Gamma ray bursts and the origin of galactic positrons

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A recent observation of the 511 keV electron-positron annihilation line from the Galactic bulge has prompted a debate on the origin of the galactic positrons responsible for this emission. We suggest that the positrons could be produced by past gamma ray bursts in our galaxy and estimate the fraction of energy per GRB that must be converted in e^+e^- pairs in order to reproduce the observed annihilation flux. Future observations can help distinguish our model from other scenarios, in particular from those that invoke decaying or annihilating dark matter particles.

PACS numbers: 98.70.Rz, 95.85.Nv, 98.35.Jk FERMILAB-Pub-04/060-A, UCLA/04/TEP/15

A recent observation of the 511 keV emission line from the galactic central region [1] has confirmed and improved the earlier data [2, 3, 4]. The emission is consistent with the e^+e^- annihilation line via positronium. However, the origin of the positrons remains unknown.

The flux reported by SPI camera aboard the INTEGRAL satellite [1] is consistent with previous measurements. In addition, the data provide some crucial information on the morphology of the annihilation region, suggesting an azimuthally symmetric Galactic bulge component with full width at half maximum ~ 9 degrees, and with a 2 σ uncertainty range covering 6–18 degrees. The 511 keV line flux in the bulge component amounts to $(9.9^{+4.7}_{-2.1})10^{-4}$ photons cm^{-2} s^{-1} [5]. The line can be explained as due to electron–positron annihilations that occur at the rate

$$\Gamma_{(e^+e^-\rightarrow\gamma\gamma)} \sim 10^{50}\,\mathrm{yr}^{-1}. \tag{1}$$

Several astrophysical scenarios have been proposed to explain this large population of positrons in the Galactic bulge. It has been suggested that the positrons might come from neutron stars, black holes, radioactive nuclei from past supernovae, novae, red giants or Wolf-Rayet stars, cosmic ray interactions with the interstellar medium, pulsars and stellar flares, mirror matter, *etc.* (See *e.g.* Ref. [6] and references therein). Some of these scenarios are problematic, while others have a wide range of uncertainties. For example, the predicted yields and distributions of positrons from radionuclei synthesized in supernovae are only marginally compatible with observations [7]. Supernovae produce positrons mainly from the decay $^{56}Ni \rightarrow^{56} Co \rightarrow^{56} Fe$, although the fraction of positrons that would escape the SN ejecta is poorly known. Different estimates suggest that typically 30 %–50% of galactic positrons may be explained by SNe Ia and massive stars (SNII/Ib and WR stars). If ^{56}Co positrons do not escape from the ejecta of SNe Ia, then the contribution of massive stars to the galactic positrons is subdominant (see Ref. [7] and references therein). In Ref. [6], a new class of SN, SN Ic, interpreted as the result of a bipolar Wolf-Rayet explosion, was proposed as a source of galactic positrons, from the decays of ^{56}Co. The supernovae of this class are short and bright and may be associated to GRBs [8], but their rate is unfortunately unknown. It was also suggested that the positrons may be produced from annihilations of relatively light dark matter particles, with mass in the 1–100 MeV range [9]. It is essential for this scenario that the dark matter particles are light. The usual dark matter candidates, with mass in the (0.1–1) TeV range, are expected to produce a large number of electrons and positrons through annihilations. However, they would also produce high-energy gamma rays. If one requires the electron-positron annihilations to occur at a high enough rate to explain the 511 keV emission, the associated flux of gamma rays would exceed the flux observed by EGRET in the direction of the Galactic Center by several orders of magnitude. However, if dark matter is made up of particles with masses below the muon mass, the annihilation produces only electron-positron pairs, or, perhaps, lower energy photons which evade this bound. Other proposed sources of positrons include the decay of exotic particles, such as axinos [10], sterile neutrinos [11], scalars with gravitational strength interactions [11], and mirror matter [12].

Here we suggest that a sufficiently large population of positrons could be due to gamma-ray bursts (GRB) which took place in our galaxy in the past (see, *e.g.*, Ref. [13] for review of GRB). This scenario is appealing for several reasons. First, GRB are known to exist. Second, jets in GRBs are expected to lose energy through pair production. Positron production in GRBs has been modeled and was suggested as a way to identify the location of a single recent GRB [14]. The positrons produced by a large number of past GRBs may have filled the bulge with a sufficient steady population of positrons to explain the observed 511 keV signal. A comparison of the Milky Way with other galaxies can help confirm or rule out this scenario. Our scenario is substantially different from that of Cassé *et al.* [6], in which the positrons come from heavy nuclei decay in the hypernova ejecta; here we consider direct e^+e^- production from photons in the GRB.

