the string energy gets converted to ionizing radiation, this amounts to $\sim 10^{-20}N_s$ eV per atom in the cosmological medium. Hence enough energy is injected to reionize 1 in $10^{21}N_s^{-1}$ atoms and this is miniscule compared to say the number density of e^- due to residual ionization at recombination (10^{-5}).

The above discussion shows that dark strings would be very hard to detect even if they are present in our galaxy, primarily because the length density is expected to be very small based on our current understanding of the string network. There is one situation where there may be a better chance of a detectable signature. This is if dark strings are also superconducting. Then the string density increases as the strings are stretched due to turbulence in the galaxy. Such a scenario has been discussed in Ref. [15].

Let us now discuss nonminimal models of the type in Eq. (1). More generally the dark sector has a symmetry group, $G_{\rm dark}$, that is completely broken at low energy scales. We have considered the case $G_{\rm dark} = U(1)$ so far but $G_{\rm dark}$ could be larger. In this case, the dark gauge field in $L_{\rm int}$, a_μ, is one of a gauge multiplet and has to be selected, e.g. $\Phi^a a_\mu^a$ where the index a is the group index and the adjoint field Φ^a gets a vacuum expectation value (VEV). However, the VEV of an adjoint scalar field leads to an unbroken $U(1)$ and hence "dark magnetic monopoles." When the surviving $U(1)$ is broken at the GeV scale, the $U(1)$ magnetic flux is confined and the monopoles get connected by strings. The string segments, with monopoles at either end, annihilate to produce e^+e^- with energy at the scale of the monopoles, i.e. VEV of Φ^a which, for concreteness, we take to be the TeV scale. Eventually the annihilation of positrons gives TeV gamma rays. If these gamma rays are produced relatively late (close to recombination), they may not thermalize and would be constrained by the observed gamma ray background, as discussed in [20].

In addition to the string segments that connect monopoles, closed loops of strings will also be produced and the length distribution of loops depends on the number density of monopoles that are present during string formation. In particular, if the monopoles have been inflated away, the string distribution is identical to the $U(1)$ case and the closed loops of strings will follow the evolution discussed above in the context of the $U(1)$ model. On the other hand, if the monopoles are relatively dense during string formation, very few loops are formed and the segments connect nearby monopoles and are short. (Strings can break by nucleating monopole-antimonopole pairs, but this process is suppressed by the factor $\exp(-\pi m^2/\mu)$ [21] and can be neglected for modest separation of monopole and string energy scales.)

If GeV scale dark strings exist, it may also be possible to create them in the laboratory via the AB interaction by scattering electrically charged particles. A 10^{-11} cm loop has ~ 1 TeV energy, well within the energy range of existing colliders. However, studies of kink creation in $1 + 1$ dimension [22] suggest that *low* energy scattering of a large number of electrically charged particles, such as atomic nuclei, may be more suitable for creating solitons than two particle scatterings.

Finally, even if the observed positron signatures have an astrophysical origin, our discussion applies quite generally to models where there is a separate dark sector of the kind given in Eq. (1). Dark strings may provide a novel window to this class of models.

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