



Investigating the Origin of Ultra-high-energy γ -ray Sources from Supernova Remnants Interacting with Molecular Clouds

Yu-Jun Xian and Jun Fang

Department of Astronomy, Yunnan University, Kunming 650091, China; fangjun@ynu.edu.cn
 Received 2025 February 14; revised 2025 June 11; accepted 2025 June 27; published 2025 July 17

Abstract

Supernova remnants (SNRs) interacting with molecular clouds (MCs) are recognized as the sources of γ -rays and cosmic rays in the Galaxy. Based on the SNR-MC system, this study establishes a particle cumulative diffusion model to investigate the mechanism by which high-energy protons escaping from SNRs interact with dense MCs through proton–proton interactions to produce high-energy γ -rays. Using the W51 complex, a typical star-forming region, as a research sample, we analyze the production and propagation characteristics of γ -rays. By employing the Exponential Cutoff Power-Law model and the Markov Chain Monte Carlo method, we fit the γ -ray observational data of W51C, successfully constraining the key physical parameters. Additionally, we systematically search for 1LHAASO sources spatially coincident with SNR-MC systems to explore the potential origins of ultra-high-energy (UHE) γ -ray sources. The results indicate that the radiation characteristics of the UHE γ -ray sources are highly consistent with the SNR-MC systems, further supporting their candidacy as PeVatrons in the Galaxy.

Key words: radiation mechanisms: non-thermal – ISM: supernova remnants – gamma-rays: ISM

1. Introduction

In recent years, with the development of ground-based particle detectors such as HAWC and LHAASO, an increasing number of ultra-high-energy (UHE, $E \geq 100$ TeV) γ -ray sources have been identified (e.g., Guepin & Poemma Collaboration Team 2022; Albert et al. 2024; Alfaro et al. 2024; Cao et al. 2025; Gao et al. 2024). Many of these sources emit γ -rays reaching the PeV energy range and are referred to as PeVatrons, one of the most powerful particle accelerators known in the Galaxy (e.g., Fang et al. 2022; Cardillo & Giuliani 2023; de Oña Wilhelmi et al. 2024). The cosmic ray (CR) energy spectrum shows a distinct “knee” feature in the PeV range, indicating changes in both acceleration efficiency and propagation mechanisms at these energies. Therefore, identifying and studying “PeVatrons” that accelerate particles to PeV energies is now a key scientific issue in understanding the origin of CRs.

Supernova remnants (SNRs) are widely regarded as one of the primary accelerators of CRs within the Galaxy (Berezhko et al. 2003; Gelfand et al. 2013). Within their shock waves, particles are accelerated through the diffusive shock acceleration (DSA) mechanism (e.g., Bell 1978; Blandford & Ostriker 1978; Caprioli et al. 2010). When the SNR shell interacts with molecular clouds (MCs), the resulting SNR-MC systems possess unique physical conditions that can further enhance the γ -ray-emitting capabilities. In these systems, a large number of high-energy protons escape from the SNRs

and enter the high-density environment of the MCs, where they undergo proton–proton (p–p) interactions (Abdo et al. 2009; Tavani et al. 2010). These interactions produce secondary particles (such as pions), which decay rapidly and release high-energy γ -rays. Currently, the γ -rays produced by such systems have been detected by ground-based detectors such as H.E.S.S. and LHAASO (e.g., Aharonian et al. 2008; Sarmah et al. 2023). These observational results further confirm that SNRs can accelerate atomic nuclei, making them an important source of CRs in the Galaxy.

