Non-Thermal Photon Emission from Shell-Type Supernova Remnants *

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We study the non-thermal photon emission from shell-type supernova remnants (SNRs) in the frame of a two-zone model. In this model, the sites of acceleration, escape and subsequent radiation of particles (both electron and proton) are divided into acceleration and escape zones, respectively. The particle distributions consist of two components, one is produced inside the acceleration zone, the other in the escape zone. We apply this model to two young and one old shell-type SNRs and show that the observed multi-waveband photon spectra for the three SNRs can be explained well in this model and high-energy γ-rays from these SNRs may have hadronic origins.

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Supernova remnants (SNRs) are generally believed to be the origins of Galactic cosmic rays. Recent observations in x-ray and TeV bands[1−5] provided the direct evidence for the acceleration of particles at the SNRs to multi-TeV energies, especially strong evidence for electron acceleration to high energies in the SNRs were established by observations of non-thermal x-ray emission. However, it is not clear that the origin of TeV photon emission from the SNRs is leptonic, or hadronic.

The multi-wavelength photon spectrum for a given SNR can be produced through leptonic processes such as electron synchrotron radiation, bremsstrahlung and inverse Compton (IC) scattering as well as hadronic interaction. Particularly, the IC process of radio and infrared photons by multi TeV accelerated electrons or the pion decay as a consequence of proton-proton interactions of multi TeV accelerated protons with ambient target protons may be responsible for the TeV photon emission.[6] Various models have been developed for describing non-thermal photon emission from the SNRs.[7−10]

Recently, Moraitis and Mastichiadis[10] studied the acceleration and radiation of charged particles in the shock waves of supernova remnants in the frame of the two zone model and applied this model to explain observed multi-band spectrum of SNR G347.3–0.5. In this Letter, we apply this model to interpret the multi-band nonthermal emission from three shell-type SNRs, including two young and one old SNRs.

In the two zone model,[10,11] the sites of acceleration, escape and subsequent radiation of particles (both electron and proton) are divided into acceleration and escape zones respectively. The particles (electrons and protons) are accelerated in the acceleration with an energy-dependent size through diffusive shock acceleration (first order Fermi acceleration) mechanism but simultaneously escape from the acceleration zone into the escape zone at a rate $r_{\rm esc}$, where the synchrotron and the IC scattering energy losses are included. Therefore, the particle distribution functions (both for electrons and protons) are solutions to two coupled partial differential equations, one describing the particles inside the acceleration zone and the other the ones that have escaped from it.

The accelerated particles in the acceleration zone is assumed to have differential energy spectrum $N_1(E)$ and to be gaining energy at rate $r_{\rm acc}(E) = 1/t_{\rm acc}(E)$ as well as losing energy at rate $\dot{E}_1$, but to simultaneously escape from the acceleration zone at the rate $r_{\rm esc}(E) = 1/t_{\rm esc}(E)$. In the escape zone, it is assumed that the particles have differential energy spectrum $N_2(E)$ and are losing energy at rate $\dot{E}_2$. Based on conservation of particle numbers, therefore, the particle distributions in both the zones satisfy following coupled partial differential equations

$$\frac{\partial N_1}{\partial t} + \frac{\partial}{\partial E}\Big[\Big(\frac{E}{t_{\rm acc}} + \dot{E}_1\Big)N_1\Big] + \frac{N_1}{t_{\rm esc}} = Q(E,t), \quad (1)$$

$$\frac{\partial N_2}{\partial t} + \frac{\partial}{\partial E}[\dot{E}_2 N_2] = \frac{N_1}{t_{\rm esc}}, \quad (2)$$

where $Q(E,t) = Q_0\delta(E-E_0)H(t)$ represents injection of particles at low energy E_0 with the constant rate Q_0; $\delta(x)$ and $H(x)$ are the Dirac and the Heaviside functions respectively. In Eqs. (1) and (2), we have to give the expressions of $t_{\rm acc}$ and $t_{\rm esc}$. Following Refs. [10,11], the particles acceleration takes place in a region around the shock of size $L = L_u + L_d = K_u/U_u + K_d/U_d$, where $K_{u(d)}$ and $U_{u(d)}$ are the upstream (downstream) diffusion coefficient and gas velocity respectively. Under the assumptions that $K_u = K_d = K$ and the diffusion coefficient is an energy-dependent power-law form $K(E) = \kappa E^{\delta}$, the size of the acceleration zone can be written as $L(E) = \kappa(r+1)E^{\delta}/U_u$, where $U_u = U_{\rm shock}$ is the shock velocity and $r = U_u/U_d$ is the compression ratio of the shock. Therefore, the acceleration timescale