Some positrons escape into the intergalactic medium, where they lose energy, due to ionization, on the time scale [15]

$$\tau_{\rm ioniz} \sim 10^7 \frac{\gamma}{\log\gamma + 6.2}\left(\frac{N_H}{10^5{\rm m}^{-3}}\right)^{-1} {\rm yrs}, \qquad (2)$$

where N_H is the number density of atoms and γ is the initial gamma factor of the positrons. In the Galactic bulge, $N_H \sim 10^5{\rm m}^{-3}$ [15] and the resulting stopping time is $\tau_{\rm ioniz} \sim 10^8$yrs, for positrons with $\gamma \simeq 10^2$. This time scale is much longer than the typical interval between GRBs in our galaxy (see eq. (8) below); therefore, one can treat the injection as approximately continuous.

During the time $\tau_{\rm ioniz}$, positrons diffuse in the Galactic magnetic field. Unfortunately, little is known about the properties of the magnetic field in the bulge. One expects this field to have both regular and turbulent components [16]. There is compelling evidence of turbulence in the local Galactic magnetic field, where the largest scale of the turbulent component is $l_{\rm cell} \sim 50\,{\rm pc}$ [17]. If this turbulence is present in the bulge, then positrons with $\gamma \sim 10^2$ or less, have Larmor radii much smaller than the characteristic size of turbulence cells. In this regime, we can write the diffusion coefficient as (see e.g. Ref. [18] and references therein)

$$D(E) = 3\times 10^{26}\gamma^{\frac{1}{3}}\left(\frac{B}{1\mu{\rm G}}\right)^{-\frac{1}{3}}\left(\frac{l_{\rm cell}}{50{\rm pc}}\right)^{\frac{2}{3}} {\rm cm}^2{\rm s}^{-1}. \quad (3)$$

This is a phenomenological formula, which only applies when the turbulent component is comparable with, or smaller than, the regular component of the magnetic field. In the limit of strong turbulence numerical simulations suggest that $D(E) \propto E$. Monte-Carlo simulations and analytical approximations for diffusive propagation in different regimes have been studied in Ref.[19]. The product $D(E)\tau_{\rm ioniz}$ provides an estimate of the (square of the) distance traveled by the diffusing particle in the case where energy losses are negligible. The distance traveled by positrons before being stopped is

$$\begin{aligned} d &= \sqrt{2D(E)\tau_{\rm ioniz}} \qquad (4)\\ &\approx 50\,{\rm pc}\,\gamma^{\frac{2}{3}}\left(\frac{B}{1\mu{\rm G}}\right)^{-\frac{1}{6}}\left(\frac{l_{\rm cell}}{50{\rm pc}}\right)^{\frac{1}{3}}\left(\frac{N_H}{10^5{\rm m}^{-3}}\right)^{-\frac{1}{2}}. \end{aligned}$$

If the regular component is significant, it can help spread the positrons quickly over the entire bulge. Hence, eq. (4) gives a lower bound on the size of the positron cloud from a single GRB.

Gamma ray bursts produce photons with energies from about 100 keV to 1 MeV over a relatively short time scale, 1–100 seconds. Based on observations of the afterglows associated with long GRB, one concludes that the GRB have cosmological origin. This implies that the energy of each burst should be of the order of $10^{52} - 10^{53}$ ergs, assuming isotropy. A more realistic estimate of energy, for an anisotropic GRB with an opening angle Ω yields $E \sim 10^{52}\,(\Omega/4\pi)$ erg. For a typical solid angle is $\Omega \sim 4^\circ$, the energy of GRB is [20]

$$E_\Omega \sim 5\times 10^{50}\ {\rm erg}. \qquad (5)$$

Although there is some variation in the observed energy and the opening angle, the combined energy estimate in eq. (5) is quite robust and is probably correct within a factor of 2 [20].

Recent observations have provided a strong evidence that GRB is a supernova-like event [8]. Supernovae release an energy $E_{\rm SN} \sim 10^{53}$ erg, 99% of which is carried away by neutrinos. The remaining 1% can accommodate the energetic requirements of a GRB (assuming some reasonable beaming).