In the theoretical model for the γ -rays from the SNR-MC system, Li & Chen (2010) pointed out that when MCs are located at the shock front of an SNR explosion, the point-source model is inadequate to describe the interaction between the SNR and the MCs. They proposed a cumulative diffusion model, assuming that the energy spectrum of escaping protons follows a power-law distribution with a certain index. Li & Chen (2012) further explored the impact of the effective volume of MCs on particle dynamics and analyzed the effects of different diffusion and propagation coefficients on the shape of the energy spectrum. Building on these studies, Ohira et al. (2011) simplified the computational model and provided an analytic solution for the distribution of CRs within a finite region. LHAASO, a world-leading ground-based observational array, is primarily used for CR detection through detectors such as KM2A, WCDA, and WFCTA, and has made significant contributions to the in-depth study of the SNR-MC system (He & Lhaaso Collaboration 2018; Aharonian et al. 2021; Ma et al. 2022). Based on LHAASO data,

Cao et al. (2024b) successfully explained the γ -ray emission of the W51 complex in the energy range from Fermi-LAT to LHAASO. They did so using the p-p interaction model and demonstrated for the first time that the SNR-MC system may act as a “PeVatron.” Mitchell & Celli (2024) compiled a list of known SNR-MC systems and compared it with LHAASO’s first source catalog (1LHAASO) (Cao et al. 2024a).

In this paper, we study the γ -ray spectrum of SNR-MC systems. The structure of the paper is as follows: Section 2 describes the theoretical model; Section 3 fits the γ -ray spectrum of the W51 complex and constrains the relevant parameters; Section 4 systematically searches for SNR-MC interaction systems spatially coincident with 1LHAASO γ -ray sources; and Section 5 presents the discussion and conclusion.

2. SNR-MC Cumulative Diffusion Model

In this section, based on the CR diffusion models proposed by Aharonian & Atoyan (1996) and Gabici et al. (2009), we derive in detail the CR distribution function $f(t, r, p)$ at a distance r from the center of the SNR at any arbitrary time t after the explosion. Assuming the system is spherically symmetric, the propagation of CRs produced by the SNR can be described by the following diffusion Equation (Ohira et al. 2011)

$$\frac{\partial f(t, r, p)}{\partial t} - D(p)\Delta f(t, r, p) = q_s(t, r, p) \quad (1)$$

where $q_s(t, r, p)$ represents the source term of CRs, and the diffusion coefficient $D(p)$ can be determined by the following Equation (Li & Chen 2010)

$$D(p) = 10^{28} \chi \left(\frac{cp}{10 \text{ GeV}} \right)^\delta \text{ cm}^2 \text{ s}^{-1} \quad (2)$$

where the diffusion index δ characterizes the dependence of the diffusion coefficient on particle energy (Vecchi et al. 2022); the normalization coefficient χ is used to reflect the slow diffusion phenomenon near the SNR, indicating a reduction in the diffusion efficiency of particles in this region (Fujita et al. 2009).

Considering that CRs escape from the SNR surface at $t = t_s$, their source term can be expressed by the following Equation (Ohira & Takahara 2010)

$$q_s = \frac{N_s(p)}{4\pi r^2} \delta[r - R_s(p)] \delta[t - t_s(p)] \quad (3)$$

where $N_s(p)$, $t_s(p)$, and $R_s(p)$ denote the proton spectrum, escape time, and escape radius for CRs with momentum p when they escape from the SNR. The escape radius $R_s(p)$ can

be obtained from the following Equation (Ohira et al. 2011)

$$R_s(p) = \begin{cases} (1 + \kappa) R_{\text{Sedov}} \left(\frac{p}{p_{\text{knee}}} \right)^{-1/\alpha} & \text{for } p > p_{\text{br},1} \\ L_1 & \text{for } p \leq p_{\text{br},1} \end{cases} \quad (4)$$

where k is a proportionality constant, R_{Sedov} represents the typical radius of the SNR when it enters the Sedov–Taylor phase, and p_{knee} corresponds to the “knee” momentum in the CR energy spectrum, with an energy of approximately $10^{15.5}$ eV. α is the spectral index in the thermal leakage model, L_1 denotes the inner boundary radius of the MC, i.e., the minimum distance from the SNR center to the inner edge of the cloud. The momentum break point $p_{\text{br},1}$ can be derived from

$$p_{\text{br},1} = p_{\text{knee}} \left(\frac{L_1}{R_{\text{Sedov}}(1 + \kappa)} \right)^{-\alpha} \quad (5)$$

