Cosmic-Ray Positrons from Astrophysical Sources: GRBs, Pulsars and SNRs

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Abstract

We discuss that a nearby astrophysical source, such as pulsar, supernova remnant or gamma-ray burst (GRB), about 10^{5-6} years ago may be responsible for the excesses of cosmic-ray positrons and electrons recently observed by the PAMELA, ATIC/PPB-BETS, Fermi and HESS experiments. We can reproduce the smooth Fermi/HESS spectra as well as the spiky ATIC/PPB-BETS spectra. The spectra can possess a sharp cutoff that is similar to the dark matter predictions since higher energy cosmic-rays cool faster where the cutoff energy marks the source age. A burst-like astrophysical source is expected to have a small but finite spread in the cutoff as well as anisotropy in the cosmic-ray and diffuse gamma-ray flux, providing a method for the Fermi and future CALET experiments to discriminate between dark matter and astrophysical origins and also to constrain the source duration. Whether the source is leptonic or hadronic may be probed by the antiprotons. Such GRB-like sources may leave remnants observed as mysterious TeV unidentified sources.

Key words: cosmic rays — diffusion — gamma rays: bursts — gamma rays: theory — pulsars: general — radiation mechanism: non-thermal

1. Introduction

Recent observations by the PAMELA (Adriani et al. 2008) and ATIC/PPB-BETS (Chang et al. 2008, Torii 2008) experiments have revealed the electron and positron excesses in the cosmic-ray spectrum. These results strongly indicate the presence of nearby sources of electron-positron pairs (less than 1kpc away). Possible candidates include astrophysical objects such as pulsars (e.g., Kawanaka et al. 2009), supernova (SN) remnants (e.g., Fujita et al. 2009) or microquasars, or dark matter annihilations/decays. Instead we might be observing the propagation effects or the proton contamination.

The ATIC/PPB-BETS excess has a possible cutoff at $\varepsilon_e \sim 600$GeV, which might fix the dark matter mass. From the astrophysical viewpoint, the cutoff implies a single or at least a few sources since many sources usually broaden the cutoff. The source age should be less than 10^{6-7} years because electrons lose energy through synchrotron and inverse Compton processes, suggesting the Galactic rate of $\sim (10\text{kpc}/1\text{kpc})^2/10^{6-7}\text{yr} \sim 1/10^{4-5}\text{yr}$, i.e., $\sim 10^2$-10^3 times rarer than SNe. This ratio $\sim 10^2$-10^3 is comparable with that of energy density between cosmic-ray nuclei and positrons. Therefore the electron-positron source may also produce a huge energy $\sim 10^{50}$ erg like a SN that releases $\sim 10^{50}$ erg for providing cosmic-ray nuclei.

We propose a new possibility that a nearby ($d \sim 1$kpc) gamma-ray burst (GRB) or GRB-like pulsar/SN remnant/microquasar about $t_{\rm age} \sim 10^{5-6}$ years ago may be responsible for the PAMELA and ATIC/PPB-BETS excesses, and predict a sharp spectral cutoff that is similar to the dark matter predictions, in addition to a possible line (Ioka 2008). We also show that a finite duration of the pair injection produces a broad cutoff and a high energy tail above the cutoff, which can constrain the source duration ($\lesssim 10^5$yr with the current data; Kawanaka et al. 2009).

Very recently, the Fermi Large Area Telescope measures the electron spectrum up to $\sim$ 1 TeV that is very smooth $\sim \varepsilon_e^{-3}$ without any spectral peak as reported by ATIC/PPB-BETS (Abdo et al. 2009). The HESS collaboration also provides the electron spectrum (Aharonian et al. 2009), which is consistent with the Fermi result and appears to show a steepening above $\sim$ 1 TeV. The differences between ATIC/PPB-BETS and Fermi/HESS are still controversial. Therefore we discuss each case separately and show that a GRB/pulsar model with sightly different parameters may reproduce the Fermi/HESS smooth spectra as well (Ioka 2008).

In this paper we try not to specify a source class in order to make discussions as model-independently as possible. We consider a GRB-like astrophysical source, denoted by GRB/Pulsar for short, that produces electron-positron pairs from a compact region in a short timescale compared with its age. If the source has these properties, we can apply the results to pulsars (Kawanaka et al. 2009), SN remnants (Fujita et al. 2009), microquasars, GRBs (Ioka 2008) etc.