The short time variability on the scale $\delta t \sim 10$ msec of observed gamma-ray signals suggests that the size of the emission region is small, $R < c\delta t \approx 3000$ km. However, the generation of such a large energy in a small region of space would result in massive energy losses due to e^+e^- pair production. The corresponding optical depth would be as large as $\tau \sim 10^{11}$, which is, of course, unacceptable. To ameliorate this problem, one assumes that the emission occurs from a relativistically moving region that has a large Lorentz factor, 10^{2-3} [13]. In such a model the optical depth can be reduced to $\tau < 1$, so that photons can escape from the emission region. In addition, $\tau < 1$ is consistent with the observed *non-thermal* spectrum of photons.

The observed GRB rate is about one GRB per million years per galaxy at the cosmological distances. The actual GRB rate must be higher by the factor $(4\pi/\Omega)$ because of the beaming effect. The observed rate is then the product of the actual rate and the solid angle of the jet, $\Omega \approx \theta^2$. The narrower the opening angle θ, the higher rate one needs to explain the observations.

The observed *local* GRB rate is [21]

$$R^{\rm local}_{\rm observed} = 0.5\,{\rm Gpc}^{-3}{\rm yr}^{-1}. \qquad (6)$$

Taking into account the beaming effect, one infers the actual rate of GRB, which is a factor $(4\pi/\Omega) \sim 500 f_\Omega$ higher. Here f_Ω is a parameter of order one [20]. Therefore, for the total observed rate we get

$$R^{\rm local}_{\rm actual} = 250\,f_\Omega\,{\rm Gpc}^{-3}{\rm yr}^{-1}, \quad f_\Omega \sim 1. \qquad (7)$$

Assuming a local density of galaxies $n_G = 0.01\,{\rm Mpc}^{-3}$, we find the GRB rate in a galaxy like our own to be

$$R^{\rm galaxy}_{\rm actual} = 25 f_\Omega\ 10^{-6}{\rm yr}^{-1}. \qquad (8)$$

Of course, this estimate assumes that our galaxy is "average" in terms of the GRB rate. This assumption may be wrong in two ways. On the one hand, the GRB rate may be related to the number of stars, in which case the actual rate is higher than our estimate in eq. (8) because our galaxy is bigger than average. On the other hand, the rate may be lower if for some reason GRBs occur predominantly in smaller galaxies or in galaxies morphologically different from the Milky Way. The afterglows are more frequently detected in smaller, blue galaxies [22], but, as emphasized in Ref. [22], this may be due to a selection effect: one is more likely to detect an optical afterglow from an unobscured galaxy than from a galaxy with a large amount of dust. Le Floc'h *et al.* [22] argue that the optically dark GRBs may originate from dust-enshrouded regions of star formation. Eq. (8) implies a galactic GRB output in γ-rays

$$E_{\rm tot,\gamma} \sim (5\times 10^{50})\, 25\, f_\Omega \frac{\rm erg}{(10^6\,{\rm yr})\ ({\rm galaxy})} \sim 1.3\times 10^{52}\, \frac{\rm MeV}{({\rm yr})\ ({\rm galaxy})} \qquad (9)$$

We write the total energy in electrons and positrons as

$$E_{{\rm tot},(e^+e^-)} = \zeta_{(e^+e^-)} E_{\rm tot,\gamma} \qquad (10)$$

where $\zeta_{(e^+e^-)}$ is the ratio to be determined. *A priori*, the value of $\zeta_{(e^+e^-)}$ is not known and, in a supernova, a "natural" value would be much greater than one. However, a successful model of GRB must explain the observed non-thermal spectrum of photons. This implies that the photons are emitted from a fireball which is sufficiently transparent [13]. Note, however, that even for $\tau \leq 1$ the e^+e^- production can have efficiency $\zeta_{(e^+e^-)} \sim O(1)$, which is significant. It is reasonable, therefore, to take $\zeta_{(e^+e^-)} \lesssim 1$.

There are three ways to get the positrons out of the fireball and into the bulge. First, some positrons can be pair-produced outside the fireball by the outgoing photons interacting with the interstellar medium. Observations support this. For example, GRB 940217 was observed simultaneously by BATSE, COMPTEL, and EGRET in the energy range from 0.3 MeV to 100 MeV. The spectrum exhibits a significant break at around 1 MeV [23]. The break point, 1 MeV, is right at the threshold of pair production, and is likely to be caused by the e^+e^- production, as suggested by Winkler *et al.* [23]. We denote by $\zeta_{\rm pair}$ the fraction of the GRB energy transferred to these positrons. Of course, it is necessary that $\zeta_{\rm pair} \ll 1$, but even a fraction as small as 1% is sufficient. The spectrum of these positrons depends on the spectrum of photons escaping from the fireball. Taking the average energy $\gtrsim 1$ MeV, we estimate the production rate of these positrons to be

$$\Gamma_{(e^+e^-),{\rm cr}} \sim \zeta_{\rm pair} \frac{E_{{\rm tot},(e^+e^-)}}{E_{(e^+)}} \sim \left(\frac{\zeta_{\rm pair}}{0.01}\right) 10^{50}{\rm yr}^{-1}. \qquad (11)$$

