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Observability of high-energy gamma-rays from core-collapse supernovae by CTA

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Cosmic rays (CRs) with energy up to the knee energy ($\sim$ 3 PeV) are believed to be accelerated by supernova remnants via the diffusive shock acceleration (DSA) process. However, based on the DSA model under typical supernova conditions, the maximum energy of CRs cannot reach to the knee energy. This is considered due to the weak interstellar magnetic field. Recently, direct numerical simulations of the DSA with magnetic field amplification by the Bell instability were performed by Inoue et al. (2021). They argued that CRs can be accelerated up to knee energy during the early phase of a supernova expansion in a dense circumstellar medium created by red supergiant wind. In this study, we focus on the propagation of gamma-rays produced by CRs in such a situation. The gamma-rays emitted at the shock front interact with soft photons from the supernova photosphere and cosmic background radiations. We calculate the evolution of the gamma-ray flux and estimate whether the CTA can detect such gamma-ray emissions. We found that CTA is able to detect 100 TeV gamma-rays from very young supernova remnants once per a few years.

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1. Introduction

It is commonly accepted that the diffusive shock acceleration (DSA) process is connected to a mechanism of CR acceleration (e.g., [3]). This acceleration mechanism is believed to work in supernova remnants to produce charged particles with energies up to $10^{15.5}$eV, so-called knee energy. However, this acceleration model does not reach to the knee energy in typical magnetic environment. To solve this problem, various improvements to the model are still being attempted. Recent theoretical studies suggest that a SNR blast wave shock propagating in a dense circumstellar medium can be a strong candiate of CR accelearation up to the knee, because stronger magnetic field is expected in the dense CSM ([7]). The accelerated CRs can produce gamma-ray via neutral pion decay. However, gamma-rays interact with photons in the photosphere of supernova remnants and cosmic background radiation that attenuate the flux (e.g., [2, 6, 9]).

In this study, we consider an opacity that incorporates a 2 photon annihilation process between gamma-rays and surrounding photons to predict the flux of gamma-rays originating from a very young SNR interacting with the CSM. We also estimate the frequency of gamma-ray detections from the very young SNRs that can be observed by the Cherenkov Telescope Array (CTA).

2. Gamma-ray Emission

2.1 Production of Neutral Pions

We consider the situation where high-energy cosmic rays (protons) generated by DSA process collide with interstellar protons. However, this reaction does not occur at any time when two protons are present. It is limited to the case where the energy $E_{\rm th}$ of cosmic ray protons in the laboratory frame (rest frame of interstellar matter protons) satisfies:

$$E_{\rm th} \gtrsim 1.2, \mathrm{GeV} \tag{1}$$

The neutral pions produced in this reaction are one type of mesons that mediate the nuclear force binding the nucleons in the pion.

2.2 Decay of Neutral Pions

Next, the neutral pions produced in the above reaction are extremely unstable with a lifetime of 8.52×10^{-17} s. Immediately after their production, they undergo a decay reaction such as:

$$\pi^0 \longrightarrow 2\gamma \tag{2}$$

where they decay into two photons. The energy of the photons produced in the rest frame of the neutral pion (π^0) is approximately:

$$\frac{1}{2} m_{\pi^0} c^2 \approx 67.5, \mathrm{MeV} \tag{3}$$

Since the neutral pions receive some of the kinetic energy from the cosmic ray protons before decay, the energy of the photons observed in the laboratory frame has higher than this value. Gamma-rays with energies on the order of 100 TeV (slightly smaller) are emitted when the kinetic energy of the cosmic ray protons is 1 PeV.

2.3 Flux of Gamma-Rays Generated from Cosmic Rays

In the vicinity of a supernova remnant's shock wave, cosmic ray protons are accelerated by DSA process, and high-energy cosmic rays are produced, leading to the production of neutral pions and subsequently gamma-rays. The flux of gamma-rays with energies above 1 TeV generated by SN1993J through this process can be described as follows [11]:

$$F_{\gamma,\mathrm{unabs}}(>1\,\mathrm{TeV}) \approx 2\times 10^{-12}\left(\frac{\eta_{\mathrm{inj}}^{\mathrm{p}}}{10^{-4}}\right)\left(\frac{D}{3.63\,\mathrm{Mpc}}\right)^{-2} \times\left(\frac{\dot{M}_{\mathrm{RSG}}}{3.8\times 10^{-5}\,M_{\odot}/\mathrm{yr}}\right)^{2}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)^{-2}\left(\frac{t}{\mathrm{days}}\right)^{-1}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \quad (4)$$

