Time evolution of broadband non-thermal emission from SNRs in different circumstellar environments

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Abstract

Supernova remnants (SNRs) are thought to be one of the major acceleration sites of galactic cosmic rays and an important class of objects for high-energy astrophysics. SNRs produce multi-wavelength, non-thermal emission via accelerated particles at collision-less shocks generated by the interactions between the SN ejecta and the circumstellar medium (CSM). Although it is expected that the rich diversities observed in supernovae (SNe) and their CSM can result in distinct very high energy (VHE) electromagnetic signals in the SNR phase, there are only a handful of SNRs observed in both GeV and TeV γ-rays so far. A systematic understanding of particle acceleration at SNRs in different ambient environments is therefore limited. Here we explore non-thermal emission from SNRs in various circumstellar environments up to 5000 yr from explosion using hydrodynamical simulations coupled with efficient particle acceleration. We find that time evolution of emission characteristics in the VHE regime is mainly dictated by two factors: the number density of the target particles and the amplified magnetic field in the shocked medium.

Introduction

Figure 1 shows the spectral energy distribution (SED) of SNRs that have been observed so far in the GeV-to-TeV energy range. In most cases, the radio and non-thermal X-ray spectrum can be satisfactorily reproduced by a synchrotron origin regardless of SNR age, but the differences in the observed γ-ray spectra among these SNRs are remarkable. Whether the γ-rays are produced by either a hadronic or leptonic (or both) channel has a large implication on the particle acceleration mechanism, such as the injection efficiencies of the supra-thermal particles, the maximum energy of the accelerated particles, and the overall acceleration efficiency. However, the model interpretation is still often found to be controversial and remains a subject for discussion.

Here, using a multi-zone hydrodynamical simulation coupled with an efficient particle acceleration, we generate a grid of evolutionary models of SNRs interacting with various kinds of ISM/CSM environments up to a few times 10^3 yr over an observation-based parameter space. Our results are analyzed to explore general trends in the characteristics of the time-evolving SED that can be used in the future as a probe of the structure of the surrounding environment.

