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The galactic 511 keV line and the intergalactic positron density

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Abstract

10^{43} positrons per second annihilate in a compact spherical region around the centre of the Milky Way. At present, known astrophysical sources cannot account for this signal. In Ref. [1] we propose a novel scenario in which extragalactic positron sources such as radio jets of active galactic nuclei (AGN) fill the intergalactic medium (IGM) with MeV-scale e^+e^- pairs, which are then accreted into galaxies like the Milky Way. Interpreting the diffuse cosmic radio background (CRB) as arising from synchrotron radiation by such sources suggests that the intergalactic positron-to-electron ratio may be as high as 10^{-6}. Assuming a simple spherical accretion model, this could account for the 511 keV emission of the galaxy.

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1. Introduction

First observed in balloon experiments over 40 years ago, the 511 keV gamma-ray line characterized most recently by INTEGRAL/SPI [2, 3] provides overwhelming evidence of the annihilation of 2×10^{43} electron-positron pairs per second in a spherical region of a few hundred pc around the galactic centre, and to a lesser extent in the galactic disk. If a steady state is assumed, this implies the creation and subsequent destruction of 3 solar masses of positrons over the history of the Galaxy.

Although positrons are copiously produced in astrophysics, constraints from the spectrum, intensity and morphology of the INTEGRAL signal severely limit candidate sources. The single most important constraint is the large bulge-to-disk (B/D) ratio of luminosities, which must be greater than ~ 1.4 [2], and is uncorrelated with any known astrophysical source distribution.

Massive stars, novae and supernovae produce unstable ^{26}Al, ^{44}Ti, ^{56}Ni, which emit positrons via β^+ decay. Indeed, INTEGRAL/SPI has mapped the distribution of ^{26}Al in the Milky Way via the 1809 keV gamma-ray line that is also emitted during the decay process [4]. While the intensity implies a large enough

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β^+ component to account for around half of the 511 keV signal [2], the spatial distributableion is almost entirely in the disk. Positron production rates from other elements are not as well-determined, but the source distribution also severely constrains their contribution to the INTEGRAL signal. High-energy processes such as proton-proton collisions in the interstellar medium, as well as γ–γ pair-creation in low-mass X-ray binaries, microquasars, pulsars, or even the black hole at the galactic centre, can also generate astrophysical positrons. However, these typically occur at higher-energies, which would lead to a distortion of the line shape in the observed INTEGRAL spectrum [5]. Exotic scenarios, such as the leptophillic annihilation of galactic halo dark matter (*e.g.* [6, 7]) have also been invoked to explain such a signal. These scenarios are reviewed in detail in Ref. [8].

In this work [1] we turn our attention to a novel possibility: that the positrons that we observe in the central part of the galaxy originate outside of the Milky Way. This naturally leads to the question of the density of positrons in the intergalactic medium, which has not been directly addressed in the literature. We begin by using the cosmic radio background to estimate an upper limit to this density, which should have its origins in high-energy synchrotron-emitting processes. We follow this with a description of the required accretion method to produce a signal like the one seen by INTEGRAL/SPI.

2. The intergalactic positron fraction

The radio-emitting regions of high-energy jets of active galactic nuclei are dominated by electron-positron pairs [9]. If we take the density of positrons in the intergalactic medium (IGM) to be produced in such high-energy synchrotron-emitting processes, we may use the cosmic radio background (CRB) radiation as a conservative upper bound on this component. The CRB consists of an excess of power between 0.01 and 90 GHz above the cosmic microwave background and was most-recently characterized by the ARCADE-2 collaboration [10]. It can be parametrized as:

$$T_{\rm radio} = (1.26 \pm 0.09{\rm K}) \left(\frac{\nu}{\rm GHz}\right)^{-2.6\pm0.04}. \quad (1)$$

This power law can be obtained by synchrotron emission [11, 12] from a population of electrons and positrons with a power-law distribution of energies $E = \gamma m_e c^2$,

$$n_p(\gamma)\, d\gamma \propto \gamma^{-p}\, d\gamma, \quad (2)$$

with an index $p = 2.2$, although extrapolations from luminosity functions of known synchrotron-emitting sources account only for about one sixth of the observed background intensity [11]. The tight errors of the estimated Galactic emission [13] at these frequencies, 5 (0.4) mK at 3.3 (10) GHz, imply an extragalactic source to explain the CRB.