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can be written as[11]

$$t_{\rm acc}(E) = \frac{3L(E)}{U_u - U_d} = \frac{3(r+1)r}{(r-1)U_u^2}K(E). \tag{3}$$

Because of energy losses in the acceleration zone, a downward flux in the energy space is generated and when combined with the increasing size of the acceleration region, an additional escape process is produced. Therefore, the velocity of escape increases and the escape timescale is estimated as[11]

$$t_{\rm esc}(E) = \frac{L(E)}{U_d + \dot{E}_1(dL_d(E)/dE)}. \tag{4}$$

The second term in the denominator vanishes for constant diffusion coefficient or no energy losses. We denote quantities in the acceleration region with the subscript 1 and in the escape region with the subscript 2.

We now consider two cases that the accelerated particles are electrons and protons respectively. In the case of the accelerated electrons, the electrons loss energy through the synchrotron radiation and/or the IC process, corresponding energy loss rate can be written as

$$\dot{E}_i = -\alpha_i E^2 = -\frac{4}{3}\frac{\sigma_T(U_{B,i} + \sum_j U_{j,i})}{m_e^2 c^3}E^2, \tag{5}$$

where $i = 1, 2$, m_e is electron mass, c is the velocity of light, and the IC is assumed to be in the Thomson limit. For the IC process, the temperatures and energy densities corresponding to the infrared, the microwave, and two stellar background diffuse radiation fields are 25, 2.7, 5000, and 10000 K and $U_{\rm IR} = 0.5 \times 10^{-7}\,{\rm MeV{\cdot}cm^{-3}}$ [4], $U_{\rm CMB} = 2.5 \times 10^{-7}\,{\rm MeV{\cdot}cm^{-3}}$, $U_{5000} = 2.2 \times 10^{-7}\,{\rm MeV{\cdot}cm^{-3}}$, and $U_{10000} = 2.2 \times 10^{-7}\,{\rm MeV{\cdot}cm^{-3}}$ [7], respectively. Since the scattering of CMB photon should dominate over that of locally produced photon fields,[12] we only include scattering of CMB and infrared in this study.

Equations (1) and (2) can be analytically solved. Moraitis and Mastichiadis[10] have given the analytic solutions. For the accelerated electrons, the solution of Eq. (1) is

$$N_1^e(E,t) = \frac{Q_0^e t_{a,0}}{E_0}\Big(\frac{E}{E_0}\Big)^{-s_1}\frac{[1-(\frac{E_0}{E_{\max}})^{\delta+1}]^{b-1}}{[1-(\frac{E}{E_{\max}})^{\delta+1}]^{b}} \tag{6}$$

in the energy range $E_0 < E < E_1(t)$ and zero otherwise, where $E_1(t)$ is the maximum energy of the particles at time t and is determined from the solution of equation describing the evolution of a particle' energy, i.e. $dE/dt = E/t_{\rm acc}(E) - \alpha E^2$. Following Ref. [10], the value of $E_1(t)$ is estimated from the inverse function of time $t_1(E)$ describing that a particle of initial energy E_0 needs to reach energy E and $t_1(E)$ is given by

$$t_1 = t_{c,1}\Big[\frac{x^\delta}{\delta}\,{}_2F_1\Big(\frac{\delta}{\delta+1}, 1, 1+\frac{\delta}{\delta+1}, x^{\delta+1}\Big)\Big]_{x_0}^{x}, \tag{7}$$

where ${}_2F_1(\xi_1, \xi_2, \xi_3, x)$ is the hypergeometric function with parameters of ξ_1, ξ_2 and ξ_3, $t_{c,1} = (\alpha_1 E_{\max})^{-1}$, $x_0 = E_0/E_{\max}$, $x = E/E_{\max}$, and $E_{e,\max} = [(r-1)U_u^2/3r(r+1)\alpha_1\kappa]^{1/\delta+1}$ is the energy in which the acceleration and cooling timescales are equal. In Eq. (6), $t_{a,0} = t_{\rm acc}(E_0)$ is the minimum acceleration timescale, $s_1 = (r+2)/(r-1) - \delta$, and $b = [(r-4)/(r-1) + \delta/(r+1)]/(\delta+1)$.