Furthermore, the flux of gamma-rays with energies above 100 TeV generated by typical SNe can be described as:

$$F_{\gamma,\mathrm{unabs}}(>100\,\mathrm{TeV}) \approx 2\times 10^{-10}\left(\frac{\eta_{\mathrm{inj}}^{\mathrm{p}}}{10^{-4}}\right)\left(\frac{D}{1\,\mathrm{Mpc}}\right)^{-2} \times\left(\frac{\dot{M}_{\mathrm{RSG}}}{10^{-3}\,M_{\odot}/\mathrm{yr}}\right)^{2}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)^{-2}\left(\frac{t}{\mathrm{days}}\right)^{-1}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \quad (5)$$

Here, η_{inj}^{p} represents an injection rate of cosmic ray protons, D is distance from the supernova remnant to the Earth, u_{w} is stellar wind velocity of the red supergiant, $\dot{M}_{\mathrm{RSG}}$ is mass loss rate from the red supergiant star, and t represents time elapsed since the supernova explosion.

3. Two-Photons Annihilation (Electron-Positron Pair Production)

3.1 Two-Photons Annihilation

When the photon energy exceeds 2 times the electron rest mass energy mc^2, an electron-positron pair can be generated. When a gamma-ray is irradiated on a Wilson paulownia box or a nuclear dry plate, in addition to electrons bounced off by Compton scattering, two charged particles are sometimes observed to be generated from a point with a narrow angle. When a magnetic field is applied to the experimental setup, the directions of motion of these two particles are bent in opposite directions, indicating that the two particles have positive and negative charges, respectively. The negatively charged particle is an electron, whereas the positively charged particle is called a positron. This phenomenon is called electron-positron pair production.

3.2 Gamma-Ray Opacity due to Two-Photon Annihilation

As described above, the electron-positron pairing process causes the annihilation of 2 photons above certain energy threshold. We consider a model in which gamma rays emitted from a supernova remnant are scattered by soft photons on their way to the earth. (cf. Fig. 1) To quantitatively express the attenuation of gamma-rays, we introduce the "opacity $\tau_{\gamma\gamma}$" for the case of gamma-ray propagation in photons (medium) regarding the previous study [2]. The attenuation of gamma-rays propagating in the scatterer photons due to electron-positron pair production reactions can be written as:

$$\tau_{\gamma\gamma}\left(t,\Psi_0,E\right)=\int_0^{+\infty}\mathrm{d}l\int_{c_{\min}}^{1}\mathrm{d}\cos\theta\int_0^{2\pi}\mathrm{d}\phi\int_{\epsilon_{\min}}^{+\infty}\mathrm{d}\epsilon\, n_{\epsilon}\,\sigma_{\gamma\gamma}\left(1-\boldsymbol{e}_{\gamma}\cdot\boldsymbol{e}_{\star}\right) \quad (6)$$