2. ATIC/PAMELA excess from an astrophysical source

Let us first consider the most simple model that a GRB/pulsar produces electron-positron pairs with energy $E_{e^+} \simeq E_{e^-}$ at a distance d from the Earth a time $t_{\rm age}$ ago, assuming that the pairs have a power-law spectrum. The observed spectrum after propagation is obtained by solving the diffusion equation,

$$\frac{\partial}{\partial t} f = K(\varepsilon_e)\nabla^2 f + \frac{\partial}{\partial \varepsilon_e}[B(\varepsilon_e) f] + Q, \tag{1}$$

where $f(t,\vec{x},\varepsilon_e)$ is the distribution function of particles at time t and position $\vec{x}$ with energy ε_e. The flux at $\vec{x}$ is given by $\Phi(t,\vec{x},\varepsilon_e) = (c/4\pi) f(t,\vec{x},\varepsilon_e)$ [m^{-2} s^{-1} sr^{-1} GeV^{-1}]. We adopt the diffusion constant $K(\varepsilon_e) = K_0(1+\varepsilon_e/3{\rm GeV})^\delta$ with $K_0 = 5.8\times 10^{28}$ cm^2 s^{-1} and $\delta = 1/3$ that is consistent with the boron/carbon ratio according to the latest GALPROP code, and the energy loss rate $B(\varepsilon_e) = b\varepsilon_e^2$ with $b = 10^{-16}$ GeV^{-1} s^{-1} via synchrotron and inverse Compton.

In the limit of a single burst from a point source with a power-law spectrum $Q(t,\vec{x},\varepsilon_e) = Q_0\varepsilon_e^{-\alpha}\delta(\vec{x})\delta(t)$ up to $\varepsilon_e < \varepsilon_{\max}$, the diffusion Eq. (1) has an analytical solution as

$$f = \frac{Q_0 \varepsilon_e^{-\alpha}}{\pi^{3/2} d_{diff}^3}(1-bt\varepsilon_e)^{\alpha-2} e^{-(d/d_{diff})^2}, \tag{2}$$

where $\varepsilon_e < (bt + 1/\varepsilon_{\max})^{-1} < \varepsilon_{\rm cut} = (bt)^{-1}$ (otherwise $f = 0$) and

$$d_{diff} \simeq 2\sqrt{K(\varepsilon_e) t \frac{1-(1-\varepsilon_e/\varepsilon_{\rm cut})^{1-\delta}}{(1-\delta)\varepsilon_e/\varepsilon_{\rm cut}}}. \tag{3}$$

The physical picture is that cosmic-rays below $\varepsilon_e \lesssim \varepsilon_{\rm cut}$ diffuse out almost uniformly within a radius $d_{diff} \sim 2\sqrt{K(\varepsilon_e)t}$.

In Figs. 1 and 2, we show the positron fraction and the electron plus positron flux resulting from a GRB/pulsar and background. We can see that the PAMELA and ATIC/PPB-BETS excesses can be reproduced well if a GRB/pulsar produces electron-positron pairs with energy $\sim 10^{50}$ erg and a power-law spectral index $\alpha \sim 1.8$ at $d \sim 1$ kpc from the Earth a time $t_{\rm age} \sim 6\times 10^5$ yr ago. This energy can be yielded by a GRB, SN remnant, a 10msec pulsar with a rotational energy $\sim 10^{50}$ erg or a microquasar (a black hole with a disk and jet) that has the Eddington luminosity $\sim 10^{38}$ erg s^{-1} for $\sim 10^5$ yr. The chance probability of having such a GRB is $t_{\rm age}/10^{5-6}{\rm yr}/(10{\rm kpc}/1{\rm kpc})^2 \sim$ 0.6-6%, not too bad. Or a pulsar/SN remnant/microquasar per 6-60 SNe may be responsible.