Moraitis and Mastichiadis[10] obtained the solution of Eq. (2) using a simplified analytic approach, which is

$$N_2^e(E,t) = \begin{cases} N_0^e\Big(\dfrac{E}{E_0}\Big)^{-s_2} I, \quad E < E_c(t), \\ N_0^e\Big(\dfrac{E}{E_0}\Big)^{-s_2} I\,\dfrac{E_c(t)}{E}, \\ \qquad E_c(t) < E < E_1(t), \end{cases} \tag{8}$$

where $N_0^e = Q_0^e(t - t_1(E))/E_0$, $s_2 = (r+2)/(r-1)$,

$$I = \frac{[1-(\frac{E_0}{E_{\max}})^{\delta+1}]^{b-1}}{[1-(\frac{E}{E_{\max}})^{\delta+1}]^{b}}\Big[\frac{3}{r-1} + \frac{r\delta}{r+1}\Big(\frac{E}{E_{\max}}\Big)^{\delta+1}\Big], \tag{9}$$

$$E_c(t) = \frac{E_1(t)}{1 + \alpha_2 E_1(t) t}, \tag{10}$$

which describes the evolution of energy of the highest energy particles as they cool in the escape zone.

In the case of the accelerated protons, protons loss energy mainly through catastrophic losses because of the production of pions, in which a proton loses 1/3 of its energy per pion-producing collision and the timescale for this catastrophic is given by[7]

$$t_{\rm pion}(E) = \frac{1}{c\beta_{\rm p} n_{\rm snr}(\sigma_{\rm H} + 0.1\sigma_{\rm He})}, \tag{11}$$

where β_p is the proton velocity in units of speed of light, $\sigma_{\rm H}$ is the cross section for inelastic pion-producing collisions with other protons, and $\sigma_{\rm He}$ is the cross section for pion-producing collisions with helium. Using $\sigma_{\rm H} \sim 28\,{\rm mb}$ and $\sigma_{\rm He} = 100\,{\rm mb}$, we have $t_{\rm pion} \sim 3.2 \times 10^7 n_{\rm snr}^{-1}\,{\rm s}$, which is much larger than the ages of the SNRs considered here even though $n_{\rm snr}$ is as large as $100\,{\rm cm^{-3}}$. Therefore, we can neglect the protons energy losses and then solve Eqs. (1) and (2) without the energy losses term for a source term $Q_p(t) = Q_0^p\delta(E - E_{p0})H(t)$. The solutions in the energy range $E_{p0} < E < E_{p,1}(t)$ are

$$N_1^p(E,t) = \frac{Q_0^p t_{p,a0}}{E_{p0}}\Big(\frac{E}{E_{p0}}\Big)^{-s_1}, \tag{12}$$

$$N_2^p(E,t) = \frac{3}{r-1}\frac{Q_0^p(t - t_{p,1})}{E_{p0}}\Big(\frac{E}{E_{p0}}\Big)^{-s_2}, \tag{13}$$

respectively, where $t_{p,a0} = t_{\rm acc}(E_{p0})$ and $E_{p,1}(t) = E_{p0}[1 + \delta(t/t_{p,a0})]^{1/\delta}$. It should be noted that if $t_{\rm pion}$ is less than or comparable with the ages of the

SNRs, $1/t_{\rm esc}$ in Eqs. (1) and (2) must be replaced by $1/t_{\rm esc} + 1/t_{\rm pion}$.