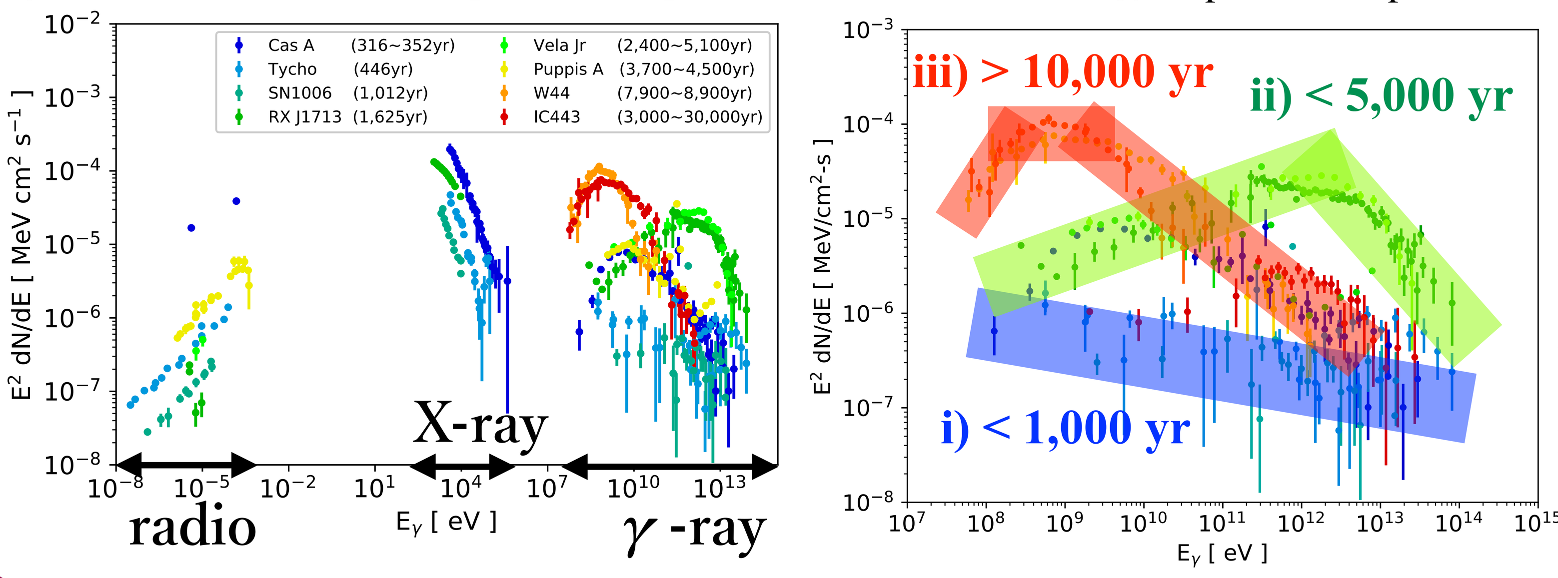


Figure 1: Left panel: multi-wavelength SED of the SNRs whose γ-ray flux is detected. The color of data points almost represents the SNR age; the redder the color becomes, the older the age of SNRs becomes. Bottom panel: same as the top panel, but the energy range is from 10 MeV to 1 PeV.

Method : CR-Hydrodynamics

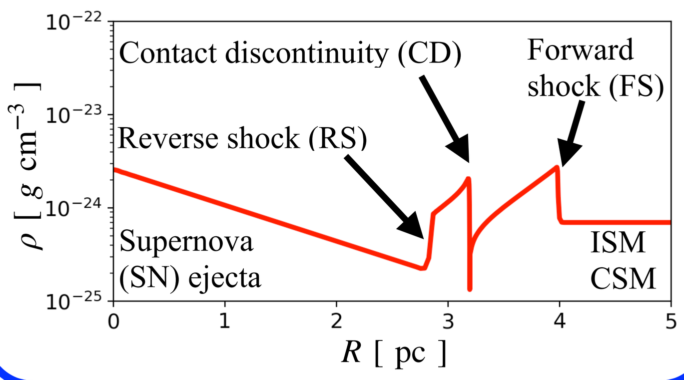
- We develop the hydro code which can **self-consistently** solve the **hydrodynamics coupling with effective particle acceleration**.
- We follow the long-term **time-evolution of γ-ray** from SNRs in **different circumstellar environments**.

Hydrodynamics

- code : VH-1
- spherical symmetric SN-like explosion → two ejecta model
  (i) exponential (Dwarkadas+1998)
  (ii) power-law (Truelove+1999)

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \qquad \frac{\partial E}{\partial t} = -\frac{\partial (P_{\rm tot} u)}{\partial m}$$

$$\frac{\partial u}{\partial t} = -\frac{\partial P_{\rm tot}}{\partial m} \qquad E = \frac{1}{2}\rho u^2 + \frac{P_{\rm tot}}{\gamma_{\rm eff} - 1}$$



$R_{\rm sk}$, $V_{\rm sk}$, $T_{\rm age}$, B_0, T_0 →

← $P_{\rm tot}$, $\gamma_{\rm eff}$

feedback of CR

- modify hydro eqs. & EoS using CR pressure

(i) total pressure $P_{\rm tot}$:

$$P_{\rm tot}(x) \equiv P_{\rm g}(x) + P_{\rm CR}(x) + P_{\rm B}(x)$$

gas, CR, magnetic

$$P_{\rm CR}(x) = \frac{4\pi}{3}\int_{p_{\rm inj}}^{p_{\rm max}} p^3 v\, f_p(x,p)\, dp, \quad P_{\rm B}(x) = \frac{B(x)^2}{8\pi}$$

(ii) effective specific ratio $\gamma_{\rm eff}$:

$$\frac{\gamma_{\rm eff}}{\gamma_{\rm eff}-1}P_{\rm tot} = \frac{\gamma_{\rm gas}}{\gamma_{\rm gas}-1}P_{\rm gas} + \frac{\gamma_{\rm CR}}{\gamma_{\rm CR}-1}P_{\rm CR}$$

Nonlinear diffusive shock acceleration (NLDSA)

