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

Tomotaka Nishikawa[1,*] **and Tsuyoshi Inoue**[2]

[1] *Nagoya University, Department of Physics,*
Furo-cho 1, Nagoya-shi, Aichi, JAPAN
[2] *Konan University, Department of Physics,*
8-9-1, Okamoto, Higashinada-ku, Kobe-shi, Hyogo, JAPAN
E-mail: nshikawa.tomotaka.c4@s.mail.nagoya-u.ac.jp, tsuyoshi.inoue@konan-u.ac.jp

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 the knee energy. This is considered due to the weak interstellar magnetic field. Recently, direct numerical simulations of the DSA with Bell instability that amplify upstream magnetic fields were performed by Inoue et al. (2021). They argue 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 2.2 years.

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*Speaker

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1. Introduction

The existence of cosmic rays was confirmed by observation in the mid-1920s. They consist mainly of protons and include charged particles such as electrons and nuclei, as well as high-energy photons such as gamma-rays and neutrinos. The origin of these particles and the principle of their generation are still not clearly understood, even after 100 years since their discovery. Also, the energy that can be artificially produced by particle accelerators is about 10^{13} eV in the center-of-mass system, whereas the energy of cosmic rays is about 10^{13} eV. whereas cosmic rays have energies as high as 10^{20} eV. The mechanism by which cosmic rays are accelerated to this tremendous energy is called diffuse shock wave acceleration (e.g. [3]) is widely accepted as the mechanism by which cosmic rays are accelerated to such tremendous energy. And this acceleration mechanism works in supernova remnants to produce charged particles with energies of $10^{10} \sim 10^{15.5}$ eV energy. However, this acceleration model does not reach the knee energy of $10^{15.5}$ eV. To solve this problem, various improvements to the model are still being attempted.

One model of the acceleration mechanism in supernova remnants ([7]) claims that the shock wave can be accelerated to knee energy during the period of propagation in the circumstellar material during the first ten days after the explosion, because a stronger upstream magnetic field is expected. However, this has not been verified by current instruments. The magnetic field in the galaxy can readily change the protons' motion's direction, making it very challenging to pinpoint their source. Therefore, we focus on high-energy photons (gamma-rays) produced when proton cosmic rays with knee energies collide with circumstellar matter to produce neutral pions, which then decay into neutral pions. Since the direction of motion cannot be changed by the magnetic field, the gamma-rays are observed for verification. However, gamma-rays are predicted to interact with photons in the photosphere of supernova remnants and cosmic background radiation in the form of annihilation ([6]) and to attenuate the flux (e.g., [2, 9]).

In this study, we introduce an opacity that incorporates a 2 photon annihilation process between gamma-rays and surrounding photons to predict the amount of flux of gamma-rays originating from supernova remnants. Therefore, we use a model that considers the interaction between gamma-rays and photons from the photosphere ([2, 4]), and a model that considers the interaction between gamma-rays and cosmic background radiation ([9]). We also estimate the frequency of gamma-ray detections from supernova remnants that can be observed by the Cherenkov Telescope Array (CTA), a gamma-ray telescope that is currently undergoing initial observations and has a sensitivity that is 1 orders of magnitude higher than other current gamma-ray telescopes.

2. Gamma-ray Emission

2.1 Gamma-Rays Generated from Cosmic Rays

In this subsection, we discuss the process of generating gamma-rays from high-energy cosmic rays through Fermi acceleration.

2.2 Production of Neutral Pions

Let's consider the situation where high-energy cosmic rays (protons) generated by Fermi acceleration collide with interstellar protons. The reaction is as follows:

$$\mathrm{p}\,(\text{cosmic rays}) + \mathrm{p}\,(\text{interstellar matter}) \to \mathrm{p} + \mathrm{p} + \pi^0 \tag{1}$$

However, this reaction does not occur at any time when two protons are present. It is limited to the case where the energy E_{th} of cosmic ray protons in the laboratory frame (rest frame of interstellar matter protons) satisfies:

$$E_{\mathrm{th}} \gtrsim 1.2, \mathrm{GeV} \tag{2}$$

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

2.3 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:

$$\pi^0 \to 2\gamma \tag{3}$$

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

$$\frac{1}{2} m_{\pi^0}\, c^2 \approx 67.5, \mathrm{MeV} \tag{4}$$

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.

