

Is the PAMELA anomaly caused by supernova explosions near the Earth?

Yutaka Fujita,¹ Kazunori Kohri,^{2,3} Ryo Yamazaki,⁴ and Kunihito Ioka⁵

¹*Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*

²*Department of Physics, Tohoku University, Sendai 980-8578, Japan*

³*Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom*

⁴*Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan*

⁵*KEK Theory Center and the Graduate University for Advanced Studies (Sokendai), 1-1 Oho, Tsukuba 305-0801, Japan*

(Received 12 April 2009; revised manuscript received 15 June 2009; published 10 September 2009)

We show that the anomaly of the positron fraction observed by the PAMELA experiment can be attributed to recent supernova explosion(s) in a dense gas cloud near the Earth. Protons are accelerated around the supernova remnant. Electrons and positrons are created through hadronic interactions inside the dense gas cloud. Their spectrum is harder than that of the background because the supernova remnant spends much time in a radiative phase. Our scenario predicts that the antiproton flux dominates that of the background for ≥ 100 GeV. We compare the results with observations (Fermi, HESS, PPB-BETS, and ATIC).

DOI: [10.1103/PhysRevD.80.063003](https://doi.org/10.1103/PhysRevD.80.063003)

PACS numbers: 98.70.Sa, 97.60.Bw, 98.38.-j, 98.58.Mj

I. INTRODUCTION

Observations with the PAMELA [1] and ATIC/PPB-BETS [2] experiments have implied or shown anomaly in the positron fraction and a sharp feature in the cosmic-ray electron spectrum, although Fermi satellite recently reported that the feature in the electron spectrum is much smaller or even absent depending on the uncertainty of the background cosmic-ray electron and positron spectrum [3]. The PAMELA (and ATIC/PPB-BETS) results indicate that there should be an unknown source of electrons and positrons. One attractive idea of the source is the annihilation or decay of weakly interacting dark matter particles [4,5]. The other is astrophysical scenarios such as pulsars [5–7].

Among the astrophysical sources, supernova remnants (SNRs) are one of the promising candidates for the electron and positron source. Their synchrotron emission reveals the existence of high energy electrons in SNRs [8], and their γ -ray emission would indicate that of high energy protons [9], although there has been no direct evidence of proton acceleration in SNRs yet.

In this paper, we show that the observed electron and positron excesses can naturally be explained by recent supernova explosions near the Earth. In fact, the low-density local bubble, in which the solar system locates, and the adjacent bubble (Loop I) with sizes of ~ 100 pc are often thought to be created through ~ 20 – 40 supernova explosions that started $\sim 10^7$ yrs ago [10]. Since those explosions occurred close to us (~ 100 – 200 pc), they could have affected the environment around the solar system more significantly than the supernova explosions in the spiral arms $\sim$ kpc away [11].

II. SUPERNOVA(E) IN A DENSE CLOUD

We consider supernova explosions that happened $\sim 10^{5-6}$ yrs ago in a dense gas cloud (DC) ~ 100 – 200 pc away from the Earth. The DC does not necessarily corre-

spond to the host DCs of the supernovae that created the local bubble or Loop I. Massive stars that explode as supernovae tend to be born in giant DCs [12]. They may explode near or inside the host DCs, because their durations of life are short. In this paper, we assume that although a DC had not been destroyed by ultraviolet radiation from massive, short-lived OB stars, it is ionized and the temperature is $\sim 10^4$ K when those stars explode [13]. In such environments, the shock front of an SNR accelerates protons, which create electrons and positrons through hadronic interactions in the surrounding DC.