We now consider non-thermal photon emission produced by the accelerated particles. As mentioned above, the differential energy spectrum of the particles (electrons and protons) is the sum of that produced in the acceleration zone and that in the escape zone, corresponding densities are $J_e(E,t) = (c\beta/4\pi V_{\rm snr})(N_1^e + N_2^e)$ and $J_p(E,t) = (c\beta/4\pi V_{\rm snr})(N_1^p + N_2^p)$ respectively, where $V_{\rm snr} = (4\pi/3)R_{\rm snr}^3$ is the volume of the SNR considered. Given electron and proton densities, we can calculate the photon emission from a given SNR. The non-thermal radiation processes of the accelerated particles involved in the SNR are synchrotron radiation, bremsstrahlung, IC scattering for leptons including electrons and positrons, and p–p interaction for protons, corresponding photon emissivities are $Q_{\rm syn}(E_\gamma,t)$, $Q_{\rm brem}(E_\gamma,t)$, $Q_{\rm comp}(E_\gamma,t)$ and $Q_{\rm pp}(E_\gamma,t)$, where the formulae for above radiation processes can be seen in Ref. [9]. Therefore, the total multi-waveband non-thermal phone spectrum of a given SNR with a distance D and an age $t_{\rm snr}$ is given by

$$F_{\rm tot}(E_\gamma) = \frac{1}{4\pi d^2} E_\gamma^2 V_{\rm snr} Q_{\rm tot}(E_\gamma, t_{\rm snr}), \qquad (14)$$

where d is the distance to the SNR and $Q_{\rm tot} = Q_{\rm syn} + Q_{\rm brem} + Q_{\rm comp} + Q_{\rm pp}$.

In this model, the parameters r, δ, B, $E_{e,\max}$, Q_0^e and Q_0^p are estimated by fitting the multi-wavelength spectrum of a given. When Q_0^e and Q_0^p are given, the total amount of kinetic energy contained in both the injected electrons and the injected protons $E_{\rm par}$ is given by

$$E_{\rm par} = \int_{E_{e,\min}}^{E_{e,\max}} EN^e dE + \int_{E_{p,\min}}^{E_{p,\max}} EN^p dE. \qquad (15)$$

We now apply the model to three shell-type SNRs whose emission has been detected in radio, x-ray and TeV bands. It is commonly thought that SNRs evolve through three stages in the analytical model of the shock dynamics of SNRs expanding into the uniform ambient medium with density n_0: the free expansion stage, the self-similar Sedov stage and the radiative stage. The free expansion stage with a constant shock velocity v_0 ends at time $t = t_{\rm Sed} \sim 210(E_{51}/n_0)^{1/3} v_0^{-5/3}$ yr, the shock velocity satisfies $v_s(t) = v_0(t/t_{\rm Sed})^{-3/5}$ during the Sedov stage, and the radiative stage with a shock velocity $v_s(t) = v_0(t_{\rm rad}/t_{\rm Sed})^{-3/5}(t/t_{\rm rad})^{-2/3}$ starts at time $t = t_{\rm rad} \sim 4 \times 10^4 E_{51}^{4/17} n_0^{-9/17}$ yr[8,9,13], where E_{51} is the initial explosion energy of SN in units of 10^{51} erg and v_0 is the initial velocity in units of 10^9 cm/s. In this paper, we assume that $v_0 = 1$ and use the mean velocity $U_u = \int v_s(t)dt/t_{\rm snr}$ to describe the shock velocity. Furthermore, we adopt that the injection energies of electrons and protons are $E_{e0} = 5$ MeV and $E_{\rm p0} = 2$ GeV respectively as treated by Ref. [10].

Table 1. Parameters for modelling the SNRs in the two zone model (see text for details).

