511 keV Photons from Superconducting Cosmic Strings

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We show that a tangle of light superconducting strings in the Milky Way could be the source of the observed 511 keV emission from electron-positron annihilation in the Galactic bulge. The scenario predicts a flux that is in agreement with observations if the strings are at the ∼ 1 TeV scale making the particle physics within reach of planned accelerator experiments. The emission is directly proportional to the galactic magnetic field and future observations should be able to differentiate the superconducting string scenario from other proposals.

The detection of a bright 511 keV line by the SPI spectrometer on the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite, has established the presence of a diffuse source of positrons in the Galactic Center (GC) [1]. The observed photon flux of

\[9.9^{+4.7}_{-2.1} \times 10^{-4} \text{ cm}^{-2}\text{s}^{-1}\]

with a linewidth of about 3 keV is in good agreement with previous measurements [2]. The observations suggest a spherical symmetric distribution. Assuming a Gaussian spatial distribution for the flux, a full width at half maximum of 9° is indicated.

The origin of these Galactic positrons remains a mystery. Several scenarios involving astrophysical sources have been proposed, including neutron stars or black holes, massive stars, supernovae, hypernovae, gamma-ray bursts or cosmic rays [3]. However, the fraction of positrons produced in such processes is uncertain, and it is unclear that the positrons could fill the whole bulge.

Alternatively, mechanisms associated with the Dark Matter (DM) at the GC have been put forward. If DM is constituted by a light (1-100 MeV) scalar, its annihilations could account for the observed signal [4]. Another possibility is that DM could be in the form of non-hadronic color superconducting droplets. Positrons on the surface of the droplet could annihilate with ambient electrons producing a gamma-ray line [5].

In this Letter, we show that a network of light superconducting strings [6] occurring in particle physics just beyond the standard model could also be a source of positrons. More detailed observations of the positron distribution could be used to distinguish this source from the other possibilities. Moreover, this resolution of the positron observation works with strings at an energy scale of ∼ 1 TeV, since the flux from heavier strings is lower. Therefore, experiments at the Large Hadron Collider in the near future will also probe particle physics relevant for this explanation of the positrons.

We assume that a tangle of light superconducting strings exists in the Milky Way. The strings are frozen in the Milky Way plasma as long as the radius of curvature is larger than a certain critical length scale. If the curvature radius is smaller, the string tension wins over the plasma forces and the string moves with respect to the magnetized plasma. During the string motion, the loop will cut across the Milky Way magnetic field, generating current as given by Faraday’s law of induction. The current is composed of zero modes of charged particles, including positrons, propagating along the string. Once the energy of a positron on the string exceeds the rest energy of 511 keV, it becomes possible for it to leave the string primarily due to scattering by counter-propagating particles. Even though the scattering rates are model dependent, general arguments discussed below [7] indicate that the scattering of positrons with counter-propagating light quarks will be very efficient at ejecting the positrons at the threshold of 511 keV. The ejected positrons will annihilate with the ambient electrons, thus emitting 511 keV gamma rays.

The string dynamics is determined by comparing the force due to string tension to the plasma drag force. The force per unit length due to string tension μ is

\[F_s \sim \frac{\mu}{R},\]

where R is the string radius of curvature. The drag force is more complicated, needing an analysis of the plasma flow around a current carrying string [8,9]. The string effectively behaves like a cylindrical body around which the plasma flows. The radius of the cylinder, in natural units, is \[r_s = J/(v_{rel}\sqrt{\rho}),\] J being the current on the string, \[v_{rel}\] the velocity of the string relative to the plasma, and \[\rho\] the plasma density. The drag force on such a cylinder is

\[F_d \sim \rho v_{rel}^2 r_s \sim \sqrt{\rho} v_{rel} J.\]

The maximum value of the damping force occurs when \[v_{rel} = 1\]. Therefore, \[F_{d,\text{max}} \sim \sqrt{\rho} J\]. If \[F_s \gg F_{d,\text{max}}\], the string moves under its own tension and the damping force is insufficient to prevent the string from accelerating to relativistic velocities. String loops will then emit electromagnetic radiation and eventually dissipate. If, however, \[F_s < F_{d,\text{max}}\], the string will accelerate until the damping force grows so as to cancel the tension. Then the string moves at a terminal velocity relative to the plasma found...
by equating $F_s$ and $F_d$:

$$v_{\text{term}} \sim \frac{\mu}{\sqrt{\rho J R}}.$$  

(4)

Setting $v_{\text{term}} = 1$, we find the critical radius of curvature $R_c$ when the strings move relativistically:

$$R_c \sim \frac{\mu}{\sqrt{\rho J}}.$$  

(5)

To summarize, strings with tension $\mu$, current $J$, and curvature radius $R > R_c$, move at $v_{\text{term}}$ with respect to a plasma of density $\rho$. If $R < R_c$, the string moves at relativistic speeds.