The escape time t_s of CRs with momentum p from the SNR can be described by the following Equation (Ohira et al. 2011)

$$t_s(p) \approx \begin{cases} t_{\text{Sedov}} \left(\frac{p}{p_{\text{knee}}} \right)^{-5/2\alpha} & \text{for } p > p_{\text{br},1} \\ t_{\text{Sedov}} \left(\frac{p_{\text{br},1}}{p_{\text{knee}}} \right)^{-5/2\alpha} & \text{for } p \leq p_{\text{br},1} \end{cases} \quad (6)$$

where t_{Sedov} denotes the onset time of the Sedov–Taylor phase of the SNR, thus, we obtain the solution to Equation (1), given by

$$f(t, r, p) = \frac{\exp\left[-\left(\frac{r - R_s(p)}{R_d(t, p)}\right)^2\right] - \exp\left[-\left(\frac{r + R_s(p)}{R_d(t, p)}\right)^2\right]}{4\pi^{3/2} R_d(t, p) R_s(p) r} N_s(p) \quad (7)$$

where the diffusion radius $R_d(t, p)$ for CRs with momentum p is obtained from the following Equation (Aharonian & Atoyan 1996)

$$R_d(t, p) = \sqrt{4D(p)[t - t_s(p)]} \quad (8)$$

For the escape spectrum of particles $N_s(p)$, we adopt a power-law spectrum with an exponential cutoff based on the equations proposed by Ohira et al. (2011), which can be expressed as follows

$$N_s(p) = \begin{cases} N_0 p^{-\frac{\beta}{\alpha}} p^{-s} & \text{for } p \leq p_{\text{br},1} \\ N_0 p^{-(s+\frac{\beta}{\alpha})} \exp\left(-\frac{p}{p_{\text{cut}}}\right) & \text{for } p > p_{\text{br},1} \end{cases} \quad (9)$$

where N_0 is a constant coefficient, s is the spectral index, and p_{cut} is the cutoff momentum. Assuming that the injection model follows the thermal leakage model, β can be obtained

from the following Equation (Ohira & Takahara 2010)

$$\beta = \frac{3(3-s)}{2} \quad (10)$$

In this model, we consider the finite size source effect (Li & Chen 2012), so the observed γ -ray spectrum must be calculated by performing a volume integral of the CR spectrum. For the system of SNR interacting with MCs, the radiation region is the dense cloud or cavity wall, with the spatial range $L_1 \leq r \leq L_2$. When the SNR age is t_{age} , the volume-integrated CR spectrum in this region can be expressed as

$$F(p) = \eta \int_{L_1}^{L_2} f(t_{\text{age}}, r, p) 4\pi r^2 dr \quad (11)$$

where η represents the fraction of protons that, after escaping from the SNR, subsequently collide with MCs, relative to the total number of escaping protons. ηN_0 can be determined from the observed radiation flux. L_2 is the outer boundary radius of the MC, i.e., the maximum distance from the SNR center to the outer edge of the cloud. Next, by substituting Equation (7) into Equation (11), we obtain the final detailed analytical expression as follows (Ohira et al. 2011)

$$\begin{aligned} F(p) = \frac{N_s(p)}{2} & \left\{ \frac{R_d(t, p)}{\sqrt{\pi} R_s(p)} \left[\exp\left(-\left(\frac{L_1 - R_s(p)}{R_d(t, p)}\right)^2\right) \right. \right. \\ & - \exp\left(-\left(\frac{L_2 - R_s(p)}{R_d(t, p)}\right)^2\right) \\ & - \exp\left(-\left(\frac{L_1 + R_s(p)}{R_d(t, p)}\right)^2\right) \\ & + \exp\left(-\left(\frac{L_2 + R_s(p)}{R_d(t, p)}\right)^2\right) \\ & + \operatorname{erf}\left(\frac{L_2 - R_s(p)}{R_d(t, p)}\right) - \operatorname{erf}\left(\frac{L_1 - R_s(p)}{R_d(t, p)}\right) \\ & \left. + \operatorname{erf}\left(\frac{L_2 + R_s(p)}{R_d(t, p)}\right) - \operatorname{erf}\left(\frac{L_1 + R_s(p)}{R_d(t, p)}\right) \right\} \quad (12) \end{aligned}$$

where $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$ is the error function.

