Implications of Ultra-High-Energy Cosmic Rays for Transient Sources

Kohta Murase* **and Hajime Takami**†

*YITP, Kyoto University, Kyoto, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto, 606-8502, Japan
†Department Physics, School of Science, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

***Abstract*. The origin of ultra-high-energy cosmic rays (UHECRs) is one of the biggest mysteries in astroparticle physics. We study the possibility that UHECRs come from transient sources, propagating in the Galactic and intergalactic space. Based on the recent observational results, we estimate upper and lower bounds on the rate of transient UHECR sources and required isotropic cosmic-ray energy input per burst as** $0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} < \rho_0 < 10^{3.5}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ **and** $10^{49.5}\ \mathrm{ergs} < \tilde{\mathcal{E}}^{\mathrm{iso}}_{\mathrm{HECR}} < 10^{54}\ \mathrm{ergs}$**, through constraining the apparent burst duration, i.e., dispersion in arrival times of UHECRs. Then, we discuss implications of proposed transient candidates such as gamma-ray bursts and active galactic nuclei. Especially, we demonstrate expected spectra of cumulative high-energy neutrinos and ultra-high-energy gamma rays from individual nearby transient sources.**

***Keywords*: cosmic rays — gamma rays: bursts — galaxies: active**

I. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) is one of the biggest mysteries in astroparticle physics. So far, a number of possibilities were proposed, and several acceleration mechanisms have been theoretically developed [1], [2]. However, physical conditions in these potential sources are uncertain, and observational progress for source identification has been limited by the scarcity of experimental data at the highest energies.

The recent observational results of large area detectors such as the Akeno Giant Air Shower Array (AGASA), High Resolution Fly's Eye (HiRes), and especially the Pierre Auger Southern Observatory (PAO), have started to give us crucial clues to the association of UHECRs with UHECR sources. Indeed, the first results of the PAO reported a significant correlation between the arrival directions of the highest-energy cosmic rays with active galactic nuclei (AGNs) closer than 75 Mpc [3], [4]. Although this result has not been confirmed by the HiRes [5] and criticized by several works, it has also received some confirmations, and it may be an important step towards solving the UHECR mystery [6], [7]. However, one should not overinterpret the significance of these results. Although several authors also reported correlations of UHECRs with AGNs [9], [10], one cannot exclude the possibility of other objects associated with the large scale structure of the universe, which is inhomogeneous up to dozens of Mpc. Significant correlations of UHECRs with galaxies can also be found [8], [7], so that gamma-ray bursts (GRBs) [12], [13] and magnetars [14] can be sources.

Even if the association of UHECRs with AGNs is real, the report by the PAO brought us several questions on the nature of AGNs generating UHECRs. The large majority of the correlating AGNs seems radio-quiet, a class of objects not showing any nonthermal high-energy emission in their photon spectrum [9]. Radio-loud AGNs, showing high-energy nonthermal emission, are more plausible candidates in the conventional jet paradigm [11]. Although the association with them is argued, it seems that the power of the correlating AGNs are insufficient to produce UHECRs [10]. The above problem may be solved if UHECRs are produced during active episodes such as flares [15]. The magnetic fields in the universe deflect UHECRs, so that UHECRs are significantly delayed compared to photons and neutrinos generated during the bursts [16], [17]. A transient hypothesis might also help to reproduce the isotropy of the arrival distribution of UHECRs at $\sim 10^{19}$ eV [18].

Motivated by the above situation in the PAO era, we focus on the possibility that UHECR sources are transient. First, we evaluate the deflection angles and arrival times of UHECRs through numerical calculations, considering both of the Galactic magnetic field (GMF) and intergalactic magnetic field (IGMF). Then, the required cosmic-ray energy input and rate of the sources are estimated [17]. We also discuss implications of proposed candidates as transient UHECR sources. Due to the time delay of charged particles, it is important to detect associated gamma-ray and neutrino signals to prove the sources. We especially show the cumulative neutrino backgrounds from various sources [19], [20], [21], [22], [23]. As for nearby sources, it would also be important to observe ultra-high-energy gamma rays as well as ultra-high-energy neutrinos [24]. The detectability of them can be enhanced by cascaded gamma rays, if the IGMF in voids is weak enough. Throughout this paper, UHECRs are assumed to consist of protons.