In a turbulent plasma, such as in our Milky Way, there is another length scale of interest, called $R_\ast$, even when the string motion is overdamped. For $R > R_\ast$, the terminal speed of the strings is small compared to the turbulence speed of the plasma and the strings are carried along with the plasma. As the strings follow the plasma flow, they get more entangled due to turbulent eddies, and the strings get more curved until the curvature radius drops below $R_c$. Then the string velocity is large compared to the plasma velocity, and, hence, the strings break away from the turbulent flow. Therefore, $R_\ast$ is the smallest scale at which the string network follows the plasma flow. For $R_\ast > R > R_c$, the string motion is over-damped but independent of the turbulent flow. Hence, string curvature on these scales is not generated by the turbulence, and we can estimate the length of string network by

$$l \sim \frac{\mu}{\rho v_e \kappa},$$  

where, for convenience, the dimensionless parameter $\kappa$ has been introduced via $J \equiv \kappa e^2 / \mu$.

To determine $v_\ast$, we note that, on scales less than $l \sim 100 \text{pc} = 3 \times 10^{20} \text{cm}$, the interstellar plasma has velocity spectrum given by magnetohydrodynamic turbulence as $v_R \sim v_\eta (R/l)^{1/4}$, where $v_\eta \sim 10^6 \text{ cm/s}$. Inserting this expression in Eq. (6) and solving for $R_\ast$ gives

$$R_\ast \sim l \left( \frac{\mu}{\rho v_e \kappa v_\eta l} \right)^{4/5}, \quad v_\ast \sim v_\eta \left( \frac{\mu}{\rho v_e \kappa v_\eta l} \right)^{1/5}.$$  

(7)

Note that in these estimates we have assumed $R_\ast < l$; otherwise, the turbulent scaling law will be different.

The current on the string is generated by the motion of the string across the galactic magnetic field as described by Faraday’s law of induction and is limited by the microscopic interactions of the charge carriers on the string. A given charge carrier can, in principle, leave the string once it has enough energy. The escape is triggered by several factors, of which the most important is scattering off counter-propagating zero modes (bosons or fermions). The current in any particular species saturates once the scattering rate equals the growth rate due to Faraday induction. The rate of current growth for particle species (denoted $X$) with charge $e$ is given by $J_X \sim e^2 v_B$. The time scale for current growth, assuming $v \sim e$, is

$$\tau_X \sim \frac{J_X}{e^2 B}.$$  

(8)

The current decays because the charge carriers on the string can interact and leave the string. The positron current is limited mainly by scattering with counter-propagating quarks ($u$ quarks for electroweak strings). Since the lightest quarks have $\sim 1 \text{ MeV}$ mass, which is similar to the positron mass $m_e$, the decay time when the positron current is order $\tau_e = 1/n\sigma$, where $n \sim \langle J_e/c^2 \rangle m_e^2$ is the number density of positrons and $\sigma \sim \alpha^2/m_e^2$ is the electromagnetic scattering cross section, $\alpha$ being the fine structure constant. Therefore, $\tau_e \sim \kappa \alpha^{-2} J_e^{-1}$. Equating $\tau_e$ and the growth rate given by $\tau_{\text{growth}} \wedge$, we get $J_e \sim \sqrt{B} \sim 10^{-4} \text{ eV}$, with $B \sim 10^{-6} \text{ G}$ and $\kappa \sim 1$. Since this is much less than $m_e = 511 \text{ keV}$ and positrons cannot escape the string until they reach $511 \text{ keV}$ energy, the threshold for their escape is also $511 \text{ keV}$. Here we should note that the quark that scatters off the positron cannot completely escape from the string unless it gains $\sim 100 \text{ MeV}$ energy and hadronizes. However, at energies less than $100 \text{ MeV}$, the quark can still get kicked out from its zero mode state on the string to a quark that is not in a zero mode. Such a quark will be confined to a $(\Lambda_{\text{QCD}})^{-1} \sim (100 \text{ MeV})^{-1}$ shell around the string. Pion emission from the string cannot deplete the baryonic current on the string. Only at $\sim 1 \text{ GeV}$ energies can antiprotons be emitted, leading to another possible signature of galactic superconducting strings.