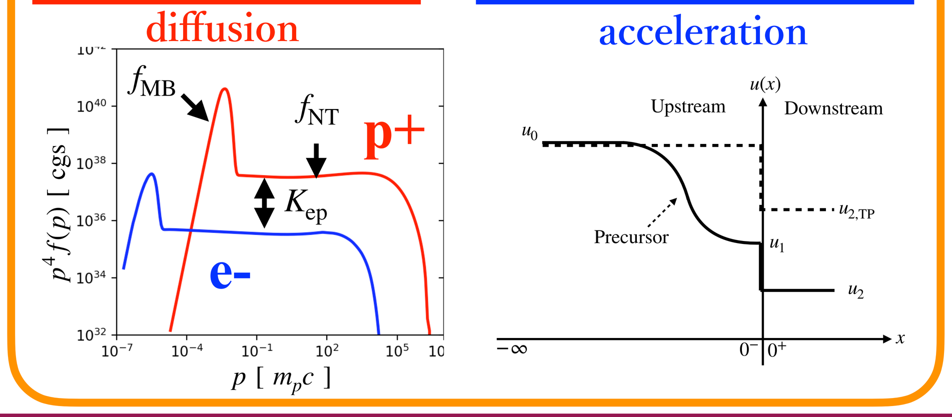
- solve diffusion-convection equation at shock using semi-analytic model (Capliori+2010a,b)
- "thermal-leakage" injection (Blasi+2004,2005)
- Magnetic field amplification (MFA) (Bell+1978a,b)

$$\{u(x) - v_A(x)\}\frac{\partial f(x,p)}{\partial x} - Q(x,p) =$$

convection, injection

$$\frac{\partial}{\partial x}\left\{D(x,p)\frac{\partial f(x,p)}{\partial x}\right\} + \frac{d\{u(x)-v_A(x)\}}{dx}\frac{p}{3}\frac{\partial f(x,p)}{\partial p}$$

diffusion, acceleration

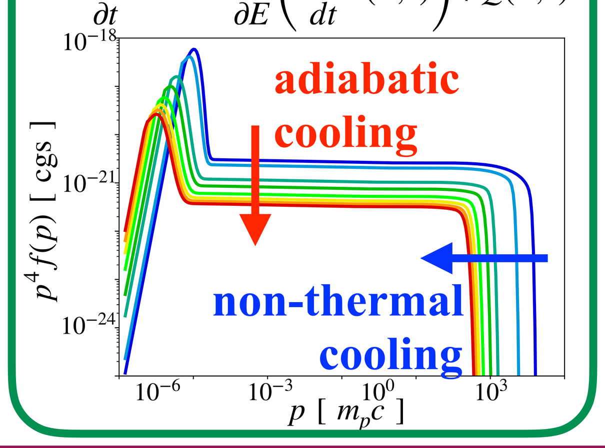


$f_p(x,p)$, $f_e(x,p)$ →

radiation cooling

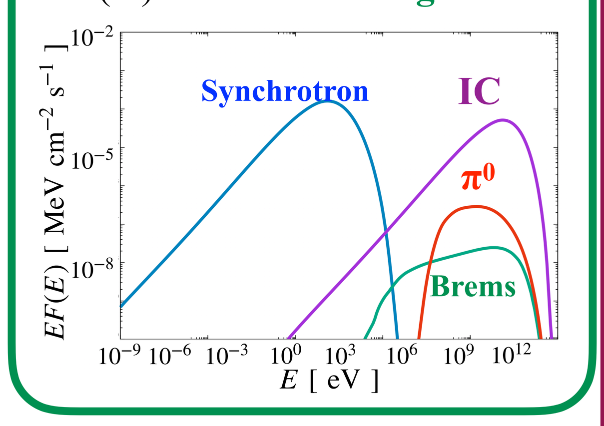
- considering energy-loss due to
  (i) non-thermal radiation
  (ii) adiabatic expansion

$$\frac{\partial n(E,t)}{\partial t} = -\frac{\partial}{\partial E}\left(\frac{dE}{dt}n(E,t)\right) + Q(E,t)$$



non-thermal emissions

- 4-components are considered as non-thermal emissions
  (i) π^0 decay
  (ii) Synchrotron
  (iii) Inverse Compton
  (iv) Bremsstrahlung



Environment model

- We prepare two environment models
  (i) **uniform ISM** model : the environment as Type Ia SN
  (ii) **power-law CSM** model : swept by stellar wind before CC SN