The evolution of a SNR and the particle acceleration around it is modeled following a previous study [14]. The shock velocity v_s is written as a function of the SNR age (t_{age}) as

$$v_s(t_{\text{age}}) = \begin{cases} v_i & (t_{\text{age}} < t_1) \\ v_i(t_{\text{age}}/t_1)^{-3/5} & (t_1 < t_{\text{age}} < t_2) \\ v_i(t_2/t_1)^{-3/5}(t_{\text{age}}/t_2)^{-2/3} & (t_2 < t_{\text{age}}) \end{cases}, \quad (1)$$

where $v_i = v_{i,9}10^9$ cm s $^{-1}$ is the initial velocity, and $E_{\text{SN}} = E_{51}10^{51}$ erg is the initial energy of the ejecta. When we consider multiple supernova explosions, we simply assume that they explode almost simultaneously (within a time-scale of the destruction of the DC) and give a larger E_{SN} than that of a single supernova. At $t_{\text{age}} < t_1 = 45(E_{51}/n_2)^{1/3}v_{i,9}^{-5/3}$ yr, the SNR is in the free expansion phase, at $t_{\text{age}} > t_2 = 3.5 \times 10^3 E_{51}^{4/17} n_2^{-9/17}$ yr, it is in the radiative phase, and at $t_1 < t_{\text{age}} < t_2$, it is in the Sedov phase. Here, $n_0 = n_2 10^2$ cm $^{-3}$ is the proton density of the DC.

We assume that the energy spectrum of the accelerated protons is

$$N_p(E) \propto E^{-s} \exp(-E/E_{\text{max},p}). \quad (2)$$

The index is represented by $s = (r + 2)/(r - 1)$, where r

is the compression ratio of the shock [15], which is given by the Rankine-Hugoniot relation for $t_1 < t_{\text{age}} < t_2$, and $r \sim \sqrt{2}v_s/v_{\text{Au}}$ for $t_{\text{age}} > t_2$, where v_{Au} is the upstream Alfvén velocity [14]. The maximum energy is determined by the age of SNR:

$$E_{\text{max},p} = 1.6 \times 10^2 h^{-1} v_{s,8}^2 \left(\frac{B_d}{10 \mu\text{G}} \right) \left(\frac{t_{\text{age}}}{10^5 \text{ yr}} \right) \text{ TeV}, \quad (3)$$

where $v_{s,8} = v_s/10^8 \text{ cm s}^{-1}$, $h(\sim 1)$ is the factor determined by the shock angle and the gyro-factor, and B_d is the downstream magnetic field, which is expressed by $B_d = rB_{\text{DC}}$, where B_{DC} is the magnetic field in the DC [14]. Since we consider an ionized DC, we ignore the ion-neutral wave damping at the upstream of a shock (for particle acceleration in a radiative phase, see [16]). We equate the minimum energy of the protons with the proton rest-mass energy.

We assume that supernovae explode at the center of a DC for the sake of simplicity. We take $v_{i,9} = 1$, $h = 1$, and $B_{\text{DC}} = 10 \mu\text{G}$ from now on.

We consider the case where a few supernovae (or one hypernova) explode almost simultaneously. Thus, we assume that $E_{51} = 3$, from which we obtain $t_1 = 65 \text{ yr}$ and $t_2 = 4.5 \times 10^3 \text{ yr}$, if the proton density inside the DC is $n_0 = 100 \text{ cm}^{-3}$. At $t_{\text{age}} = 8.0 \times 10^4 \text{ yr}$, the Mach number and radius of the SNR are $M_a = 7$ and $R = 26 \text{ pc}$, respectively. At this point, the SNR is in the radiative phase. We assume that particle acceleration around a SNR ceases for $M_a \lesssim 7$ (see e.g. [17]), although the exact value is not clear. We refer to the age at which $M_a = 7$ as $t_{\text{age}} = t_{\text{acc}}$.