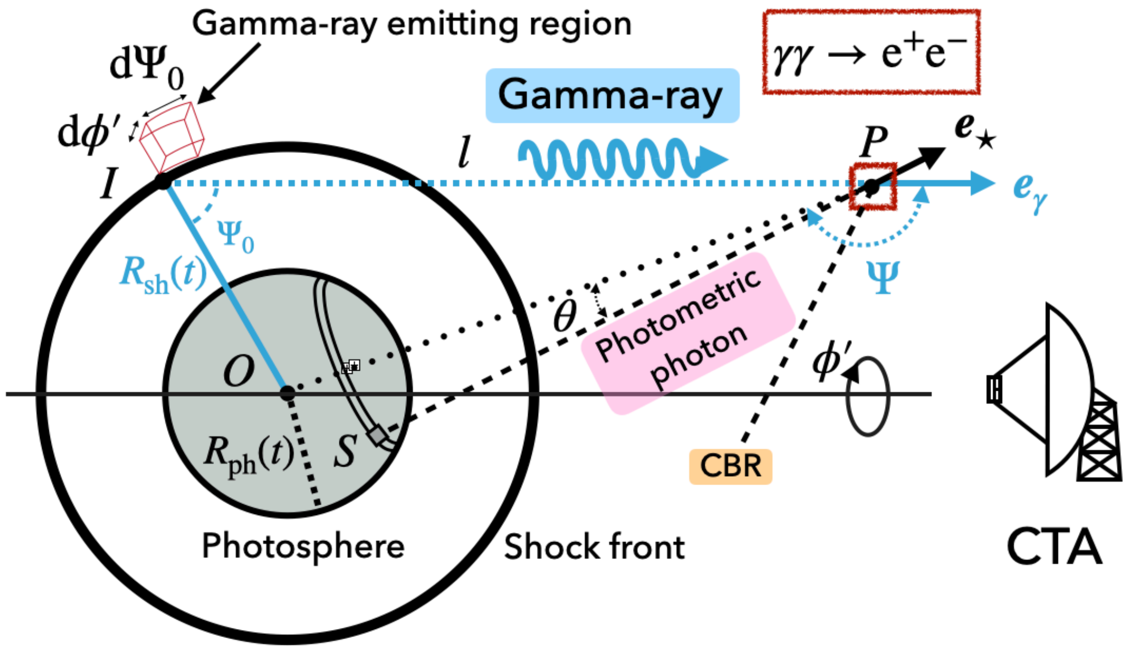

Figure 1: Scattering of gamma-rays from the vicinity of the shock wave and photons from the photosphere. The figure shows the time t after the supernova explosion. The 2 circles on the left of the figure are the supernova remnant and the observer (CTA) is at infinity on the right. The point O is the center of the supernova remnant, and a photosphere of radius R_{ph} (inner circle) and a shock wavefront of radius R_{sh} (outer circle) are isotropically extended from there. gamma-rays emitted from point I and soft photons emitted from point S (photosphere surface) interact at point P.

where t is time since the SN explosion, E is energy of the gamma-rays, Ψ_0 shows gamma-rays emitting region, l is optical path length from gamma-rays emitting region to the interaction point, θ and ϕ show photometric photons emitting region, and ϵ is energy of the photometric photons. For the function under integration, n_ε denotes number density at the interaction point of photometric photons emitted on photosphere surface (assuming blackbody radiation), $\sigma_{\gamma\gamma}$ cross-section of electron-positron pair production ($\gamma\gamma \longrightarrow e^+e^-$), and the inner product term: angular dependence of a gamma-ray direction ($\boldsymbol{e}_\gamma$) and a photometric (or CBR) photon ($\boldsymbol{e}_\star$). For the integral range, ϵ_{min} denotes the energy threshold of the photometric photon at which gamma-ray annihilation occurs and c_{min} effect of gamma-rays being blocked by the photosphere. The following model is used for the time evolution of the photosphere and the shock wave surface [8, 10]. (cf. Fig. 2)

Similarly, the opacity due to cosmic background radiation can be written as

$$\tau_{\mathrm{CBR}}\left(t, \Psi_0, E\right) = \int_0^{+\infty} \mathrm{d}l \int_{-1}^{1} \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \int_{\epsilon_{\mathrm{min}}}^{+\infty} \mathrm{d}\epsilon\, n_{\mathrm{CBR}}\, \sigma_{\gamma\gamma} \left(1 - \boldsymbol{e}_\gamma \cdot \boldsymbol{e}_\star\right) \tag{7}$$

where n_{CBR} is number density at the interaction point of cosmic background radiation, and cosmic background radiation is assumed to come uniformly from all directions [9]. Using these two

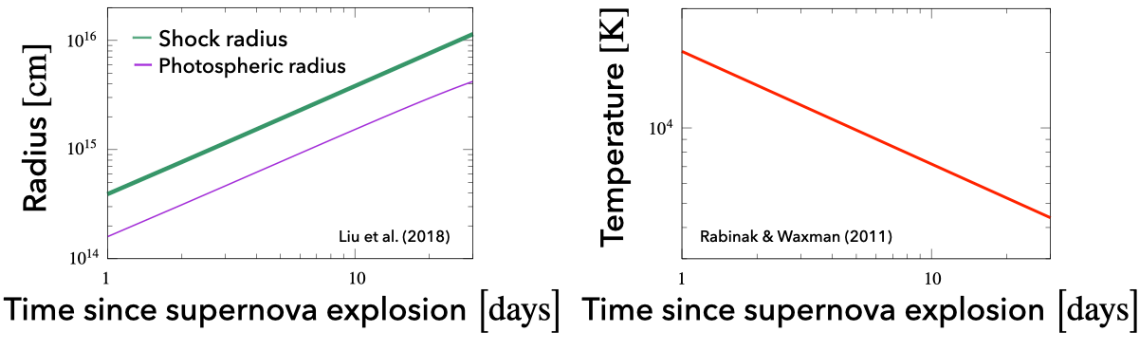

Figure 2: The left panel shows time evolution of the shock wave and the radius of the photosphere [8], and the right panel shows time evolution of the surface of the photosphere [10].