3. Spectral Fitting of γ -ray in the W51 Complex

Due to its vast spatial extent and highly active star formation processes, the W51 complex is recognized as one of the largest star-forming regions in the Galaxy (Ginsburg 2017). This complex hosts a prototypical SNR-MC system, comprising MC W51B and SNR W51C (G49.2-0.7), located southeast of W51B (Jogler & Funk 2016). With a luminosity exceeding $1 \times 10^{36} \text{ erg s}^{-1}$, W51C ranks among the brightest γ -ray sources in the Galaxy (Abdo et al. 2009). To date, multiwavelength observations of the W51 complex have yielded significant

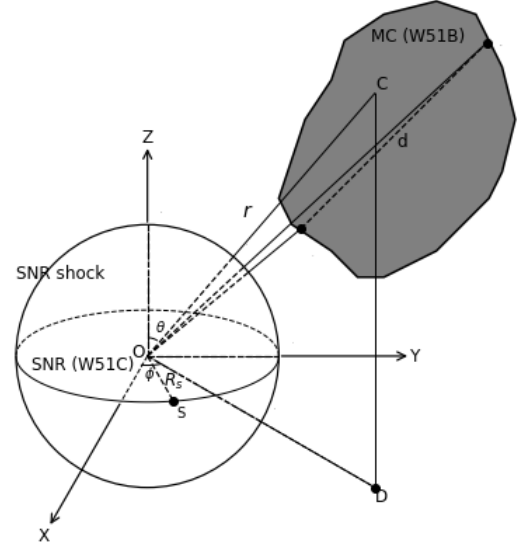


Figure 1. Schematic diagram of proton escape from W51C (where d represents the thickness of the MC, and the definitions of the related parameters are provided in Section 2).

advancements, covering energy ranges from MeV to PeV. These data are primarily provided by advanced observational facilities such as Fermi-LAT, HAWC, H.E.S.S., and LHAASO (e.g., Aleksić et al. 2012; Cao et al. 2024b).

In this section of the study, we employed the Exponential Cutoff Power-Law (ECPL) model proposed in Section 2 to conduct a detailed fitting analysis of the γ -ray observational data for the W51 complex, thus determining the key parameters of the model. Specifically, to ensure the accuracy of the model and the consistency of the results, we adopted the following parameter values for W51C: $R_{\text{sedov}} = 2.1 \text{ pc}$, $t_{\text{sedov}} = 210 \text{ yr}$, $\alpha = 6.5$, and $t_{\text{age}} = 31.5 \text{ kyr}$. These parameters are consistent with the methodology outlined by Ohira et al. (2011). Furthermore, we assumed that the W51 complex is located approximately 6 kpc from the Earth, with an overall radius of about 26.2 pc (Li & Chen 2012).

To further explore the mechanisms governing the escape of protons from the SNR (see Figure 1) and their spectral characteristics, Equation (9) was used to calculate the proton escape spectrum. The results of these calculations are visualized in Figure 2, with the corresponding numerical data summarized in Table 1.