At $t_{\text{age}} = t_{\text{acc}}$, we obtain $s = 1.0$ and $E_{\text{max},p} \sim 120 \text{ TeV}$. Although particle acceleration stops at this time, the SNR continues to expand. The radius is $R_s = 50 \text{ pc}$ at $t_{\text{age}} = 5 \times 10^5 \text{ yr}$. Since it is comparable to the size of a giant DC [18] and E_{SN} is larger than the binding energy of a DC, the cloud would be destroyed around this time. Until destroyed, the DC is illuminated by the accelerated protons from the inside with the spectrum of Eq. (2) given at $t_{\text{age}} \sim t_{\text{acc}}$. The duration of the exposure (t_{pp}) could be approximated by the time elapsing from the explosion of the supernovae to the destruction of the DC because of the short time scale of t_{acc} . The protons create e^- , e^+ , p , and $\bar{p}$ through pp collisions in the DC for the period of $\sim t_{pp}$. Based on this scenario, we calculate their spectrum observed at the Earth, and search parameters that are consistent with observations. Since the model of the SNR evolution may have some uncertainties, we do not stick to the exact values of parameters in the above discussion.

After the destruction of the DC, the created e^- , e^+ , p , and $\bar{p}$ propagate through diffusion processes and reach to the Earth. Since we assume that the DC has already been destroyed until the current epoch, there is a difference in the last arrival time between massless neutral particles such as photons and neutrinos, and charged particles. We would

not detect any photon and neutrino signals from the DC $\sim 10^{5-6} \text{ yrs}$ after the destruction.

We have calculated spectra of those daughter particles of the pp collisions by performing the PYTHIA Monte Carlo event generator [19]. Then we solve the diffusion equation of the charged particle “ i ” (i runs e^- , e^+ , p , and $\bar{p}$),

$$\frac{\partial f_i}{\partial t} = K(\varepsilon_i) \nabla^2 f_i + \frac{\partial}{\partial \varepsilon_i} [B(\varepsilon_i) f_i] + Q(\varepsilon_i), \quad (4)$$

where $f_i(t, x, \varepsilon_i)$ is the distribution function of i and $\varepsilon_i = E_i/\text{GeV}$ with E_i being the energy of i . The flux $\Phi_i(t, x, \varepsilon_i)$ is given by $\Phi_i = (c/4\pi) f_i$. For electrons and positrons, according to a model 08-005 in [20], we take

$$K(\varepsilon_e) = K_0 (1 + \varepsilon_e/3 \text{ GeV})^\delta, \quad (5)$$

with $K_0 = 2 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and $\delta = 0.6$. The cooling rate through the synchrotron emission and the inverse Compton scattering is given by

$$B(\varepsilon_e) = 10^{-16} \text{ s}^{-1} \varepsilon_e^2 [0.2(B_{\text{diff}}/3 \mu\text{G})^2 + 0.9]/1.1 \quad (6)$$

[21], where B_{diff} is the magnetic field outside the DC. These parameters approximately correspond to so-called “med model” of the particle propagation [22].

If we assume that the time scale of the production is shorter than the diffusion time scale $\sim d^2/(Kc)$, and the daughter-particle source is spatially localized well, we can also use the analytical solution in [23]. When the shape of the source spectrum is a power law with an index α , $Q = Q_0 \varepsilon^{-\alpha} \delta(x) \delta(t)$, the solution is represented by

$$f_e = \frac{Q_0 \varepsilon_e^{-\alpha}}{\pi^{3/2} d_{\text{diff}}^3} \left(1 - \frac{\varepsilon_e}{\varepsilon_{\text{cut}}} \right)^{\alpha-2} e^{-(\bar{d}/d_{\text{diff}})^2}, \quad (7)$$

with $\varepsilon_{\text{cut}} = (B t_{\text{diff}})^{-1}$ and the diffusion length

$$d_{\text{diff}} = 2 \sqrt{K t_{\text{diff}} \frac{1 - (1 - \varepsilon_e/\varepsilon_{\text{cut}})^{1-\delta}}{(1 - \delta) \varepsilon_e/\varepsilon_{\text{cut}}}}. \quad (8)$$