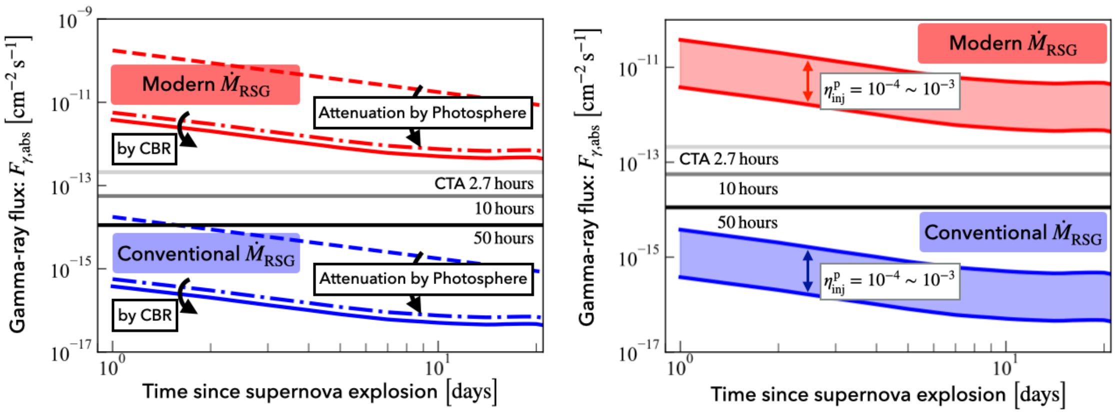

Figure 3: For the attenuation by photon annihilation (cf. the left panel), the gamma-ray flux is attenuated to $\sim 1/10$ or less by photons from the photosphere at the 14 days after the explosion. It is further attenuated to $\sim 2/3$ by cosmic background radiation. For the mass loss model (cf. the left and right panel), Recent observations revealed that the mass-loss rate of most RSGs is enhanced to 100 times the conventional value a few years before the explosion [5]. This increases the flux of gamma-ray by two to four orders of magnitude. If we employ the modern mass loss rates $\dot{M} = 10^{-3}\, M_{\odot}\,\mathrm{yr}^{-1}$, the flux exceeds CTA 2.7 hours sensitivity [1].

opacities, net flux of gamma-rays reaching the Earth (CTA) can be written as

$$F_{\gamma,\mathrm{abs}} = F_{\gamma,\mathrm{unabs}} \times \frac{1}{4\pi} \int_0^{2\pi} \mathrm{d}\phi' \int_{\Psi_{0,\mathrm{min}}}^{\pi} \mathrm{d}\Psi_0 \, \sin\Psi_0 \, \exp\left(-\tau_{\gamma\gamma} - \tau_{\mathrm{CBR}}\right) . \tag{8}$$

4. Gamma-ray Flux Observed on the Earth (CTA)

By integrating equation 8, we can calculate evolution of gamma-ray flux above 100 TeV after SN explosion. (cf. The left panel of Fig. 3) Also, we calculate evolution of gamma-ray flux using different cosmic ray injection rates: $\eta^{\mathrm{p}}_{\mathrm{inj}} = 10^{-4} \sim 10^{-3}$ (cf. The right panel of Fig. 3).

5. Detection by CTA 2.7 hours

We estimated the detection rate of gamma-rays from PeV cosmic ray by CTA 2.7 hours observations. If we employ the modern mass loss rates ($\dot{M} = 10^{-3}\, M_\odot\, \mathrm{yr}^{-1}$), and the cosmic rays injection rate $\eta^{\mathrm{p}}_{\mathrm{inj}} = 10^{-3}$ (see the solid line in the right panel of Fig.3), the observable distance is 3.8 Mpc, and the detection frequency from nearby galaxies within 3.8 Mpc is $0.43\,\mathrm{yr}^{-1}$, which is 1 every 2.3 years. Given the detection frequency from the Milky Way is $2 \times 10^{-2}\,\mathrm{yr}^{-1}$, the detection from extragalactic sources is much higher than that of the Milky Way Galaxy, and thus gamma-rays from very young SNRs can be detected by the CTA.

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