The final spectral energy distribution (SED) was computed and visualized using Equation (10), with the computational process implemented through the Python package Naima (Zabalza 2015). The model incorporates three adjustable parameters: p_{cut} , δ , and χ . In this study, we employed the Markov Chain Monte Carlo (MCMC) method (Foreman-Mackey et al. 2013) to systematically explore and analyze the parameter space. The best-fit values obtained are $p_{\text{cut}} \approx 0.9 \text{ PeV}/c$, $\delta = 0.23$, and $\chi = 0.13$. As shown in Figure 3(a), the posterior probability distributions of all

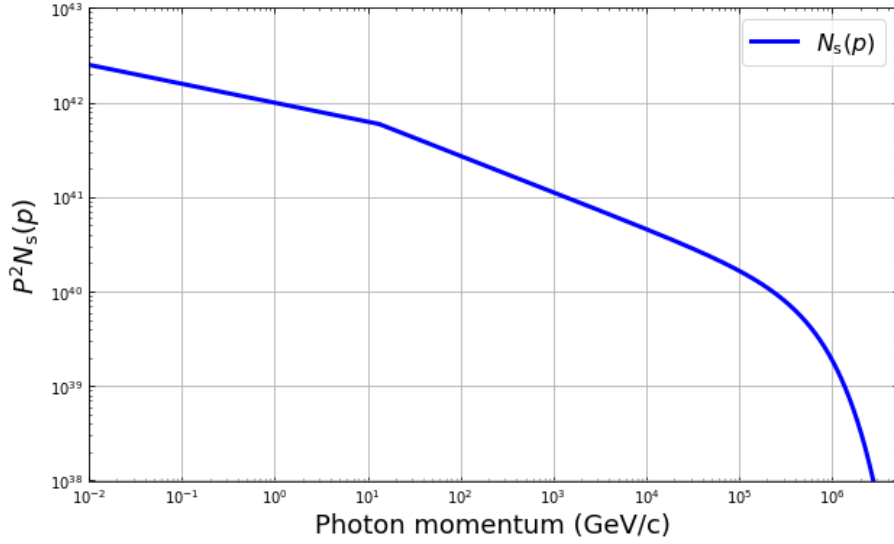


Figure 2. The momentum-dependent distribution of escaping protons in W51C, with the parameter $p_{\text{cut}} = 7 \times 10^5 \text{ GeV}/c$.

Table 1
Evolution and Physical Parameters of SNR W51

Parameter Description	Symbol	Value	Reference
Evolution Parameters of W51C			
Age (kyr)	t_{age} (kyr)	31.5	Ohira et al. (2011)
Distance (kpc)	d (kpc)	6.0	Koo et al. (2005)
Angular size (arcmin)	...	30'	Green (2019)
Radius (pc)	R_{SNR} (pc)	26.2	Li & Chen (2012)
Escape and Diffusion Parameters			
Spectral index for thermal leakage	α	6.5	Ohira et al. (2010)
Scaling factor	κ	0.4	Ptuskin & Zirakashvili (2005)
Spectral index	s	2.2	Ohira et al. (2010)
Escape spectral break momentum	$p_{\text{br},1}$ (GeV/c)	13.1	Ohira et al. (2011)
Normalization coefficient	χ	0.1	Li & Chen (2010)
Diffusion index	δ	0.22	Ohira et al. (2011)
Molecular Cloud Parameters			
Atomic gas density (cm ⁻³)	n (cm ⁻³)	100	Cao et al. (2024b)
Inner boundary radius of MC (pc)	L_1 (pc)	14.7	Ohira et al. (2011)
Outer boundary radius of MC (pc)	L_2 (pc)	23.7	Ohira et al. (2011)

parameters exhibit unimodal and smooth profiles, indicating good convergence and statistical robustness of the parameter estimation process.

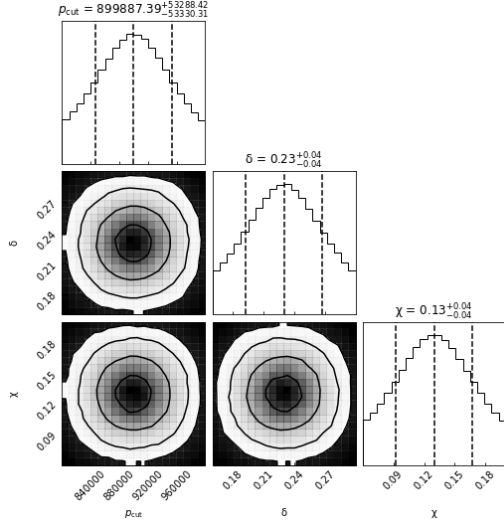
The fitting results reveal a pronounced exponential cutoff in the proton spectrum at a momentum of approximately 0.9 PeV/c.