Here, we took an effective distance to the source $\bar{d}$, which is calculated by spatially averaging the distance to the volume element of the source, and $\alpha \simeq s$ in the current calculation. The time after the input of the daughter particles is defined by t_{diff} . Approximately $Q_0 \varepsilon_i^{-\alpha}$ is represented by $\sim V_s t_{pp} d^2 n_i / (dt dE_i)$ with V_s the volume of the source and

$$\frac{d^2 n_i}{dt dE_i} = \int dE_p n_0 N_p \sum_j g_j c \frac{d\sigma_j}{dE_i}. \quad (9)$$

Here, the differential cross section of the “ j ” mode for the production of i particle is $d\sigma_j(E_p, E_i)/dE_i$ with its multiplicity $g_j = g_j(E_p, E_i)$. We also consider the neutron decay for the electron/positron production, which is not included in the original version of PYTHIA. The initial proton spectrum $N_p(E_p)$ is normalized to be

$$V_s \int dE_p N_p(E_p) = E_{\text{tot},p}, \quad (10)$$

which is given later.

For the local propagation of p and $\bar{p}$, the cooling term is negligible. In addition, we may omit the annihilation of antiprotons through scattering off the background protons because the mean free path for the annihilation reaction is large. We can also omit the convection by the convective wind. Thus the analytical solution for the proton and antiproton can be also given by Eq. (7) with taking a limit of $\varepsilon_p/\varepsilon_{\text{cut}} \rightarrow 0$.

III. RESULTS

Figure 1 shows the positron fraction and the $e^- - e^+$ flux observed at the Earth. We assume that a spherical DC with a radius of $R_{\text{DC}} = 40$ pc and proton density of $n_0 = 100 \text{ cm}^{-3}$ is uniformly illuminated by protons with the spectrum given by Eq. (2) with $s = 1.4$ and $E_{\text{max}} = 100$ TeV for the duration of $t_{pp} = 5 \times 10^5$ yr. The total energy of the primary cosmic-ray protons is taken to be $E_{\text{tot},p} = 3 \times 10^{50}$ erg. The distance to the front side of the DC is $d = 200$ pc. We assume that the diffusion time of e^- and e^+ is $t_{\text{diff}} = 5 \times 10^5$ yr, and $B_{\text{diff}} = 3 \mu\text{G}$. We refer to this parameter set as Case A. Observational results are also

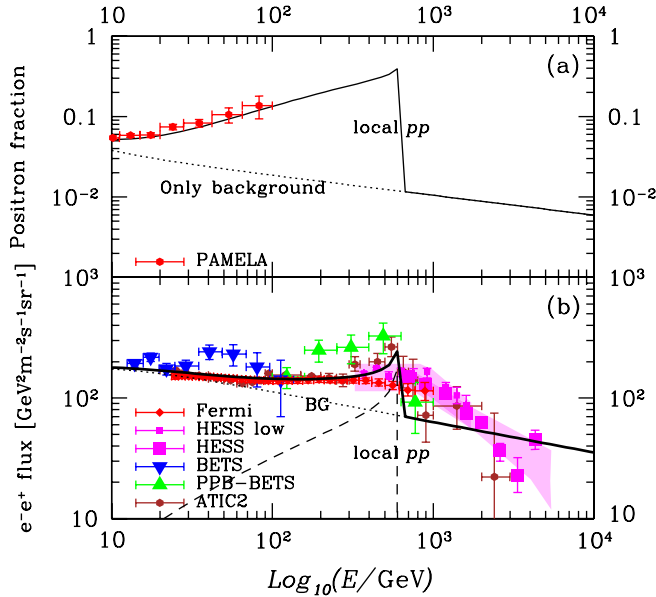


FIG. 1 (color online). (a) Positron fraction for Case A (solid line), which includes the electrons and positrons coming from the DC and background electrons (dotted line). Filled circles correspond to the PAMELA data [1]. (b) Electron and positron flux for Case A (solid line). The flux of the electrons and positrons created in the DC is shown by the dashed line, and that of the background ones is shown by the dotted line. Observational results (Fermi, HESS, BETS, PPB-BETS, and ATIC2 [2,3,29]) are also presented. The shadow shows the uncertainty of the HESS data.

shown. This result is consistent with observations for the positron fraction, and the $e^- - e^+$ flux obtained with PPB-BETS and ATIC2.