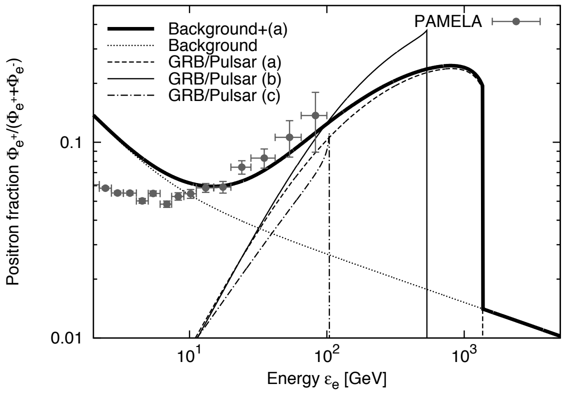
Interestingly, the electron and positron spectra in Figs. 1 and 2 have a sharp cutoff that is very similar to the dark matter predictions in addition to a line at energy,

$$\varepsilon_{\rm cut} = \frac{1}{bt} \simeq 300 \left(\frac{10^6 {\rm yr}}{t_{\rm age}}\right) {\rm GeV}. \tag{4}$$

This is because the energy loss time via synchrotron and inverse Compton is shorter for higher energy cosmic-rays by ε_e. Then after time $t_{\rm age}$ all electrons above $\varepsilon_{\rm cut}$ cool down to the cutoff energy $\varepsilon_{\rm cut}$ with no electrons above $\varepsilon_{\rm cut}$. Independently of the maximum energy all electrons above $\varepsilon_{\rm cut}$ lose their energies during propagation. A line or cusp is produced if the source spectrum has $\alpha < 2$, although the number of electrons and positrons remain finite and constant. Note that the electron and positron lines produced by the dark matter are smeared out because the observed electrons and positrons are created at different time having different line energy due to cooling. Note also that only the direct annihilation or two-body decay into electrons and positrons can produce a sharp cutoff in dark matter models.

3. Fermi/PAMELA excess from an astrophysical source

In Figs. 1 and 2, we also show a GRB/pulsar model (a) that can reproduce the Fermi/HESS smooth data as well as the PAMELA data without producing the ATIC/PPB-BETS peak. Interestingly the model parameters are relatively similar to that for the ATIC/PPB-BETS data, i.e., the age is just slightly shorter (6×10^5 yr $\rightarrow 2\times 10^5$ yr) and the spectral index is softer ($1.8 \rightarrow 2.5$), where $\alpha = 2$ is the boundary between the smooth and spiky spectra in Eq. (2). We still have a cutoff at $\varepsilon_e = \varepsilon_{\rm cut}$ in Eq. (4), while we have no line for $\alpha > 2$ with Eqs. (2) and (4). The cutoff may be relevant to the steepening observed by HESS around $\sim$ 1 TeV, though



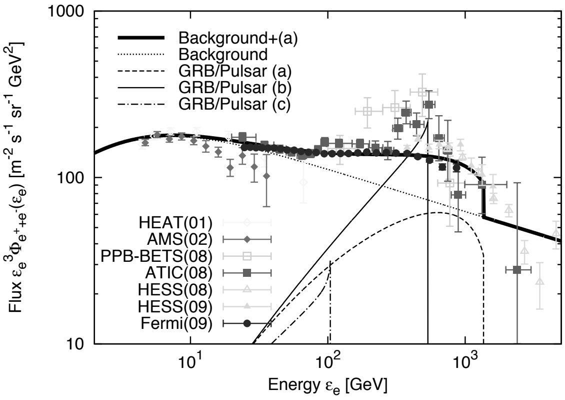


Fig. 1. The positron fraction $\Phi_{e^+}/(\Phi_{e^-}+\Phi_{e^-})$ resulting from a GRB/pulsar [(a), (b), (c)] and secondary positrons produced by the collisions of cosmic-ray nuclei with interstellar medium (ISM) [Background], compared with the PAMELA data (Ioka 2008). The fit is well and the spectrum has a cutoff at $\varepsilon_e \sim \varepsilon_{\rm cut}$ in Eq. (4). We adopt $(t_{\rm age}, E_{e^+}, \alpha) = (2\times10^5\ {\rm yr}, 0.9\times10^{50}\ {\rm erg}, 2.5), (5.6\times10^5\ {\rm yr}, 0.8\times10^{50}\ {\rm erg}, 1.8)$ and $(3\times10^6\ {\rm yr}, 3\times10^{50}\ {\rm erg}, 1.8)$ for (a), (b) and (c), respectively, where a GRB/pulsar at $d = 1$kpc from the Earth a time $t_{\rm age}$ ago produces electron-positron pairs with energy $E_{e^+} = E_{e^-}$ and spectral index α up to $\varepsilon_{\max} = 10$TeV. Note that the solar modulation is important below ~ 10 GeV.