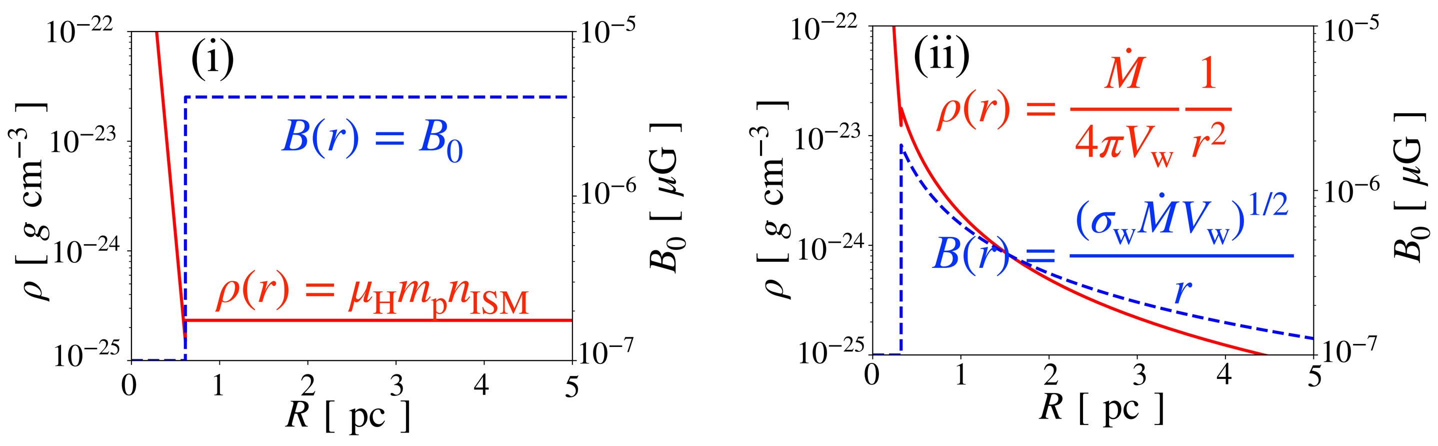


Table 2. Model parameter

Model	$M_{\rm ej}$ [$M_\odot$]	$n_{\rm ISM}$ [cm^{-3}]	$\dot{M}$ [$M_\odot$ yr^{-1}]	$V_{\rm w}$ [km s^{-1}]	$\dot{M}_2$ [$M_\odot$ yr^{-1}]	$V_{\rm w,2}$ [km s^{-1}]	$\chi_{\rm inj}$
A0[a]	1.4	0.3	-	-	-	-	3.6
A1	1.4	0.01	-	-	-	-	3.6
A2	1.4	0.1	-	-	-	-	3.6
A3	1.4	1.0	-	-	-	-	3.6
A4	1.4	0.01	-	-	-	-	4.0
A5	1.4	0.1	-	-	-	-	4.0
A6	1.4	1.0	-	-	-	-	4.0
B0[b]	3.0	-	7.5×10^{-6}	20	-	-	3.75
B1	3.0	-	1.0×10^{-6}	20	-	-	3.75
B2	3.0	-	1.0×10^{-5}	20	-	-	3.75
B3	3.0	-	1.0×10^{-4}	20	-	-	3.75
B4	10.0	-	1.0×10^{-6}	20	-	-	3.75
B5	10.0	-	1.0×10^{-5}	20	-	-	3.75
B6	10.0	-	1.0×10^{-4}	20	-	-	3.75

[a] All model A use an exponential profile for ejecta, $E_{\rm SN} = 10^{51}$ erg, $T_0 = 10^4$ K, and $d_{\rm SNR} = 3.2$ kpc.