The feature of the positron spectrum can intuitively be understood as follows: The spectrum of the secondary e^- and e^+ from the DC is harder than that of the background one, because the primary protons are mainly produced in the radiative phase of the SNR with the compression ratio r much larger than 4. The cutoff scale is given by $E_{\text{cut}} = (Bt_{\text{diff}})^{-1} \text{ GeV} \sim 600 \text{ GeV}/(t_{\text{diff}}/5 \times 10^5 \text{ yrs})$. The sharp rise around the cutoff energy is made by e^- and e^+ accumulated through cooling. That is because we are considering the case of $s < 2$, which means that many of the cooled electrons sizably contribute to modifying the spectral shape around the cutoff energy. However, the actual spectrum would be broader with a width of $\Delta E_{\text{cut}}/E_{\text{cut}} \sim t_{pp}/t_{\text{diff}} \sim 1$, because the injection continues for a finite duration t_{pp} [7].

Figure 2 is another example of the positron fraction and the $e^- - e^+$ flux. In this case (Case B), we adopt $R_{\text{DC}} = 40$ pc, $n_0 = 50 \text{ cm}^{-3}$, $s = 1.75$, $E_{\text{max}} = 100$ TeV, $t_{pp} = 2 \times 10^5$ yr, $E_{\text{tot},p} = 3 \times 10^{50}$ erg, $d = 200$ pc, $t_{\text{diff}} = 2 \times 10^5$ yr, and $B_{\text{diff}} = 3 \mu\text{G}$. The results are consistent with observations for the positron fraction and the $e^- - e^+$ flux obtained with Fermi. Since we have not performed a complete parameter search, Cases A and B should be regarded as examples among possibilities.

Figure 3 shows the antiproton fraction at the Earth. In our scenario, the flux of antiprotons dominates that of the background for ≥ 100 GeV, which can be used to discriminate our hadronic scenario from other leptonic ones. Antiproton fraction rises at higher energies than that of the positron fraction (Figs. 1 and 2), because the spectral index

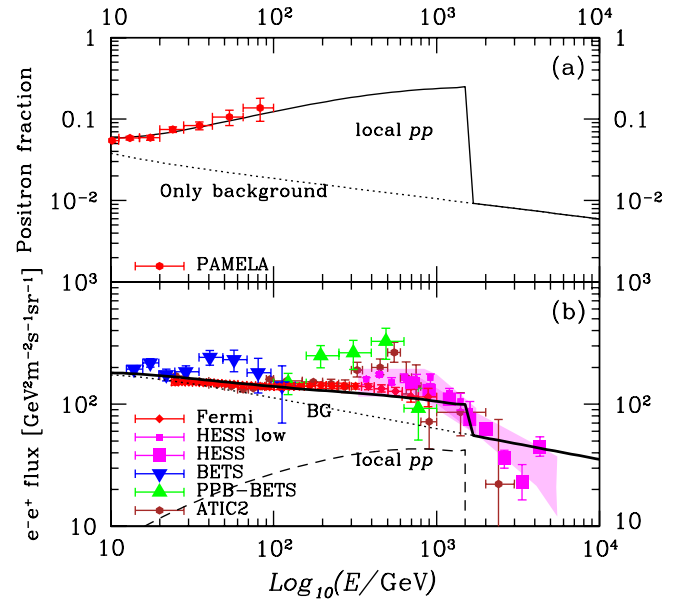


FIG. 2 (color online). Same as Fig. 1 but for Case B.