This feature suggests that the SNR is capable of accelerating protons to ultra-high energies approaching the PeV scale, thereby providing further support for the theoretical hypothesis that SNR-MC interaction systems may serve as potential “PeVatron” candidates within the Galaxy. Moreover, the derived diffusion index of $\delta = 0.23$ indicates that the magnetic turbulence in the vicinity of W51C is close to Kolmogorov-type turbulence (Kolmogorov 1991). At the same time, the diffusion coefficient normalization factor $\chi = 0.13$ is significantly lower than the average Galactic diffusion level, implying a substantial suppression of CR diffusion efficiency near the source region. This pronounced “slow diffusion” effect effectively prolongs the residence time of CR protons in the vicinity of the source, thereby enhancing their probability of undergoing p-p interaction with the dense gas in the nearby MCs and producing γ -ray emission.

The statistical analysis shows that the reduced chi-squared statistic (χ^2_{ν}) corresponding to the best-fit parameters obtained in this study is 1.51, indicating that the proposed model provides a good fit to the observational data. This result further validates the statistical robustness and physical plausibility of the selected parameters. In addition, as illustrated in Figure 3(b), the γ -ray emission model based on the SNR-MC systems successfully reproduces the multi-band γ -ray observations from Fermi-LAT to LHAASO, achieving a smooth spectral connection across different energy ranges. This spectral consistency lends strong support to a unified interpretation of the observed high-energy radiation via the π^0 decay mechanism.

4. Exploration of Contributions to 1LHAASO Sources

In this section, we explore whether the UHE or unidentified (UNID: the emission is not well known or is ambiguous) γ -ray



(a) Corner Plot.

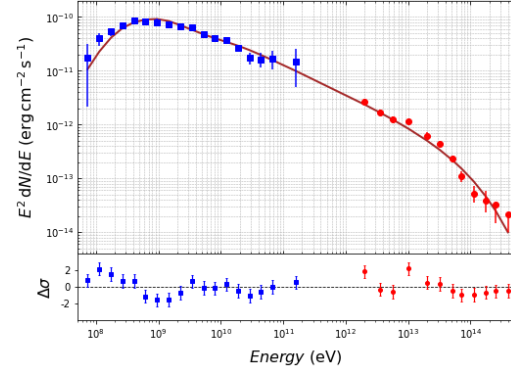
(b) Best-fit curve of the γ -ray spectrum and normalized residuals.

Figure 3. The fitting results of the γ -ray spectrum observational data of W51C based on the π^0 -decay model. The fitting process utilized the Fermi-LAT spectrum (Jogler & Funk 2016) and the LHAASO spectrum (Cao et al. 2024b) as observational data sources. Left panel: Corner plot of the model parameters. Right panel: the upper main plot shows the best-fit curve of the γ -ray spectrum, while the lower inset presents the normalized residuals between the best-fit curve and the observational data.

sources proposed by Cao et al. (2024a) can be attributed to γ -ray emissions arising from interactions between nearby SNRs and MCs. Mitchell & Celli (2024) employed the SNR catalog (SNRcat) compiled by Ferrand & Safi-Harb (2012) and MC data identified by Rice et al. (2016). Using the latest version of SNRcat, they matched SNRs with MCs based on spatial coordinates and distances. In this process, two classes of SNRs were considered separately: Type II SNRs and Type Ia SNRs, which correspond respectively to different types of supernova explosion events.