Fig. 2. The electron plus positron flux from a GRB/pulsar [(a), (b), (c) defined in Fig. 1] and the primary plus secondary background, compared with the data (Ioka 2008). A GRB/pulsar (a) fits the Fermi/HESS data, while a GRB/pulsar (b) fits the ATIC/PPB-BETS data well. A GRB/pulsar (c) is an older one. The spectrum has a cutoff at $\varepsilon_e = \varepsilon_{\rm cut}$ in Eq. (4). The primary background is conventionally attributed to SN remnants. Note that the solar modulation is important below ~ 10 GeV.

we need more data to claim the presence of the cutoff. (If the steepening continues to higher energy, the background would also have a cutoff.)

Considering an older source, for which the chance probability gets higher, we may fit the PAMELA data, leaving the electron data to other sources [see the case (c) in Figs. 1 and 2]. However, if the electron spectrum is as smooth as the Fermi data, it may be difficult to hide the peak under the other contributions (Note that $\alpha < 2$ is needed to fit the PAMELA data by a single old source). Thus, a single GRB-like source only for the PAMELA data is unlikely.

4. Single or multiple? Leptonic or hadronic?

It is an important question whether the source is single or multiple. In order to answer this question, an anisotropy measurement could be useful. In Fig. 3, we show the expected anisotropy of electron and positron fluxes

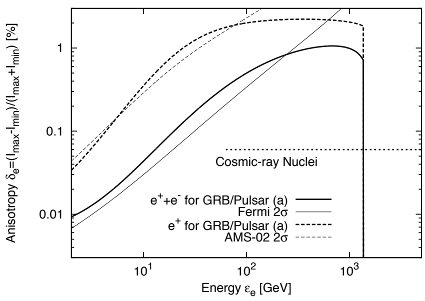
$$\delta_e = \frac{I_{\rm cut} - I_{\rm min}}{I_{\rm cut} + I_{\rm min}} = \frac{3K|\nabla f|}{cf}, \quad (5)$$

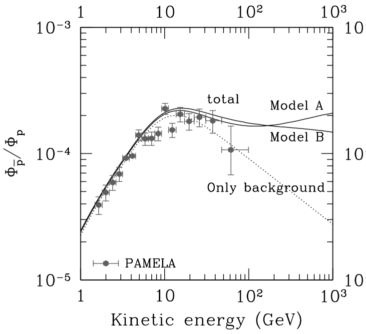
for the GRB/pulsar model (a) in Figs. 1 and 2. The anisotropy is larger than that of the observed cosmic-ray nuclei $\delta_N \sim 0.06\%$, so that the anisotropy is in principle detectable, not to be disturbed by the local magnetic structure. The Fermi and upcoming AMS-02 experiments may be able to detect the anisotropy, while the actual measurement should be challenging and also model-dependent e.g., the GRB/pulsar model (b) in Figs. 1 and 2 predicts the anisotropy below the sensitivities (not shown in Fig. 3). Once an anisotropy is detected, it would support a single source model, not a multiple source model.

Whether the anti-matter origin is hadronic or leptonic is also an important problem (e.g., the pulsar model is leptonic and the SN remnant model with *pp* interactions is hadronic.) Fujita et al. (2009) first pointed out that the hadronic models predict an anti-proton excess above ~ 100 GeV, which will be probed by PAMELA and future AMS-02. The secondary nuclei such as the boron-to-carbon and titanium-to-iron ratio would be also an interesting probe (Mertsch & Sarkar 2009).

5. Discussions and Summary

We have proposed that a nearby gamma-ray burst (GRB) or GRB-like (old, single and short-lived) pulsar/SN remnant/microquasar about 10^{5-6} years ago may be responsible for the excesses of cosmic-ray positrons and electrons recently observed by the PAMELA, ATIC/PPB-BETS and Fermi/HESS experiments. Such a scenario looks rather extreme but still consistent with the current observations. In particular, a GRB/pulsar model can reproduce the smooth Fermi/HESS spectra as well as the spiky ATIC/PPB-BETS spectra by slightly changing parameters (see Fig. 2). Although such a burst-like scenario has been discussed before, it is the first to argue the similarities (e.g., sharp cutoff) and differences (e.g., cutoff width) between





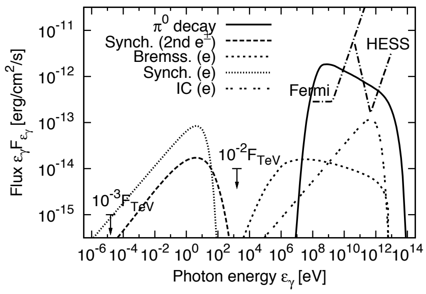


Fig. 3. Anisotropy of the electron plus positron flux (thick solid line) and the positron flux (thick dashed line) for the GRB/pulsar model (a) in Figs. 1 and 2, compared with sensitivities of the Fermi satellite for the electron plus positron flux (thin solid line), the future AMS-02 experiment for the positron flux (thin dashed line) and the observed anisotropy of cosmic-ray nuclei $\delta_N \sim 0.06\%$ (dotted line) (Ioka 2008).