The brightness temperature in equation (1) corresponds to an energy density per unit frequency, u_ν, of

$$\begin{aligned} \nu\, u_\nu &= \frac{8\pi\nu^3 k_B}{c^3} T_{\rm radio} \\ &= (1.0 \pm 0.1) \times 10^{-7} \left(\frac{\nu}{1\,{\rm GHz}}\right)^{0.4} {\rm eV\ cm^{-3}}. \quad (3) \end{aligned}$$

If these photons were produced in a region with approximately constant magnetic field B, associated with a Larmor frequency $\omega_B = eB/(m_e c)$, this quantity can be used to infer the number density $n_{\rm pairs}$ of electron-positron pairs required to produce the CRB signal [1]:

$$n_{\rm pairs} = \frac{\nu u_\nu}{m_e c^2} \left(\frac{A\omega_B}{\nu}\right)^{\frac{3-p}{2}} \frac{9c\,(1+z_r)^{\frac{p-1}{2}}}{4(p-1) r_e \omega_B^2 t_e \gamma_{\rm min}^{p-1}} \Gamma^{\frac{p-1}{2}}. \quad (4)$$

Here, z_r is the redshift at which the signal is produced, t_e, associated with the source lifetime, is the typical time over which an $e^\pm$ radiates, r_e is the classical electron radius and the constant A is obtained by integrating over the synchrotron emission frequencies, angles and modes [14], and depends only on the $e^{\pm}$ energy spectrum; for $p = 2.2$, $A = 0.84$. $\gamma_{\rm min}$ is the minimum Lorentz factor in the distribution of pairs (2), which is near one in the rest frame of the source quantified by Γ, the bulk Lorentz factor of the source, which is important if the source is an AGN jet.

Since we are interested in the number of positrons that finally escape into the IGM, (4) must be multiplied by a factor f_I, which quantifies the fraction of e^+ that can actually escape.

We use typical values for the lobes of radio-loud AGN of $B \sim 10\,\mu$G, $z_r = 1$, and $t_e \sim 10^{7.5}$ yr (assuming that radio lobes expand at the typical intracluster sound speed). We divide by the mean electron density in the universe at present, $\bar{n}_e = 2.3 \times 10^{-7}\,\mathrm{cm}^{-3}$ [15], yielding the IGM positron-to-electron ratio:

$$n_{e^+}/\bar{n}_{e^-} = 7.5 \times 10^{-6} \left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-1.6} \frac{10^{7.5}\,\mathrm{yr}}{t_e} \frac{f_I}{\gamma_{min}^{1.2}} \Gamma^{\frac{p-1}{2}} \,. \tag{5}$$

Thus, for typical parameters of a radio lobe, $n_{e^+}/\bar{n}_{e^-} \simeq 10^{-5} f_I$. We find that the typical value of the magnetic field in the core region of AGN jets, as estimated from a sample of resolved sources [16] showing the characteristic spectrum of synchrotron radiation and self-absorption [17], is $B \sim 3$ mG in the rest-frame. These same sources also have a typical bulk Lorentz factor of $\Gamma \sim 3.4$, and a light-crossing time of the core region of $t_{lc} \sim 25$ years, implying a core crossing time in the rest-frame $t_e \sim t_{lc}/\Gamma \sim 7$ years. In this case, the positron-to-electron ratio would be even higher than in radio lobes. Note that many radio jets may be produced in isolated galaxies without a massive intracluster medium surrounding them, so the relativistic jet may be directly expelled to the IGM without producing observable radio lobes.

3. Galactic accretion and the 511 keV signal

These extragalactic positrons have an energy of order $\sim$ MeV and above as they reach the Milky Way today. At such energies, losses due to scattering with the CMB and the IGM particles are negligible (see *e.g.* [18]). A proper description of their behaviour as they are accreted into the galaxy along with other extragalactic material is a complicated problem, and a complete picture is far from being understood in detail.

For the Milky Way, we expect a gas accretion rate of $\sim 1\,M_{\odot}\,\mathrm{yr}^{-1}$ [19], and reproducing the total INTEGRAL 511 keV bulge luminosity implying an annihilation rate of $2 \times 10^{43}\,\mathrm{s}^{-1}$ therefore requires $N_p/\bar{n}_e \sim 10^{-6}$, which is safely below our estimated maximum and can be matched by assuming $f_I \sim 0.1$.

A positron with an initial energy $E_{\rm IGM}$ before infall will annihilate when it reaches a region of high enough density for it to efficiently thermalize; this location depends on the matter distribution and the energy $E_{\rm IGM}$. Notice that the energy of the accreted positrons is peaked at 1 MeV, consistent with bounds from the observed diffuse Galactic gamma-ray data [20].

If infalling positrons are free, they will essentially annihilate uniformly throughout the galactic disk, since their propagation would be diffusive and relatively rapid. This can be seen from simple geometry, and is confirmed by detailed propagation calculation using *e.g.* GALPROP [21, 22], with a wide range of parametrizations for the propagation of sub-GeV cosmic rays.

We instead focus on a more promising scenario: if the relic positrons are accreted in bound electromagnetic structure, as they are likely to escape a high-powered jet or cocoon, their infall bulk velocity can be slow enough that their trajectory is dominated by the spherically-symmetric dark matter gravitational potential of the Milky Way.