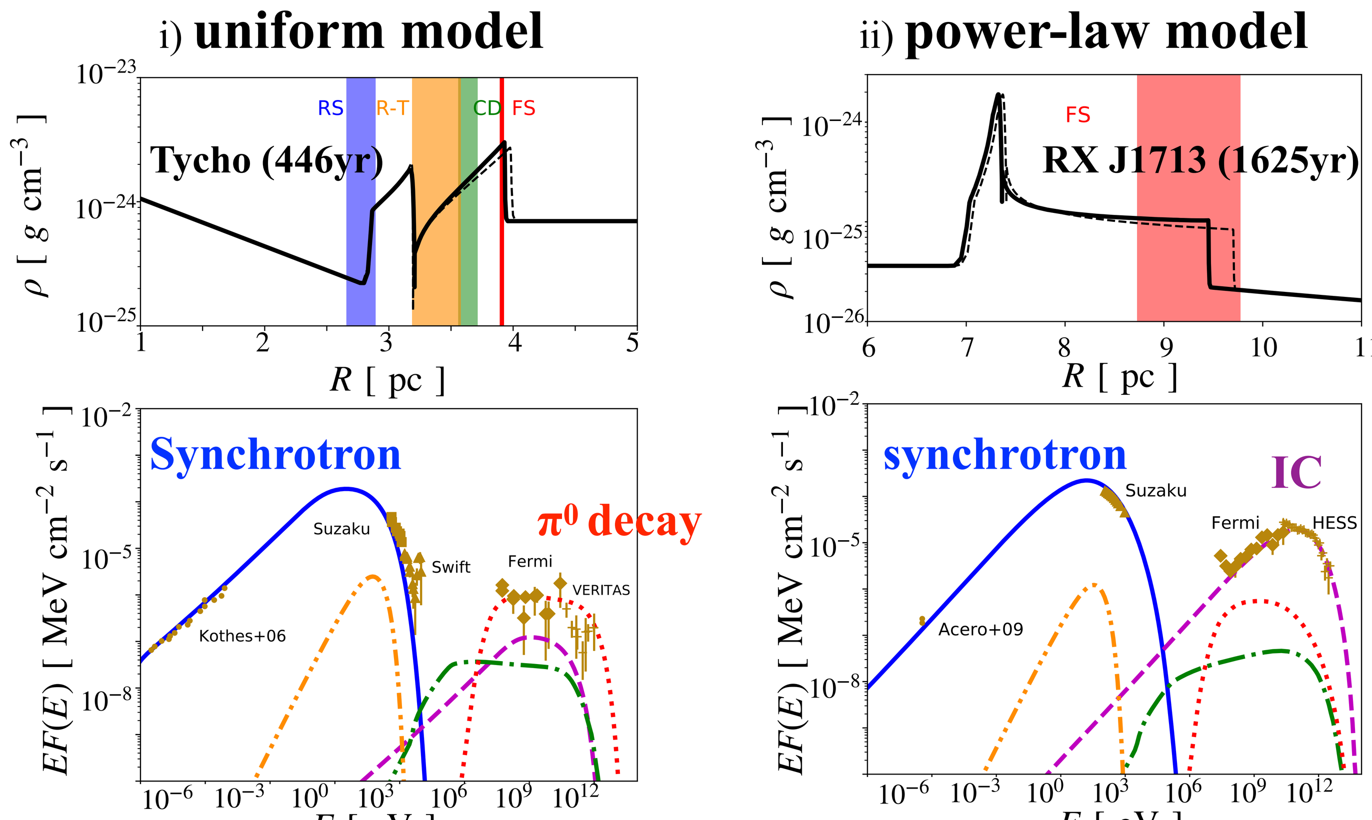
[b] All model B use a power-law profile for ejecta, $n_{\rm pl} = 7$, $E_{\rm SN} = 10^{51}$ erg, $T_0 = 10^4$ K, and $d_{\rm SNR} = 1.0$ kpc.