As a piece of string of length $R_c$ cuts through a magnetic field $B$, it will produce electrons or positrons, with equal likelihood, at the rate $dN/dt \sim e v_\ast B R_c$. In a volume $V = 4\pi L^3/3$, there are $\sim L^3 / R_c^2$ such pieces of string, and, hence, the rate of particle production in the entire volume is

$$\frac{dN_V}{dt} \sim e v_\ast B L^3 / R_c^2.$$  

(9)

The current in the positrons will grow at first but then saturate at $511 \text{ keV}$. After that, further motion of the string across the galactic magnetic field will generate positrons that leave the string. So $N_V$ is also the number of positrons being produced in the volume $V$ which we denote by $N_\ast$. Inserting Eq. (7) in (9) we get

$$\frac{dN_\ast}{dt} \sim e^{12/5} B \kappa^{7/5} \frac{L^3}{l^3} \left( \frac{\rho}{\mu} \right)^{7/10} (v_\eta l)^{12/5}.$$  

(10)

We are interested in a region of radius 1 kpc around the galactic center and so $L^3 \sim V_1(1 \text{ kpc})^3$, where $V_1$ is a di-
mensionless parameter. The plasma density in the galactic center is higher than the average Milky Way density. For an estimate, we adopt an isothermal Milky Way scaling normalized to $\rho_8 \sim 10^{-25}$ g/cm$^3$ at 8 kpc from the center, thus giving $\rho \sim 6 \times 10^{-24} \rho_{gc}$ g/cm$^3$, where we have introduced the parameter $\rho_{gc}$. The magnetic field in the galactic center is not known very precisely but is estimated to be $\sim 10^{-3}$ G. Therefore, we will set $B = B_3 10^{-3}$ G. (Note the conversion of magnetic field strength in Gauss to particle physics units: $1 \mathrm{G} = 1.95 \times 10^{-20} \mathrm{eV}^2/\mu_0$.) The parameters $v_1$ and $l$ will be different in the galactic center but these are not known. We will write $v_1 = 10^6 v_{1,6}$ cm/s and $l = 100 l_{100}$ pc. The string tension will be taken to be $\mu = \mu_1 (1 \mathrm{TeV})^2$, where $\mu_1$ is a parameter, and $c^2 \sim 0.1$, and then Eq. (10) gives us

$$\frac{dN_+}{dt} \sim 10^{42} \frac{B_3^{7/5}}{v_{1,6}^{7/10} \rho_{gc}^{7/10} l_{100}^{12/5} \mu_1^{-3/5}} \mathrm{s}^{-1}.$$  \hspace{1cm} (11)

Although the astrophysical parameters describing the galactic center are not known very accurately, assuming equipartition of plasma kinetic energy ($\sim \rho v^2$) and magnetic energy ($\sim B^2/8\pi$), with $l \sim \rho^{-1/3}$, we find that $v_{1,6} \sim 100$ and $l_{100} \sim 0.1$, which boosts the estimate in Eq. (11) by $10^5$, yielding

$$\frac{dN_+}{dt} \lesssim 10^{47} \mathrm{s}^{-1}.$$  \hspace{1cm} (12)

From Eq. (7), the string velocity with respect to the plasma is $v_\ast \sim 10^{-5} c$. Hence, the positrons will leave the string with a small Lorentz factor, $\gamma \sim 1$, and they will gradually slow down by Coulomb collisions in the interstellar medium (ISM). The energy loss rate is approximately

$$\frac{dE}{dt} \sim 2 \times 10^{-9} (N_H/10^{6} \mathrm{m}^{-3}) (\log \gamma + 6.6) \mathrm{eV}/\mathrm{s},$$

where $N_H$ is the number density of target atoms. This rate yields a stopping distance of $10^{24}$ cm. Considering a simple random walk, with the Larmor radius on the order of $10^4$ cm, the positrons travel a distance $\sim 10^{12}$ cm, so they are easily confined to the galactic center. Note that this distance is less than the typical string separation estimated from Eq. (7), $R_s \sim 5 \times 10^{13}$ cm, so the positrons will have linelike features on angular scales $\sim 10^{-7}$, which is too small to be resolved with the $2^\circ$ angular precision of INTEGRAL. Once produced, the positrons will undergo different processes in the ISM. Pair annihilation with an ambient electron and positronium (Ps) formation and decay via para-Ps will occur both in-flight and after thermalization. The resulting spectrum depends on the specific details of the ISM, but detailed analysis shows that a narrow 511 keV line generically results, $\Delta E \sim 3$ keV, in agreement with observations. Hence, the spectral shape does not depend on the details of the strings, and in this respect the model cannot be distinguished from alternative mechanisms such as light DM or astrophysical sources.