Mitchell & Celli (2024) proposed a significant association between an MC and an LHAASO source if the angular distance between the MC and the best-fit position of the LHAASO source is less than the sum of their radii, assuming spherical symmetry. For LHAASO sources, they adopted a containment radius of 39%. Through systematic searches and analyses, they identified and summarized the SNR-MC systems associated with LHAASO sources. The study by Mitchell & Celli (2024) primarily focused on the spectral characteristics of unidentified 1LHAASO sources and provided only a qualitative comparison between these sources and the spectra of MCs illuminated by CRs escaping from SNRs. In this section, we extend the scope of investigation to include all 1LHAASO sources, encompassing both identified and unidentified ones. We perform quantitative spectral fitting within the confidence intervals of each source and systematically assess the contribution of SNR-MC systems to high-energy γ -ray emission based on a more comprehensive sample.

Based on the findings of Mitchell & Celli (2024), we selected SNR-MC systems for detailed analysis according to the following two well-defined criteria (see Table 2):

- (a) Each MC must be illuminated by a single SNR, thereby ensuring a clear and isolated SNR-MC interaction system;
- (b) Each SNR-MC system must spatially overlap with only one LHAASO source, in order to avoid cases where a single system is associated with multiple LHAASO sources simultaneously.

Employ the Sedov–Taylor solution to model the dynamical evolution of the radius of SNRs. During the adiabatic expansion phase, the radius R_{SNR} of the SNR is given by the formula $R_{\text{SNR}} = \left(\frac{2.026 E_{\text{SNR}} t^2}{\rho_0} \right)^{1/5}$, where E_{SNR} is the supernova explosion energy, and ρ_0 is the mass density of the surrounding medium. If there are no explicit observational constraints on the values of L_1 and L_2 , we assume $L_2 = L_1 + d$, and d represents the thickness of the high-density molecular cloud region. If the age of the SNR is not provided in the existing catalog, it can be inferred from the measured size of the remnant. In cases where the distance to the remnant has not been determined, it is assumed to be the same as that of the paired MC. Additionally, the CR energy conversion efficiency is assumed to be 10%, and the supernova explosion energy is taken to be 10^{50} erg. Based on these assumptions, the Sedov time is $t_{\text{Sedov}} \approx 234$ yr for Type Ia SNRs and $t_{\text{Sedov}} \approx 1.6$ kyr for Type II SNRs (Mitchell & Celli 2024). The parameters of each SNR-MC system are listed in Table 3.

Table 2
SNR-MC Systems Overlapping with the 1LHAASO Sources

Cloud	(l, b) ($^{\circ}, ^{\circ}$)	R_{cloud} ($^{\circ}$)	n (cm^{-3})	d (kpc)	$\phi_{\gamma > 10 \text{ TeV}}$ ($\text{TeV cm}^{-2} \text{ s}^{-1}$)	SNR	1LHAASO	Inst.	R_{39} ($^{\circ}$)	Sep. ($^{\circ}$)
151	(16.97, 0.53)	0.46	90	2.08	2.76e-11	G019.1+00.2	J1825-1418	WCDA KM2A	0.81 0.81	1.37 1.27
237	(16.24, -1.02)	0.17	139	4.33	6.08e-12	G016.4-00.5	J1825-1418	WCDA KM2A	0.81 0.81	1.01 1.31
173	(18.32, 2.51)	0.45	27	2.32	5.99e-12	G019.1+00.2	J1813-1245	WCDA KM2A	0.31 0.32	1.06 1.04
219	(32.73, -0.42)	0.14	134	2.91	3.81e-12	G031.5-00.6	J1850-0004u*	WCDA KM2A	0.46 0.21	0.50 0.39
208	(16.61, -0.38)	0.31	141	3.65	8.95e-11	G017.4-00.1	J1825-1418	WCDA KM2A	0.81 0.81	0.75 0.91

Note. This table is excerpted from Mitchell & Celli (2024). From left to right, it lists the coordinates of the MCs in the Galaxy (l, b), the angular radius R_{cloud} , particle number density n , distance to the Earth, and the integral γ -ray flux above 10 TeV from the SNRs; the names of the SNRs; the 1LHAASO sources overlapping with the SNR-MC systems, their ultra-high-energy radius (39% containment radius), and the distance to the cloud. The bold 1LHAASO source signifies that its astrophysical nature has not yet been determined. The MC data are from Rice et al. (2016), the SNR data from Ferrand & Safi-Harb (2012), and the 1LHAASO source data from Cao et al. (2024a).