II. Propagation and Characteristics of UHECRs from Transient Sources

Here, we briefly describe characteristics of UHECRs from transient sources. UHECRs ejected from their sources are deflected by the GMF and IGMF during their propagation. Only if the deflection angle $\theta_d(E,D)$ is small, where E is the energy of UHECRs at the Earth and D is the source distance, we could see a positional correlation of the highest-energy events with the sources at observationally suggested small-angle separations. The deflection also causes the time delay $t_d(E,D)$ between arriving times of an UHECR and a light emitted at the same time. UHECRs with the same energy have different arrival times, because of not only different particle trajectories but also stochastic photomeson production [16], [17]. Therefore, the time delay has certain distribution with an averaged delayed time $\bar{t}_d(E,D)$ and standard deviation in arrival times $\sigma_d(E,D)$. The arrival time spread σ_d can be regarded as the apparent duration of an UHECR burst.

Clearly, the magnetic fields play an essential role on both of θ_d and σ_d. For intergalactic propagation, one can typically expect $\sigma_d \sim \bar{t}_d \approx \frac{D\theta_d^2}{4c} \simeq 10^5$ yrs $E_{20}^{-2} D_{100\,\mathrm{Mpc}}^2 B_{\mathrm{EG},-9}^2 \lambda_{\mathrm{Mpc}}$ [16], [17], which is also confirmed by our numerical calculations. Due to limited statistics of the highest-energy events, it is convenient to use quantities weighted by the observed cosmic-ray spectrum. The apparent burst duration of UHECRs above the threshold energy E_{th} is

$$\tau_d(>E_{\mathrm{th}}) = \frac{1}{\mathcal{N}_0}\int_{E_{\mathrm{th}}}^{\infty} dE \frac{d\mathcal{N}_0}{dE}(E) \frac{\int_0^{D_{\max}(E)} dD D^2 \sigma_{\mathrm{d}}(E,D)}{\int_0^{D_{\max}(E)} dD D^2}, \quad (1)$$

where $d\mathcal{N}_0/dE$ is the UHECR spectrum observed at the Earth, $\mathcal{N}_0 = \int_{E_{\mathrm{th}}}^{\infty} dE \frac{d\mathcal{N}_0}{dE}(E)$ is the normalization factor, and $D_{\max}(E)$ is the maximum distance of UHECRs that can reach the Earth at the energy E. In this work, we adopt $E_{\mathrm{th}} = 10^{19.75}$ eV as the threshold energy, according to the PAO results.

Through τ_d, we can relate the local rate of transient sources ρ_0 with the apparent source density n_s. We have

$$n_s(>E_{\mathrm{th}}) = \frac{1}{\mathcal{N}_0}\int_{E_{\mathrm{th}}}^{\infty} dE \frac{d\mathcal{N}_0}{dE}(E) n_0(E), \quad (2)$$

where

$$n_0(E) \approx \rho_0 \frac{\int_0^{D_{\max}(E)} dD D^2 \sigma_d(E,D)}{\int_0^{D_{\max}(E)} dD D^2}. \quad (3)$$

Note that n_s can be estimated from the observed small scale anisotropy in the arrival distribution of the highest-energy cosmic rays with energies above E_{th}. For example, the more recent PAO data imply $n_s \sim 10^{-4}$ Mpc^{-3} [18], and we hereafter adopt this value. Then, the local burst rate is estimated via $\rho_0 \approx n_s/\tau_d$.

Assuming that the sources are uniform, we can also estimate typical values of the isotropic cosmic-ray energy input per burst at the energy E as $\tilde{\mathcal{E}}_{\mathrm{CR}}^{\mathrm{iso}}(E) \approx E^2 \frac{d\dot{N}_{\mathrm{CR}}}{dE}(E)/\rho_0$. Here, $E^2 \frac{d\dot{N}_{\mathrm{CR}}}{dE}(E)$ is the UHECR energy budget per volume per year at the energy E. We obtain $E^2 \frac{d\dot{N}_{\mathrm{CR}}}{dE}(10^{19}\ \mathrm{eV}) \simeq (0.5-2)\times 10^{44}\ \mathrm{ergs\ Mpc^{-3}\ yr^{-1}}$ (depending on the source spectral index s) from the PAO data [17].