2.4 Flux of Gamma-Rays Generated from Cosmic Rays

In the vicinity of a supernova remnant's shock wave, cosmic ray protons are accelerated by the first-order Fermi 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]:

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

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

$$F_{\gamma,\mathrm{unabs}}(>100\,\mathrm{TeV}) \approx 2\times10^{-10}\left(\frac{\eta^{\mathrm{p}}_{\mathrm{inj}}}{10^{-4}}\right)\left(\frac{D}{1\,\mathrm{Mpc}}\right)^{-2} \times\left(\frac{\dot{M}_{\mathrm{RSG}}}{10^{-3}\,M_{\odot}/\mathrm{yr}}\right)^{2}\left(\frac{u_{\mathrm{w}}}{10\,\mathrm{km/s}}\right)^{-2}\left(\frac{t}{\mathrm{days}}\right)^{-1}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \tag{6}$$

Here, η^{p}_{inj} represents the injection rate of cosmic ray protons, D is the distance from the supernova remnant to the Earth, u_{w} is the speed of the red supergiant star's stellar wind, $\dot{M}_{\mathrm{RSG}}$ is the mass loss rate from the red supergiant star, and t represents the 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 (electron-positron) can be generated. When the γ line, which is a photon with high energy, is irradiated on a Wilson paulownia box or a nuclear dry plate, in addition to electrons bounced off by Compton scattering, 2 charged particles are sometimes observed to be generated from a certain 1 point with a narrow angle. When a magnetic field is applied to the experimental setup, the directions of motion of these 2 particles are bent in opposite directions, indicating that the 2 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 a certain energy threshold. 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]. We consider a model that shows the decay of gamma-rays from the vicinity of the seed breakup of a supernova remnant by the time they reach the observer (CTA), where they are annihilated by soft photons from the photosphere of the supernova remnant. (cf. Fig. 1)

The attenuation of gamma-rays propagating in the scatterer photons due to electron-positron pair production reactions can be written as:

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

where t is the time since the SN explosion, E is the energy of the gamma-rays, Ψ_0 shows the gamma-ray emitting region, l is the optical path length from the gamma-ray emitting region to the interaction point, θ and phi show the photometric photons emitting region, and ϵ is the energy of the photometric photons. For the function under integration, n_{ε} denotes the number density at the interaction point of photometric photons emitted on the photosphere surface (assuming blackbody radiation), $\sigma_{\gamma\gamma}$ the cross-section of electron-positron pair production ($\gamma\gamma \to \mathrm{e}^{+}\mathrm{e}^{-}$), and