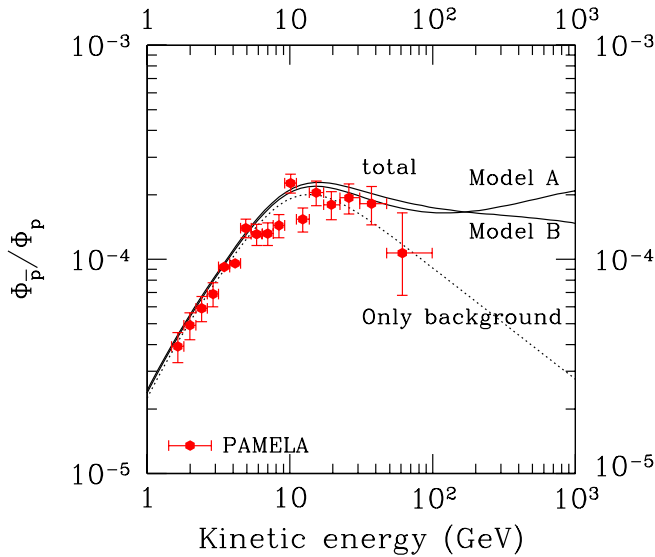


FIG. 3 (color online). Antiproton fraction for Cases A and B (solid lines). The dotted line shows the fraction calculated only from the background flux. The fitting formula of the background proton and antiproton are taken by [30]. We adopted data points taken with PAMELA [31].

of the background antiproton is harder than that of the background positron. So far the PAMELA antiproton data could not have distinguished one model from another yet (Fig. 3).

We note that old SNRs in DCs could be observed as unidentified TeV sources [14,24,25]. Broadband spectra of the old SNRs could constrain the parameters of our scenario. It is likely that the DC has made a star cluster, which might be identified near the Earth.

Recent observations have shown possible decline of boron-to-carbon (B/C) ratio toward higher energies (≥ 100 GeV), which seems to be inconsistent with the present scenario because SNRs also accelerate metals [26,27]. In our scenario, however, the source of electrons and positrons is the SNR in a specific dense cloud, and it is very localized. Thus, it is subjected to the variation of metal abundances in the Galaxy. In fact the abundance of carbon in Carina Nebula, which is a star forming region in the Galaxy, is ≤ 0.25 solar value [28]. If the dense cloud we considered has such a low metal abundance, the cosmic rays from the cloud does not increase the observed B/C ratio. Moreover, our scenario requires that the dense cloud has not been destroyed by stellar winds before the explosion of the stars. It is known that stellar winds are weaker for stars with lower metal abundances, and that the metal abundances of stars are correlated with those of the host cloud. Thus, the cloud in which electrons and positrons are effectively generated may tend to have low metal abundances. In summary, our scenario cannot be rejected only by the present observational data of the B/C ratio.

ACKNOWLEDGMENTS

We are grateful to referees for valuable comments and P. Blasi, Y. Ohira, K. Nakayama, and N. Sahu for useful discussions. This work was supported by KAKENHI under Contract Nos. 20540269 (Y.F.), 21740184 (R.Y.), 19047004 (R.Y. and K.I.), and 21684014 (K.I.). The work of K.K. was supported by the European Union through the Marie Curie Research and Training Network UniverseNet (MRTN-CT-2006-035863) and by STFC Grant No. ST/G000549/1.