The thing left to do is to calculate the distribution of deflection angles of arrival times. Our method of calculation takes into account the GMF as well as the IGMF [17]. The effective IGMF strength B_{EG} is very uncertain, but we can estimate upper bounds on B_{EG} and resulting τ_d, by comparing the calculated distribution of deflection angles to the typical angular separation of observed UHECRs. In this work, we adopt $\psi \sim 5^\circ$ as the angular separation, according to the PAO results [4], [7]. As the energy distribution of cosmic rays at a source, we assume power-law spectra of $dN/dE_g \propto E_g^{-s}$.

III. Implications for Transient UHECR Sources

By exploiting our numerical calculations, we can estimate lower and upper bounds on τ_d using $\psi \sim 5^\circ$, which allows us to estimate the allowed range of ρ_0 and $\tilde{\mathcal{E}}_{\mathrm{CR}}^{\mathrm{iso}}$ from $n_s \sim 10^{-4}\,\mathrm{Mpc}^{-3}$. As the local rate, we obtain

$$0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} < \rho_0 < (60-3000)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}. \quad (4)$$

Note that stronger upper bounds can be obtained with the GMF with a dipole magnetic field. However, since the existence of a dipole field is very tentative, we can consider the GMF without a dipole field for conservative discussions. The required cosmic-ray energy input at 10^{19} eV, $\tilde{\mathcal{E}}_{\mathrm{HECR}}^{\mathrm{iso}} \equiv \tilde{\mathcal{E}}_{\mathrm{CR}}^{\mathrm{iso}}(10^{19}\ \mathrm{eV})$ is also estimated and the results are summarized in Fig. 1.

Note that our estimates would be valid as long as UHECR sources are regarded as transient, i.e., $\delta T < \tau_d < \Delta T$, where δT is the true burst duration during which particle acceleration occurs and ΔT is the time interval between bursts. For bounds to be meaningful, $\tau_d < \Delta T$ should be satisfied. Otherwise, more than one UHECR bursts occur in τ_d within ψ, and we would see these bursts as a single but more energetic burst. When $\psi \sim 5^\circ$, the time interval is estimated as $\Delta T \sim (3/\pi)\rho_0^{-1}\psi^{-2}D_{\max}^{-3}(E_{\mathrm{th}}) \simeq 3\tau_d n_{s,-4}^{-1}$. Since $\Delta T > \tau_d$, we may expect that obtained bounds would make a sense, although we should be careful of the possibility not to see each UHECR burst as a distinctive one for larger n_s.

The total cosmic-ray energy input $\mathcal{E}_{\mathrm{CR}}^{\mathrm{iso}}$ is generally larger than $\tilde{\mathcal{E}}_{\mathrm{HECR}}^{\mathrm{iso}}$ by $R(10^{19}\ \mathrm{eV}) \equiv (\int dE'_g\ E'_g\ \frac{dN}{dE'_g})/(E_g^2 \frac{dN}{dE_g})_{E_g=10^{19}\ \mathrm{eV}}$. R depends on the cosmic-ray spectrum at a source, and we expect $R \sim 20-500$ for $s \sim 2.0-2.2$ expected in the ankle scenario while $R > 100$ for $s \sim 2.4-2.6$ expected in the proton-dip scenario, and the latter scenario generally requires the break energy below the second knee. In both scenarios, we expect that the transient hypothesis requires the relatively large cosmic-ray energy input per burst $\mathcal{E}_{\mathrm{CR}}^{\mathrm{iso}} > 10^{50.5}$ ergs, which would be a strong requirement on potential sources.

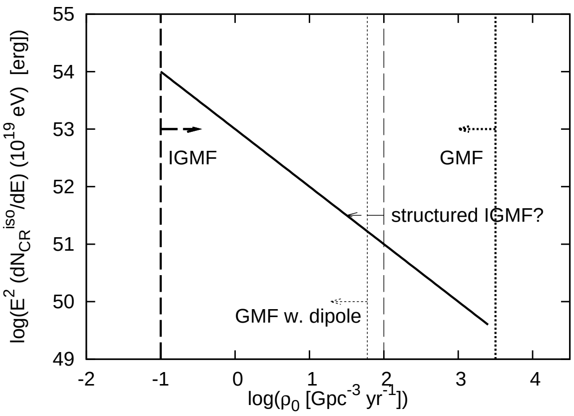

Fig. 1: The required cosmic-ray energy input at 10^{19} eV, $\mathcal{E}^{\rm iso}_{\rm HECR} \equiv \tilde{\mathcal{E}}^{\rm iso}_{\rm CR}(10^{19}\ {\rm eV})$ as a function of the local rate ρ_0.