※ Full ionized gas is assumed ※ CMB is used as the photon field of IC

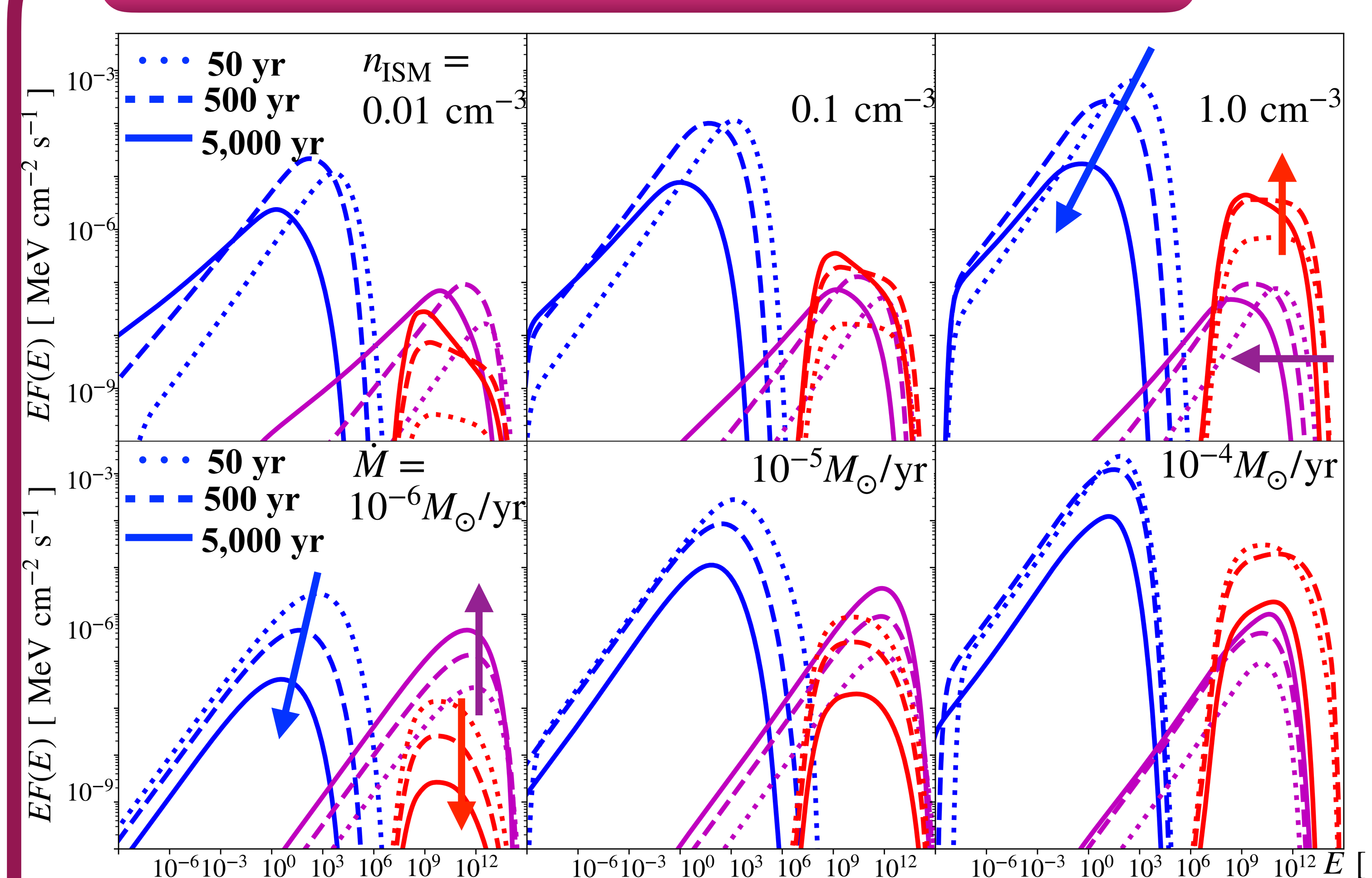
Calibration test

To fix many SNR and DSA parameters, we reproduce the hydro and multi-wavelength observations at the same time.

i) **uniform model** ii) **power-law model**



Results : time-evolution of SED



i) **uniform model**
- **π^0 decay** : constantly **increase** ↑
- **IC** : **shift** to lower energy ←

ii) **power-law model**
- **π^0 decay** : constantly **decrease** ↓
- **IC** : constantly **increase** ↑

In the Type Ia models with a uniform ISM, while the π^0decay flux increases with time, IC flux does not vary much with its spectral peak shifting to lower energy as the SNR ages. In the CC models with a simple power-law CSM, while π^0 decay flux decreases with time, the IC contribution increases with time on the contrary. We found that the key aspects that dictate these evolutionary trends are **the density distribution of the interaction targets for each emission component** and **the rate of energy loss of the electrons due to synchrotron radiation**. In our models, since the interaction target is the ambient gas for π^0 decay and the uniform CMB radiation field for IC, the spatial distribution of the ambient gas density is a key to understanding the evolution of the γ-ray spectrum, including a possible transition between a leptonic and a hadronic origin at a certain evolutionary stage. Moreover, the accelerated electrons lose their energy via synchrotron radiation owing to a highly amplified magnetic field in the uniform ISM cases.

Summary

(i) We find that the time-evolution of γ-ray is characterized by density and B-field of cirucmstellar environment.

(ii) We acquire the relationship between γ-ray spectrum and the circumstellar environment.

		$T_{\rm age}$ = 50 yr	500 yr	5,000 yr	> 10,000 yr
previous picture		No obs.	hadronic	leptonic	hadronic
uniform ISM	0.01 cm^{-3}	leptonic	leptonic	leptonic	
	0.1 cm^{-3}	leptonic	mixed	hadronic	
	1.0 cm^{-3}	hadronic	hadronic	hadronic	
power-law CSM	$10^{-6} M_\odot$/yr	mixed	leptonic	leptonic	
	$10^{-5} M_\odot$/yr	hadronic	mixed	leptonic	
	$10^{-4} M_\odot$/yr	hadronic	hadronic	mixed	

Acknowlegment

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