In a steady-state regime, the positron injection rate is equal the annihilation rate:

$$\Gamma_{(e^+e^-),{\rm annih}} \approx \Gamma_{(e^+e^-),{\rm cr}} \sim 10^{50}{\rm yr}^{-1}, \qquad (12)$$

which agrees with the observed positron annihilation rate, eq. (1).

Another source is positron leakage directly out of the fireball. The photon pressure inside the fireball, at temperatures $\sim$keV, is much greater than the magnetic pressure [24], and the mean free path of the positron is comparable to that of a photon. Such positrons have the same gamma-factor as the fireball; we denote $\zeta_{\rm leak}$ the fraction of energy transferred to these positrons. If $\zeta_{\rm leak} \sim 1$, the number of the leakage positrons is comparable to those from pair productions, eq. (11).

Finally, some fraction $\zeta_{\rm cold}$ of the positrons can stay inside the fireball and escape much later, with a greatly reduced gamma-factor. These positrons stay close to the site of the GRB and can be used to identify the location of a recent nearby GRB [14].

We propose some signatures that could help distinguishing GRBs from other sources of positrons.

First, one can test the model by looking for the 511 keV line emission from nearby galaxies, in particular the nearby Draco and Sagittarius dwarf galaxies. The number of stars, the star formation rates [25], and, hence, the rate of the GRBs are much lower in these dwarf galaxies than in the bulge of the Milky Way. The expected flux from the dwarfs is suppressed by many orders of magnitude due to both the low GRB rate and the larger distance. Boehm *et al.* [9] have estimated the emission from the nearby galaxies in the case of annihilating dark matter, which depends on the integral of the square of dark matter density. They concluded that, since the dwarf galaxies are dark matter dominated, a large flux could be expected, in contrast with the GRB case. The observation of the 511 keV emission from the dwarf galaxies would favor the dark matter scenario. In Ref. [26] the search for a 511 keV line from the Sagittarius Dwarf Galaxy (SDG) was reported, and no such emission was detected. However, the effective observation time of the SDG was only 80 ks, and the limits inferred from the data cannot rule out the MeV dark matter as the origin of the galactic positrons. In the GRB scenario, the large nearby galaxies, such as M31, could be easier to observe than the dwarf galaxies, although the flux from M31 would still be suppressed by a factor $\sim 10^4$ with respect to the Galactic bulge due to the larger distance.

Integral/SPI observations have placed a lower limit on the ratio of the contributions from the bulge and from the disk, of order $B/D \gtrsim 0.3$ [5]. Although there are indications that the average galactocentric distance of GRBs is not too large, around ~ 1.3 kpc [27], i.e. comparable to the size of the Galactic bulge, it is difficult to make definite predictions on the expected B/D ratio in our scenario. One expects that some fraction of GRBs took place in the disk in the last $10^8 - 10^9$ yrs, which means that, unlike the dark matter annihilation model, the GRB model predicts some 511 keV emission from the disk, which could be detected in the future.

If supernovae of a new type, SNe Ic, are associated with GRBs, the positrons are produced both through the pair production $\gamma\gamma \to e^+e^-$ during the burst (our model) and by decaying nuclei [6]. However, the former mechanism dominates over the latter in each supernova that also produces a GRB. This is reflected in the rates: we need one GRB per million years to explain the same population of positrons that could be produced by 200 SNe Ic per million years, as estimated in Ref. [6]. If only a fraction of supernovae produce GRBs, the amount of pair-produced positrons in the galaxy exceeds that from decaying nuclei as long as the rate of GRB per supernova is greater than 5×10^{-3}.

To summarize, the past galactic gamma-ray bursts could have produced the population of positrons detected through observations of the 511 keV annihilation line from the galactic center. Future observations should be able to distinguish between this and other proposed models.

The authors thank J. Beacom and M. Kaplinghat for useful discussions. G. B. thanks the TEP group at UCLA for hospitality. S. P.-R. and S. P. thank the Theoretical Astrophysics group at Fermilab for hospitality. This work was supported in part by the DOE grant DE-FG03-91ER40662 and the NASA ATP grants NAG 5-10842 and NAG 5-13399.

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