So far, several potential sources are proposed as transient accelerators, and high-luminosity (HL) GRB is one of them. The isotropic radiation energy is $\mathcal{E}^{\rm iso}_{\gamma} \sim 10^{53}$ ergs, and HL GRBs are the most energetic transient phenomena in the universe. The local rate is uncertain, but recently suggested rates in the Swift era, $\rho_0 \sim (0.05-0.27)\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ are smaller than previous ones [25]. If $\rho_0 < 0.1\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ is real, HL GRBs would be difficult as UHECR sources, since they require rather strong IGMFs with $B_{\rm EG} >$ nG and large isotropic energy input of $\mathcal{E}^{\rm iso}_{\rm CR} > 2 \times 10^{55} (R/20)$ ergs. Low-luminosity (LL) gamma-ray bursts may overcome the problem that the local rate of HL GRBs seems too small [13], because their local rate is likely to be much higher, $\rho_0 \sim 10^{2-3}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ [25].

About 10 % of core collapse SNe may form magnetars, which may be UHECR sources [14]. However, our results would suggest that all the magnetars (and SNe) do not produce UHECRs uniformly and only a fraction of magnetars is the main origin, which is also consistent with the theoretical expectation [14]. For example, only newly born magnetars associated with SNe Ibc could be major UHECR accelerators, which leads to $\rho_0 \sim 3000\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ and $\mathcal{E}^{\rm iso}_{\rm CR} \sim 3 \times 10^{50} (R/10)$ ergs. Giant magnetar flares could not explain UHECRs, since their radiation energy, $\mathcal{E}^{\rm iso}_{\gamma} \sim 10^{46}$ ergs is much smaller than $\mathcal{E}^{\rm iso}_{\rm CR}$.

AGNs are the most discussed UHECR accelerators, and one possibility as transient sources was recently suggested [15]. Such giant AGN flares may be UHECR sources, but the suggestion is speculative. If we adopt $\rho_0 \sim 10^{2-3}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ although the rate is also uncertain, the required energy input is $\mathcal{E}^{\rm iso}_{\rm CR} \sim 2 \times 10^{51-52} (R/20)$ ergs. The corresponding luminosity is $L^{\rm iso}_{\rm CR} \sim 2 \times 10^{46-47}\ (R/20)\ (10^5\ {\rm s}/\delta T)$ ergs ${\rm s}^{-1}$. Another possibility may be that UHECRs are produced when flares occur in jets of FR I galaxies, although the correlation between UHECRs and FR I galaxies have not been confirmed yet. In fact, blazar flares seem to have sufficient luminosities for UHECR acceleration. However, the apparent number density of blazars is too small compared to $n_s \sim 10^{-4}\ {\rm Mpc}^{-3}$. This problem can be overcome if UHECRs are deflected in radio lobes of FR I galaxies [26]. In fact, FR I galaxies themselves have the comparable number density of $\sim 10^{-4}\ {\rm Mpc}^{-3}$.

Note that, although the above implications may be interesting, we should be careful to reach definite conclusions about the sources because of current poor statistics. The suggested positional correlation is confirmed just at 2-3 sigma levels, which might disappear when we observe more UHECR events. Also, the estimate of n_s has large errors at present due to not only poor statistics but also the lack of our knowledge of the precise positions of UHECR sources, and it is not so easy to exclude the possibility that UHECR sources contains many dim accelerators, i.e., large n_s. But, once statistics will be better in the near future, the order of n_s will be accurately determined by 5 yrs observations by the PAO [27]. However, statistical analyses become more complicated when the sources are transient and/or their luminosity function is taken into account. More detailed and careful studies, taking into account the realistic structured IGMFs in clusters and filaments, will be presented in our forthcoming paper.