Three-quarters of ortho-Ps annihilate in a 3 photon continuum final state. As a result, each positron will contribute $2 - 3 f_{Ps}/2)^{-1}$ 511 keV photons, where the Ps fraction has been measured to be $f_{Ps} = 0.93 \pm 0.04$ for the galactic center. Multiplying the observed gamma-ray flux given in Eq. (1) by the area of the sphere at our location (8 kpc) around the galactic center, we get the actual positron production rate in the galactic center:

$$\frac{dN_{\gamma, 511}}{dt} \sim \frac{1}{2 - 3 f_{Ps}/2} \frac{4\pi (8 \mathrm{kpc})^2}{\mathrm{cm}^2 \mathrm{s}} \sim 1.2 \times 10^{43} \mathrm{s}^{-1}.$$  \hspace{1cm} (13)

Comparing Eqs. (12) and (13), we conclude that light superconducting strings are possible sources of positrons that lead to the flux of 511 keV gamma rays observed by the INTEGRAL collaboration.

We see from Eq. (11) that a unique prediction of our scenario is that the gamma-ray flux is proportional to the magnetic field strength in the Milky Way, with a milder dependence on the plasma density. In the disk, the magnetic field intensity decreases by $B_3 \sim 10^{-3}$. At the same time, looking towards the disk, the volume of the Milky Way that contributes positrons is larger. Taking these factors into account, for a disk with thickness 1 kpc and a radial extent of 30 kpc, we estimate a photon flux $\sim 10^{-6} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ in a 16$^\circ$ field of view as seen in SPI. In a direction perpendicular to the disk, the volume contributing to the flux will be smaller, adding to the suppression of the magnetic field to yield a flux of $\sim 10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. Thus far, there have been no reliable detections outside of the central region of our Galaxy, with SPI placing an upper bound of $2 \times 10^{-4} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 511 keV, somewhat above what is needed to map the emission from the disk in our scenario.

That the flux should follow the magnetic field is in marked contrast with the MeV DM hypothesis. There the flux follows $\rho_{DM}^2$, and a signal from nearby DM dominated regions, e.g., the Sagittarius dSph galaxy, is expected. No magnetic fields have been measured in Sagittarius, although low surface brightness galaxies, which are somewhat similar, show $\mu G$ scale magnetic fields. Therefore, if superconducting strings source the observed 511 keV, the estimate would be weaker by $10^{-3}$ than that of Eq. (11) due to the weaker magnetic field, and another factor $\sim 10^{-1}$ due to the source being 3 times further away. The volume of Sagittarius dSph is comparable to the Milky Way bulge, leading to, at most, a flux of $\sim 10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ in the direction of Sagittarius, some three orders of magnitude fainter than the MeV DM model prediction. After two Galactic Center Deep Exposures, INTEGRAL has not detected emission from Sagittarius, although the effective observation time is not yet sufficient to reach the sensitivity of the MeV DM predicted fluxes. For the color superconducting DM scenario, the flux follows $\rho_{\text{visible}}/\rho_{DM}$, which is also different from our proposed scenario.
Present-day galactic magnetic fields could have been produced by amplification of a tiny primordial field by a galactic dynamo. In that case, currents could build up in the network of superconducting strings at earlier epochs. Since there is no turbulence at last scattering, a tangle of strings will not be formed; there is only ∼ 1 string per horizon which would simply be dragged by the plasma. During recombination, the plasma density drops, and the damping force on strings is vastly reduced. String tension causes strings to move at relativistic speeds cutting across magnetic fields and generating a flux of positrons, which will once again annihilate with ambient electrons to produce 511 keV gamma rays. By the present epoch, the gamma rays would have redshifted to 511 eV lines. One string per horizon gives a positron flux of ∼ 10−17 cm−2 s−1sr−1, much smaller than the upper limit on the diffuse extragalactic component by the Chandra experiment [12] of 10−3 s−1 cm−2 sr−1 at 511 eV, assuming a redshifted width of 3 eV.

Recently, the High-Energy Antimatter Telescope (HEAT) balloon experiment has confirmed an excess of high-energy positrons in cosmic rays at energies around 10 GeV [22]. Direct production of 10 GeV positrons from superconducting strings does not seem likely, because it is hard for the positron current to build up beyond 1 MeV in the presence of counterpropagating zero modes. However, superconducting strings at the TeV scale could still produce heavy charged fermions, if such zero modes exist, which could then decay to give positrons in the 10 GeV energy range. The production rate of heavy fermions can be computed from Eq. 11 to be ∼ 10−23 cm−3 s−1. Although the actual positron yield depends on the branching ratio in the particle physics model and the details of the diffusion process, comparing this value to the typical values of ∼ 10−27 cm−3 s−1 for positrons from annihilations of dark matter particles at the electroweak scale shows that this possibility deserves further investigation.

We conclude that light superconducting strings could produce enough positrons in the galactic center to explain the flux of 511 keV gamma rays observed by the INTEGRAL collaboration. The scenario can be differentiated from other proposals by higher resolution observations and by observations in directions away from the galactic center. Light superconducting strings might also produce stellar and cosmological signatures. Since the strings may be at the 1 TeV energy scale, the involved particle physics is within the energy range of planned accelerator experiments.

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