Fig. 4. Antiproton fraction for the SNR models (solid lines). The dotted line shows the background fraction (Fujita et al. 2009).

Fig. 5. Spectrum of a GRB/hypernova remnant with age $t_{\rm age} = 10^5$ yr, which may be observed as TeV unidentified sources. The observed bright sources in the TeV sky could be dominated by GRB/hypernova remnants, even though they are fewer than SN remnants (Ioka & Mészáros 2009).

the astrophysical and dark matter scenarios. In particular we propose a new method to discriminate models by using the cutoff width (see below).

The spectral cutoff and line in Figs. 1 and 2 should have a finite dispersion under realistic circumstances, in contrast with the dark matter origin. We may be able to discriminate models by observing the cutoff shape (or width) since the future CALET experiment has a resolution better than a few % (> 100GeV). Since Eq. (4) yields $\Delta\varepsilon_{\rm cut}/\varepsilon_{\rm cut} = -\Delta b/b - \Delta t/t$, the dispersion arises from (a) the fluctuation of the energy loss rate Δb due to the difference of starlight and magnetic fields by location and (b) the duration of the source Δt. To estimate Δb, we assume that the energy loss rate fluctuates by δb over the scale d_b. Cosmic-rays travel a distance $ct_{\rm age}$ and pass through $N_b \sim ct_{\rm age}/d_b$ patches, averaging the fluctuations as $\Delta b \sim \delta b/\sqrt{N_b}$. Then we have

$$\left(\frac{\Delta\varepsilon_{\rm cut}}{\varepsilon_{\rm cut}}\right)_{\Delta b} \sim 6\% \left(\frac{\delta b}{b}\right)\left(\frac{d_b}{\rm 1kpc}\right)\left(\frac{t_{\rm age}}{10^6{\rm yr}}\right)^{-1/2}, \quad (6)$$

which may be detectable if the starlight and magnetic fields differ by $\delta b/b \sim 1$ over the disk thickness $d_b \sim$ 1kpc. As for the duration effect, GRBs are too short, but a pulsar with magnetic field B and initial rotation period P_0 has a spin-down duration $\Delta t \sim 3c^3 I/B^2 R_*^6 \Omega_0^2 \sim 6\times10^3{\rm yr}(B/10^{12}{\rm G})^{-2}(P_0/10{\rm ms})^2$ while a microquasar has an active time $\Delta t \sim 10^{50}{\rm erg}/L \sim 10^5{\rm yr}\ (L/10^{38}{\rm erg\ s}^{-1})^{-1}$, yielding

$$\left(\frac{\Delta\varepsilon_{\rm cut}}{\varepsilon_{\rm cut}}\right)_{\Delta t} \sim 10\% \left(\frac{\Delta t}{10^5{\rm yr}}\right)\left(\frac{t_{\rm age}}{10^6{\rm yr}}\right)^{-1}. \quad (7)$$

Therefore we can constrain the source duration by the cutoff width ($\lesssim 10^5$yr with the current data; Kawanaka et al. 2009).

Our GRB-like astrophysical scenario predicts a minor role of the inverse Compton emission far below the the pion decay component and is compatible with the diffuse gamma-ray background observations. The constraints are less severe in the GRB case of small chance probability. The fluctuation of the diffuse gamma-ray background due to the nonuniform distribution of GRBs/pulsars could be an interesting future probe.

Similar GRB-like sources in our Galaxy may leave remnants observed as mysterious TeV gamma-ray sources, the so-called TeV unidentified sources, which have no clear counterpart at other wavelengths as shown in Fig. 5 (Ioka & Mészáros 2009) and/or the 511 keV electron-positron annihilation line from the Galactic bulge.

This work is supported in part by the Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, No.18740147, 19047004, 21684014.

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