Parameter	G347.3–0.5	G266.2–1.2	G8.7–0.1
d(kpc)	1	0.5	6
$t_{\rm snr}$ (yrs)	10^3	10^3	1.5×10^4
U_u(km/s)	4.5×10^3	4.5×10^3	2×10^3
$B_{\rm snr}$(μG)	15	12	15
$n_{\rm snr}$(cm^{-3})	3	1	18
$E_{e,\max}$(TeV)	75	82	8
r	3.7	3.5	3.7
δ	0.7	0.8	1.0
s_1	1.41	1.4	1.11
s_2	2.11	2.2	2.11
$Q_0^e(10^{41}\,{\rm s}^{-1})$	1.6	3	15
$Q_0^p(10^{41}\,{\rm s}^{-1})$	2.0	2	0.1

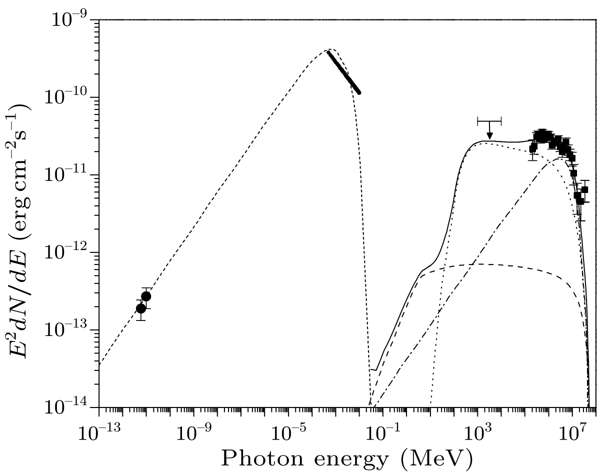

Fig. 1. The multi-wavelength spectrum for SNR G347.3–0.5 together with the best-fit model with parameters given in Table 1. The synchrotron emission, bremsstrahlung emission, Compton scattering, the π^0 decay emission and the total emission with energy $E > 0.1$ MeV are indicated by short-dashed, dashed, dot-dashed, dotted, and solid lines, respectively.

For SNR G347.3–0.5, its distance and age are 1 kpc and ~ 1000 yr respectively.[14] Figure 1 shows the best fitting of the multi-waveband spectrum for G347.3–0.5. The model parameters are listed in Table 1. For given values of $E_{e,\max}$, r, U_u, and α_1, we can estimate κ, and then $K(E)$ using a given δ, i.e. $K(E) = 4.1 \times 10^{26}(U_u/6000\,{\rm km\cdot s^{-1}})^2(E/100\,{\rm TeV})^{0.7}\,{\rm cm\cdot s^{-1}}$. Assuming $t_{\rm acc}(E_{p,\max}) = t_{\rm snr}$, we derive the maximum energy of the accelerated protons is $E_{p,\max} = 75$ TeV. Further, we use the values of Q_0^e and Q_0^p and Eq. (15) to estimate the energy contents of the accelerated protons and electrons, which are $E_{\rm par}^e \approx 3.3 \times 10^{47}$ erg and $E_{\rm par}^p \approx 1.4 \times 10^{50}$ erg. It should be noted that Moraitis and Mastichiadis[10] have calculated the multi-waveband spectrum using the two zone model, we can repeat their work very well. However, when we use 1000 yr as the age of the SNR, the case is changed, in which the important change is that the diffusion coefficient is proportional to $E^{0.7}$, which does not violate the lower limit of Bohm diffusion for any value of particle energy.

Although it remains a large uncertainty on the distance and age of the SNR G266.2–1.2, reasonable ranges are an age between 480 and 1400 years and distance of 0.26–0.50 kpc[15]. Here we adopt an age of 1000 yr and a distance of 0.5 kpc for the SNR G266.2–1.2. This SNR has been detected in radio, x-ray and VHE bands. The comparison of model result with the observed data is shown in Fig. 2 and model parameters are shown in Table 1. From Table 1, the maximum energies of accelerated protons and electrons at the present day are $\sim$ 65 TeV and $\sim$ 52 TeV respectively, and the particles in the acceleration zone are close to stead-state. The total energy contents in electrons and protons are $E^e_{\rm par} \approx 4.2 \times 10^{47}$ erg and $E^p_{\rm par} \approx 1.0 \times 10^{50}$ erg.