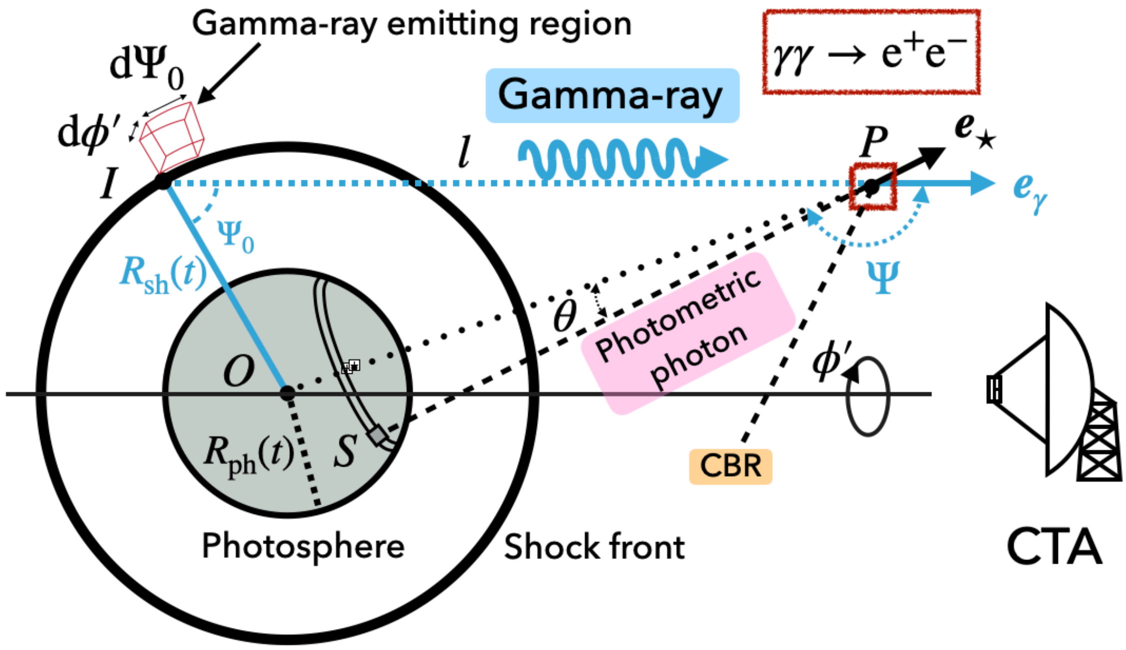

Figure 1: Scattering of gamma-rays from the vicinity of the shock wave and photons from the photosphere. The figure shows the time t after the supernova explosion. The 2 circles on the left of the figure are the supernova remnant and the observer (CTA) is at infinity on the right. The point O is the 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.

the inner product term: depending on the angle between gamma-rays and photons (scatterers), the annihilation rate varies. 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

$$\tau_{CBR}(t, \Psi_0, E) = \int_0^{+\infty} dl \int_{-1}^{1} d\cos\theta \int_0^{2\pi} d\phi \int_{\epsilon_{min}}^{+\infty} d\epsilon\, n_{CBR}\, \sigma_{\gamma\gamma} \left(1 - \boldsymbol{e}_\gamma \cdot \boldsymbol{e}_\star\right) \tag{8}$$

where n_{CBR} is the 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 opacities, the net flux of gamma-rays reaching the Earth (CTA) can be written as

$$F_{\gamma,abs} = F_{\gamma,unabs} \times \frac{1}{4\pi} \int_0^{2\pi} d\phi' \int_{\Psi_{0,min}}^{\pi} d\Psi_0\, \sin\Psi_0\, \exp\left(-\tau_{\gamma\gamma} - \tau_{CBR}\right). \tag{9}$$

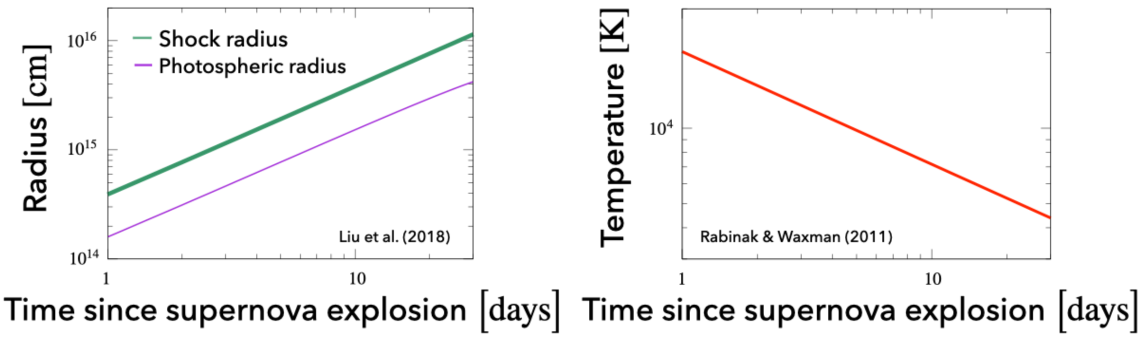

Figure 2: The left panel shows the time evolution of the shock wave and the radius of the photosphere [8], and the right panel shows the time evolution of the surface of the photosphere [10].