IV. Associated Neutrinos and Gamma Rays

We have discussed implications for the transient UHECR sources, but it is also important to know whether the sources are transient or not. The signature may be found from the observed UHECR spectrum, e.g., from the average number of multiplets. For identification of sources, the multimessenger astronomy will be particularly important. High-energy neutrinos are useful as an important probe of cosmic-ray acceleration, which may be detected by future large neutrino telescopes such as IceCube and KM3Net. For example, HL GRB is one of the most widely discussed high-energy neutrino sources [28], [19]. $\sim$ PeV neutrinos are expected in the prompt phase while $\sim$ EeV neutrinos in the early afterglow phase [20]. If LL GRBs are the relevant UHECR sources, their neutrinos may give the significant contribution to the cumulative neutrino background [13]. Magnetars can also be strong neutrino emitters, if they are the UHECR sources. Although the acceleration mechanism in magnetars is very speculative, possible detections of neutrinos may probe the origin of their strong magnetic fields. AGNs are the most frequently discussed neutrino sources, and UHECR production in AGNs has been expected in various scenarios, in the vicinity of the supermassive black hole, inside jets, at hot spots and so on. One often expects UHECRs and associated neutrinos coming from AGN jets [29]. In Fig. 2, we show the cumulative background under the giant AGN flare scenario. For comparison, we also show cosmogenic neutrinos and neutrinos from clusters of galaxies whose accretion/merger shocks could also be powerful accelerators.

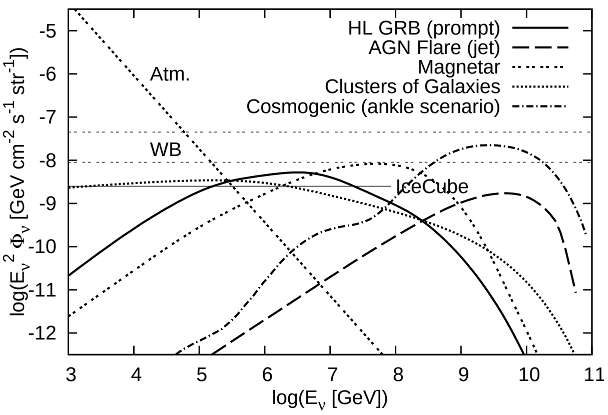

Fig. 2: The cumulative neutrino backgrounds expected for HL GRBs (in the prompt emission phase) [28], [19], [20], giant AGN flares, fast rotating magnetars [21], and clusters of galaxies [22]. Cosmogenic neutrinos for $E_p^{\max} = 10^{21}$ eV [23] are also shown. The cosmic-ray energy input is normalized with the UHECR energy input for HL GRB and AGN Flare, but with the energy input of very-high-energy cosmic rays around the second knee for clusters of galaxies. The star forming evolution model is assumed for Cosmogenic.

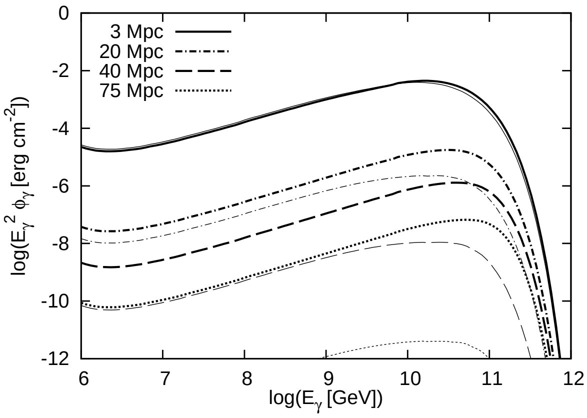

Fig. 3: Energy fluences of ultra-high-energy gamma rays from a UHECR burst with $\tilde{\mathcal{E}}_{\rm HECR}^{\rm iso} = 10^{50.5}$ erg (corresponding to $\rho \sim 10^{2.5}$ $\rm Gpc^{-3} yr^{-1}$) for each distance. Thick lines show the non-CRB case while thin lines show the CRB case.

Not only neutrinos but also ultra-high-energy photons may be relevant especially for proving acceleration of UHECRs rather than lower-energy cosmic rays. To prove the origin of the UHECR sources, detections of $E_\nu \approx 5$ EeV $E_{p,20}$ or $E_\gamma \approx 10$ EeV $E_{p,20}$ are favorable. However, it is not so easy to detect EeV neutrinos via earth-skimming ν_τs. In addition, as is demonstrated in Fig. 2 for the case of HL GRB (prompt), very high-energy neutrino emission may be suppressed since charged mesons and muons can cool down before they decay [28]. On the other hand, ultra-high-energy photons from nearby bursting sources may be detected by future detectors such as JEM-EUSO, possibly by the PAO. The cascade effect may enhance our chance to detect these signals, as long as the IGMF that ultra-high-energy pairs feel is weak enough. Note that such very weak IGMFs are possible in voids (i.e., $B_{\rm IG} \ll B_{\rm EG}$) [30], and ultra-high-energy photons may go out of the structured region. Examples of the resulting ultra-high-energy gamma-ray spectra are shown in Fig. 3 for the case of $s = 2$ with the photomeson production efficiency of $f_{p\gamma} = 0.1$ and $E_\gamma^{\max} (\approx 0.1 E_p^{\max}) = 10^{19.5}$ eV.