Since the scattering rate is typically much larger than the in-flight annihilation rate, positrons propagating through a medium first slow and thermalize before annihilating [23]. In this case, energy loss occurs mainly via scattering with gas in the interstellar medium. In practice, the gas distribution can be modelled by compiling the results of several observation studies described in detail in Ref. [24, 22]. The height-dependence of the HI and H_2 densities is Gaussian, with scale heights of 250 pc and 70 pc, respectively. The HI density on the galactic plane at our location is ~ 1 atom cm^{-3}, whereas H_2 is in a molecular ring with a galactocentric radius of $R = 5$ kpc, with a peak density on the plane of ~ 2.5 atom cm^{-3}. The HII distribution has two components, a central exponential disk with a scale height of 1 kpc and central density of 0.025 atom cm^{-3}, and an annulus around $R = 2$ kpc representing HII regions, with a scale height of 150 pc and peak density of 0.2 atom cm^{-3}. The calculation of energy loss is stopped when positrons reach energies below 100 eV, at which point thermalization and annihilation should quickly follow.

The flux of 511 keV photons can then be found from the line-of-sight (l.o.s.) integral over the annihilation rate per unit volume $dN_{e^+}/dVdt$:

$$d\Phi_{511} = 2\left(1 - \frac{3}{4} f_{\rm Ps}\right) \frac{d\Omega}{4\pi} \int_{\rm l.o.s.} \frac{dN_{e^+}}{dVdt}(x) dx, \qquad (6)$$

where $f_{\rm Ps}$ is the fraction of positrons which form positronium rather than annihilating directly in flight. Positronium annihilates into two 511 keV photons only 1/4 of the time, when the singlet state is formed; otherwise an odd number of photons must be produced, in order to conserve angular momentum, leading to a continuum spectrum. From the continuum-to-line ratio seen in the INTEGRAL/SPI spectrum, one obtains $f_{\rm Ps} = 0.97$ [5].

By combining an infalling radial distribution of positrons, with a power law with index of −2.2, with the energy-loss rate described above, we compute the 511 keV morphology according to (6). Assuming a total matter accretion rate of one solar mass per year and a moderate escape fraction $f_I = 0.1$, we find that MeV-scale positrons can fall far enough into the galaxy to produce a sharply-peaked signal near the galactic centre, with sufficient intensity to reproduce the INTEGRAL signal.

We illustrate this in Figure 1. The red line shows the exact distribution in longitude and latitude of such a signal; the black line shows how this would be binned, and compared with the INTEGRAL signal (blue dots with error bars). The major component is clearly located in the galactic centre, leaving room for astrophysical sources in the disk region. The sharp features would be mostly erased in a more complete model, once angular momentum, magnetic fields and bulk gas effects are taken into account.

This result nonetheless constitutes a powerful proof of concept: an MeV-scale intergalactic positron density can in principle lead to the accretion and annihilation of enough antimatter in the Milky Way to provide a large enough 511 keV signal to explain the bulge component of the INTEGRAL observation.

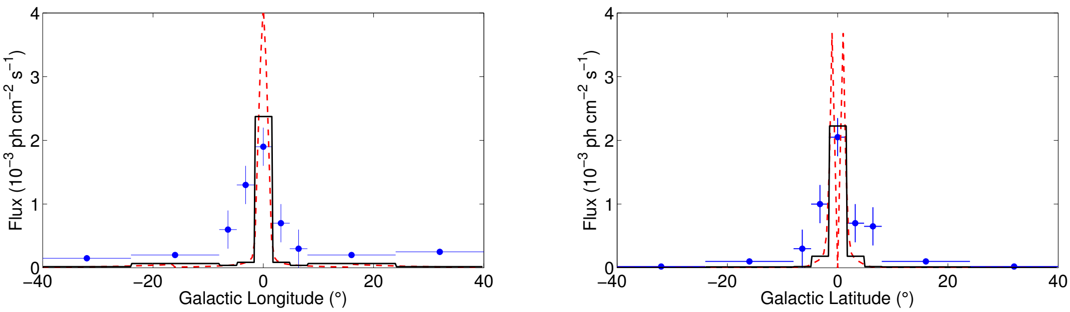

Fig. 1. *The binned INTEGRAL/SPI 511 keV data from [25], integrated over* |Latitude| < 8° (|Longitude|< 8°)*, is shown by the data points in blue in the left (right) panel. The outer four bins are* 16° *wide, and inner bins are* 3.2° *wide. Black solid line shows the predicted flux in the spherical infall model, binned in the same way. The red dashed line shows the shape of the predicted flux, with its area matching the normalization of the histogram.*

4. Discussion

This study has led to two main results: first, that the amplitude and spectrum of the cosmic radio background lead to an upper limit to the amount of MeV-scale positrons released from jet-like events into the intergalactic limit. Second, this quantity, combined with a simple model of accretion, is more than sufficient to provide an explanation of the large quantity of antimatter that is annihilating in the centre of the Milky Way galaxy, as seen most recently by the INTEGRAL spectrometer. A prediction of the exact line emission morphology will require more realistic modelling of IGM gas accretion and of the magnetic field structure in the Galactic halo.

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