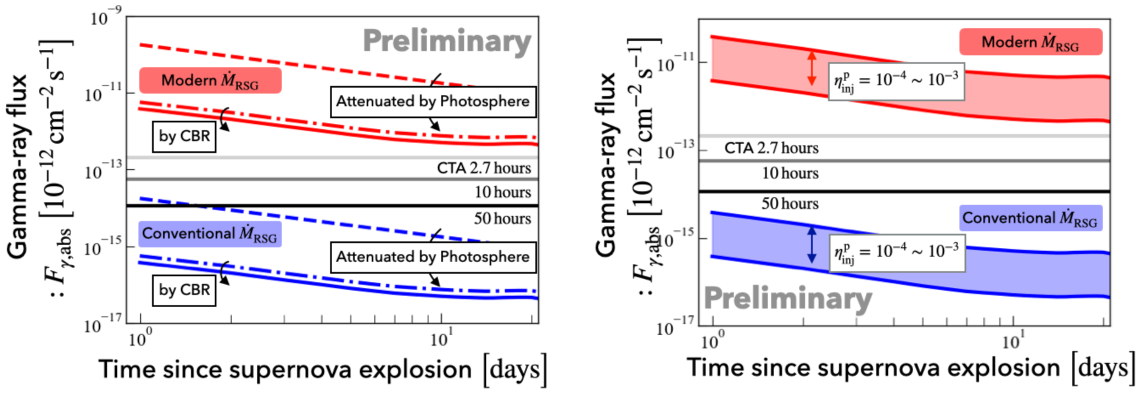

Figure 3: For the attenuation by photon annihilation (cf. the left panel), The flux is attenuated to about 1/10 or less by photons from the photosphere on the 14th day after the explosion. It is further attenuated to about 2/3 by cosmic background radiation. For the mass loss model (cf. the left and right panel), The mass-loss rate of most RSGs is about 10 to 100 times the previous value a few years before the explosion [5]. This mass-loss rate increases the flux of gamma-ray by about two to four orders of magnitude. For modern mass loss rates, the flux exceeds CTA 2.7 hours sensitivity [1].

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

Performing the integration of eq. 9, we calculate the time evolution of a gamma-ray flux above 100 TeV after SN explosion. (cf. The left panel of Fig. 3) In addition, we calculate the time evolution of the gamma-ray flux using different cosmic ray incidence rates: $\eta^{\rm p}_{\rm inj} = 10^{-4} \sim 10^{-3}$ (cf. The right panel of Fig. 3).

5. Detection by CTA 2.7 hours

We estimate the expected detection of SNR-derived gamma-rays from the CTA 2.7 hours observations. If the mass loss rate is modern value ($\dot{M}_{\rm RSG} \sim 10^{-3}\,M_\odot\,{\rm yr}^{-1}$) and the cosmic ray injection rate $\eta^{\rm p}_{\rm inj} = 10^{-3}$, i.e., if the topmost solid line in the right panel of Fig. 3, the observable distance is 3.8 Mpc, and the detection frequency from outside the galaxy is 0.43 yr^{-1}, which is 1 every about 2.3 years. Assuming that the detection frequency from the Milky Way is about

$2 \times 10^{-2}\,\mathrm{yr}^{-1}$, the total detection frequency is about 1 every 2.2 years. Based on the above, if the gamma-rays are detectable by CTA 2.7 time observations, the detection frequency from extragalactic sources is much higher than that of the Milky Way Galaxy, and thus gamma-rays from extragalactic sources can be expected to be detected sufficiently.

6. Future work

The simulation of cosmic ray acceleration incorporating Bell instability [7] is combined with the observation and prediction of gamma-rays emitted from cosmic rays in this study to obtain a more realistic observation and prediction of gamma-rays. After the observation by CTA, cosmic ray acceleration with Bell instability in supernova remnants will be verified.

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