Let us discuss associated GeV-TeV gamma-ray signals that may be detected by *Fermi*, MAGIC and other gamma-ray detectors. First, GeV-TeV gamma rays cascaded in the source can be expected [31]. Even if ultra-high-energy photons can escape from the source, a significant fraction of them should be radiated as lower-energy gamma rays via the synchrotron or inverse-Compton emission. But results are rather sensitive to the IGMF in voids. If the IGMF is very weak, they may be detected as pair echoes, i.e., long lasting cascaded gamma-ray emission [30]. If the IGMF in voids are not weak, they may be detected as a pair halo [32] but their flux should be greatly reduced due to the IGMF. If the IGMF is sufficiently strong, UHE pairs will emit $\sim$ GeV $\gamma_{e,13}^2 B_{\rm IG,-9}$ photons that could be detected by *Fermi*. In addition, electrons may be accelerated (as expected in the shock acceleration theory for high-Mach-number shocks), which also allows us to expect photon counterparts.

References

[1] C.D. Dermer, arXiv:0711.2804.
[2] M. Kachelrieß, 2008, arXiv:0801.4376.
[3] J. Abraham *et al.*, Science **318**, 938 (2007).
[4] J. Abraham *et al.*, Astropart. Phys. **29**, 188 (2008).
[5] R.U. Abbasi *et al.*, Astropart. Phys. **30**, 175 (2008).
[6] T. Stanev, arXiv:0805.1746.
[7] H. Takami *et al.*, arXiv:0812.0424.
[8] G. Ghisellini *et al.*, Mon. Not. R. Astron. Soc. **390**, L88 (2008).
[9] M.R. George *et al.*, Mon. Not. R. Astron. Soc. **388**, L59 (2008).
[10] I. Zaw, G.R. Farrar, and J. Greene, arXiv:0806.3470.
[11] J. Rachen and P.L. Biermann, Astronomy Astron. **272**, 161 (1993).
[12] E. Waxman, Phys. Rev. Lett. **75**, 386 (1995).
[13] K. Murase, K. Ioka, S. Nagataki, and T. Nakamura, Astrophys. J. **651**, L5 (2006).
[14] J. Arons, Astrophys. J. **589**, 871 (2003).
[15] G.R. Farrar and A. Gruzinov, Astrophys. J. **693**, 329 (2009).
[16] A. Miralda Escude and E. Waxman, Astrophys. J. **462**, L59 (1996).
[17] K. Murase and H. Takami, Astrophys. J. **690**, L14 (2009).
[18] H. Takami and K. Sato, Astropart. Phys. **30**, 306 (2008).
[19] K. Murase and S. Nagataki, Phys. Rev. D **73**, 063002 (2006).
[20] K. Murase, Phys. Rev. D **76**, 123001 (2007).
[21] K. Murase, P. Mészáros, and B. Zhang, Phys. Rev. D **79**, 103001 (2009).
[22] K. Murase, S. Inoue, and S. Nagataki, Astrophys. J. **689**, L105 (2008).
[23] H. Takami, K. Murase, S. Nagataki, and K. Sato, Astropart. Phys. **31**, 201 (2009).
[24] K. Murase, arXiv:0904.2087.
[25] D. Guetta and M.D. Valle, Astrophys. J. **657**, L73 (2007).
[26] C.D. Dermer *et al.*, arXiv:0811.1160.
[27] H. Takami and K. Sato, Astropart. Phys. **28**, 529 (2008).
[28] E. Waxman and J. Bahcall, Phys. Rev. Lett. **78**, 2292 (1997).
[29] A. Atoyan and C.D. Dermer, Phys. Rev. Lett. **87**, 221102 (2001).
[30] R. Plaga, Nature (London) **374**, 430 (1995).
[31] C. D. Dermer and A. Atoyan, New J. Phys. **8**, 122 (2006).
[32] F.A. Aharonian, P.S. Coppi, and H.J. Völk, Astrophys. J. **423**, L5 (1994).