- [1] O. Adriani *et al.*, *Nature* (London) **458**, 607 (2009).
- [2] J. Chang *et al.*, *Nature* (London) **456**, 362 (2008); S. Torii *et al.*, arXiv:0809.0760.
- [3] A. A. Abdo *et al.* (Fermi LAT Collaboration), *Phys. Rev. Lett.* **102**, 181101 (2009).
- [4] J. Hisano, S. Matsumoto, M. M. Nojiri, and O. Saito, *Phys. Rev. D* **71**, 063528 (2005); M. Asano, S. Matsumoto, N. Okada, and Y. Okada, *Phys. Rev. D* **75**, 063506 (2007); L. Bergström, T. Bringmann, and J. Edsjö, *Phys. Rev. D* **78**, 103520 (2008); M. Cirelli and A. Strumia, arXiv:0808.3867; J. Hisano, M. Kawasaki, K. Kohri, and K. Nakayama, *Phys. Rev. D* **79**, 063514 (2009); M. Cirelli, M. Kadastik, M. Raidal, and A. Strumia, *Nucl. Phys. B* **813**, 1 (2009); K. Ishiwata, S. Matsumoto, and T. Moroi, *Phys. Lett. B* **675**, 446 (2009); R. Harnik and G. D. Kribs, *Phys. Rev. D* **79**, 095007 (2009); S. Baek and P. Ko, arXiv:0811.1646; C. R. Chen, M. M. Nojiri, F. Takahashi, and T. T. Yanagida, arXiv:0811.3357; I. Cholis, G. Dobler, D. P. Finkbeiner, L. Goodenough, and N.

- Weiner, arXiv:0811.3641; N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, *Phys. Rev. D* **79**, 015014 (2009); C.-R. Chen, F. Takahashi, and T. T. Yanagida, *Phys. Lett. B* **671**, 71 (2009); J. Hisano, M. Kawasaki, K. Kohri, and K. Nakayama, *Phys. Rev. D* **79**, 043516 (2009); J. Zhang, X.-j. Bi, J. Liu, S.-M. Liu, P.-f. Yin, Q. Yuan, and S.-h. Zhu, *Phys. Rev. D* **80**, 023007 (2009); J. March-Russell and S. M. West, *Phys. Lett. B* **676**, 133 (2009); R. Allahverdi, B. Dutta, K. Richardson-McDaniel, and Y. Santoso, *Phys. Rev. D* **79**, 075005 (2009); K. Hamaguchi, S. Shirai, and T. T. Yanagida, *Phys. Lett. B* **673**, 247 (2009); D. Hooper, A. Stebbins, and K. M. Zurek, *Phys. Rev. D* **79**, 103513 (2009); C. R. Chen, K. Hamaguchi, M. M. Nojiri, F. Takahashi, and S. Torii, *J. Cosmol. Astropart. Phys.* **05** (2009) 015; F. Takahashi and E. Komatsu, arXiv:0901.1915; J. Mardon, Y. Nomura, D. Stolarski, and J. Thaler, *J. Cosmol. Astropart. Phys.* **05** (2009) 016; J. Hisano, M. Kawasaki, K. Kohri, T. Moroi, and K. Nakayama, *Phys. Rev. D* **79**,