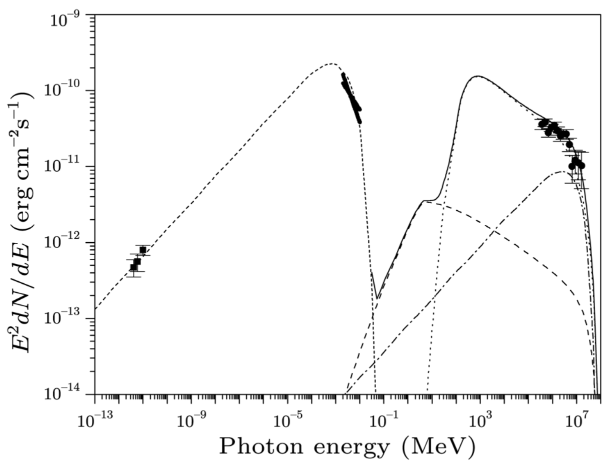

Fig. 2. The same as Fig. 1 but for SNR G266.2–1.2. The radio data[16], x-ray data[2], and VHE γ-ray data[3,17] for the whole SNR are indicated.

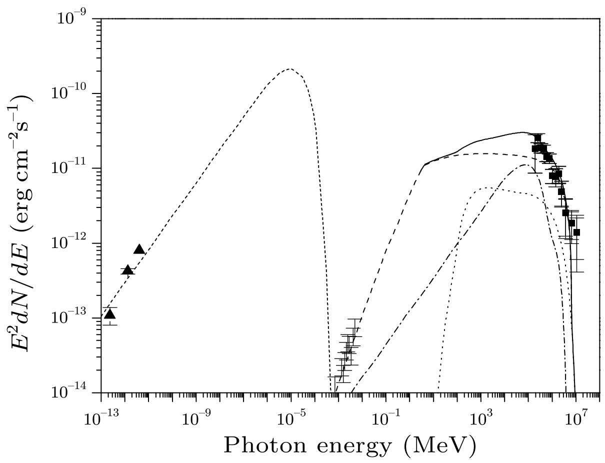

Fig. 3. The same as Fig. 1 but for SNR G8.7–0.1. The radio data[18], x-ray data[19], and VHE γ-ray data[4] for the whole SNR are indicated.

For SNR G8.7–0.1, a distance from the SNR of 6 ± 1 kpc and an age of 15000 yr were estimated by associating G8.7–0.1 with coincident HII regions.[18] Cui and Konopelko[19] reported the high-resolution x-ray observations taken with the Chandra x-ray Observatory of the field that contains the TeV γ-ray source HESS J1804–216, and found only CSOU J180351.4–213707 is the most probable x-ray counterpart of HESS J1804–216. With an age of 15000 yr, the SNR must be in the radiative phase, and the roll-off energy of the synchrotron radiation of the primary electrons decrease quickly. The parameters in our calculation are shown in Table 1, we find out that the energy-dependent diffusion coefficient adopts a form $K(E) = 4.2 \times 10^{26}(E/100\,\text{TeV})\,\text{cm}^2{\cdot}\text{s}^{-1}$, corresponding to Bohm diffusion and that particles in the acceleration zone are almost stead-state. The total energy contents in electrons and protons are $E^e_{\rm par} \approx 4.5 \times 10^{49}$ erg and $E^p_{\rm par} \approx 1.2 \times 10^{50}$ erg.

In summary, we have used the two-zone model[10,11] to investigate the basic properties of particles acceleration and broadband photon emission from the shell-type SNRs with more recent cross sections for electron bremsstrahlung and pion production. In this model, we find that radio and x-ray photons from a young SNR are from synchrotron radiation when the accelerated electrons interact with the ambient magnetic field, and the γ-rays can be from the bremsstrahlung and IC scattering and π^0 decay due to the collisions between the accelerated protons and the ambient matter. However, for an old SNR, only radio and soft x-ray photons are from synchrotron radiation, hard x-ray are from bremsstrahlung and IC scattering, γ-ray with photon energy below several TeV from the bremsstrahlung and IC scattering and π^0 decay, the VHE γ-rays mainly come from the π^0 decay. Finally we would like to point out that more accurate observations, especially the observations of the GLAST, are needed to give further limits of the model although our resulting spectra are comparable with the observed data in radio, x-ray, γ-ray band for these three SNRs.

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