- 083522 (2009); R. Allahverdi, B. Dutta, K. Richardson-McDaniel, and Y. Santoso, *Phys. Lett. B* **677**, 172 (2009); K. Ishiwata, S. Matsumoto, and T. Moroi, *J. High Energy Phys.* 05 (2009) 110; M. Cirelli and A. Strumia, arXiv:0903.3381; K. Kohri, J. McDonald, and N. Sahu, arXiv:0905.1312.
- [5] D. Malyshev, I. Cholis, and J. Gelfand, arXiv:0903.1310.
- [6] X. Chi, K. S. Cheng, and E. C. M. Young, *Astrophys. J.* **459**, L83 (1996); L. Zhang and K. S. Cheng, *Astron. Astrophys.* **368**, 1063 (2001); S. Heinz and R. Sunyaev, *Astron. Astrophys.* **390**, 751 (2002); T. Kobayashi, Y. Komori, K. Yoshida, and J. Nishimura, *Astrophys. J.* **601**, 340 (2004); C. Grimani, *Astron. Astrophys.* **474**, 339 (2007); I. Büsching, O. C. de Jager, M. S. Potgieter, and C. Venter, *Astrophys. J.* **678**, L39 (2008); D. Hooper, P. Blasi, and P. Dario Serpico, *J. Cosmol. Astropart. Phys.* 01 (2009) 025; H. Yuksel, M. D. Kistler, and T. Stanev, *Phys. Rev. Lett.* **103**, 051101 (2009); S. Profumo, arXiv:0812.4457; K. Ioka, arXiv:0812.4851; E. Borriello, A. Cuoco, and G. Miele, *Astrophys. J.* **699**, L59 (2009); P. Blasi, *Phys. Rev. Lett.* **103**, 051104 (2009); P. Blasi and P. D. Serpico, *Phys. Rev. Lett.* **103**, 081103 (2009);
- [7] N. Kawanaka, K. Ioka, and M. M. Nojiri, arXiv:0903.3782.
- [8] K. Koyama *et al.*, *Nature (London)* **378**, 255 (1995).
- [9] F. A. Aharonian *et al.*, *Nature (London)* **432**, 75 (2004).
- [10] T. W. Berghöfer and D. Breitschwerdt, *Astron. Astrophys.* **390**, 299 (2002); D. Breitschwerdt and M. A. de Aveliz, *Astron. Astrophys.* **452**, L1 (2006).
- [11] N. J. Shaviv, E. Nakar, and T. Piran, arXiv:0902.0376.
- [12] R. B. Larson, *Mon. Not. R. Astron. Soc.* **200**, 159 (1982).
- [13] A. Whitworth, *Mon. Not. R. Astron. Soc.* **186**, 59 (1979).
- [14] R. Yamazaki, K. Kohri, A. Bamba, T. Yoshida, T. Tsuribe, and F. Takahara, *Mon. Not. R. Astron. Soc.* **371**, 1975 (2006).
- [15] R. Blandford and D. Eichler, *Phys. Rep.* **154**, 1 (1987).
- [16] L. O'C Drury, P. Duffy, and J. G. Kirk, *Astron. Astrophys.* **309**, 1002 (1996); A. M. Bykov, R. A. Chevalier, D. C. Ellison, and Y. A. Uvarov, *Astrophys. J.* **538**, 203 (2000).
- [17] D. Ryu, H. Kang, E. Hallman, and T. W. Jones, *Astrophys. J.* **593**, 599 (2003).
- [18] C. F. McKee and E. C. Ostriker, *Annu. Rev. Astron. Astrophys.* **45**, 565 (2007).
- [19] T. Sjostrand, S. Mrenna, and P. Skands, *J. High Energy Phys.* 05 (2006) 026.
- [20] I. V. Moskalenko and A. W. Strong, *Astrophys. J.* **493**, 694 (1998).
- [21] E. A. Baltz and J. Edsjo, *Phys. Rev. D* **59**, 023511 (1998).
- [22] A. Bottino, F. Donato, N. Fornengo, and P. Salati, *Phys. Rev. D* **72**, 083518 (2005).
- [23] A. M. Atoyan, F. A. Aharonian, and H. J. Volk, *Phys. Rev. D* **52**, 3265 (1995).
- [24] K. Ioka and P. Meszaros, arXiv:0901.0744.
- [25] Y. Fujita *et al.*, arXiv:0907.4750.
- [26] H. S. Ahn *et al.*, *Astropart. Phys.* **30**, 133 (2008).
- [27] P. Mertsch and S. Sarkar, *Phys. Rev. Lett.* **103**, 081104 (2009).
- [28] K. Hamaguchi *et al.*, *Publ. Astron. Soc. Jpn.* **59**, S151 (2007).
- [29] F. Aharonian *et al.*, *Phys. Rev. Lett.* **101**, 261104 (2008); arXiv:0905.0105.
- [30] E. Nezri, M. H. G. Tytgat, and G. Vertongen, *J. Cosmol. Astropart. Phys.* 04 (2009) 014.
- [31] O. Adriani *et al.*, *Phys. Rev. Lett.* **102**, 051101 (2009).