4.1. G019.1+00.2

Cloud 151 is located at Galactic coordinates $(l, b) = (16^{\circ}97, -0^{\circ}53)$ and is irradiated by Type II SNR G019.1+00.2. Spatially, this region overlaps with 1LHAASO J1825-1428. SNR G019.1+00.2 has not been extensively studied and is classified as a shell-type SNR. Based on its size, the age of this SNR is estimated to be approximately 5.19 kyr. Assuming the remnant and Cloud 151 are located at the same distance, they constitute an SNR-MC system. Figure 4(a) presents the fitting results based on the parameters listed in Tables 2 and 3.

In addition to Cloud 151, Cloud 173 (located at Galactic coordinates $(l, b) = (18^{\circ}32, 2^{\circ}51)$) may also be irradiated by SNR G019.1+00.2, forming another SNR-MC system. This system spatially overlaps with 1LHAASO J1813-1245, a UNID γ -ray source. Figure 4(b) presents the corresponding fitting results. Since precise data on the SNR are lacking, the fitting was performed under the assumption that the remnant and Cloud 173 are at the same distance from the Earth.

4.2. G016.4-00.5

Cloud 237 is located at Galactic coordinates $(l, b) = (16^{\circ}24, -1^{\circ}02)$ and is also irradiated by Type II SNR G016.4-00.5. This region spatially overlaps with 1LHAASO J1825-1418. Assuming that the distance from the SNR to the Earth is the same as that of Cloud 237, they form an SNR-MC system. Figure 4(c) presents the fitting results for 1LHAASO J1825-1418.

4.3. G031.5-00.6

Cloud 219 is located at Galactic coordinates $(l, b) = (32^{\circ}73, -0^{\circ}42)$ and is influenced by radiation from Type II SNR G031.5

Table 3
Parameter Statistics for Five SNR-MC Systems

Cloud	SNR	δ	χ	p_{cut} (GeV/c)	L_1 (pc)	L_2 (pc)	t_{age} (kyr)
151	G019.1+00.2	0.6	0.45	8.0×10^6	7.0	23.7	5.19
237	G016.4-00.5	0.65	0.09	1.0×10^6	6.0	18.8	3.80
173	G019.1+00.2	0.48	1.5	6.0×10^6	5.7	23.9	5.19
219	G031.5-00.6	0.41	0.9	1.0×10^6	5.9	13.0	4.60
208	G017.4-00.1	0.6	0.8	5.0×10^6	3.0	22.7	0.58

–00.6, thereby forming an SNR-MC system. This system spatially coincides with γ -ray source 1LHAASO J1850-0004u, classified as a UNID γ -ray source. Figure 4(d) presents the fitting results of the SNR-MC system for 1LHAASO J1850-0004u.

4.4. G017.4-00.1

Cloud 208 is located at Galactic coordinates $(l, b) = (16^{\circ}61, -0^{\circ}38)$ and is irradiated by Type Ia SNR G017.4-00.1. Classified as a shell-type remnant, G017.4-00.1 has an estimated age of approximately 600 yr based on its size. Assuming Cloud 208 is at the same distance from the Earth as G017.4-00.1, these two objects constitute an interacting SNR-MC system. This SNR-MC system spatially coincides with γ -ray source 1LHAASO J1825-1418. Figure 4(e) presents the fitting results of the SNR-MC system for 1LHAASO J1825-1418.

4.5. Effects of Parameters on the Fitting Curve

Due to limitations in observational data, the age of SNRs is estimated based on their size, with the parameter L_1 manually

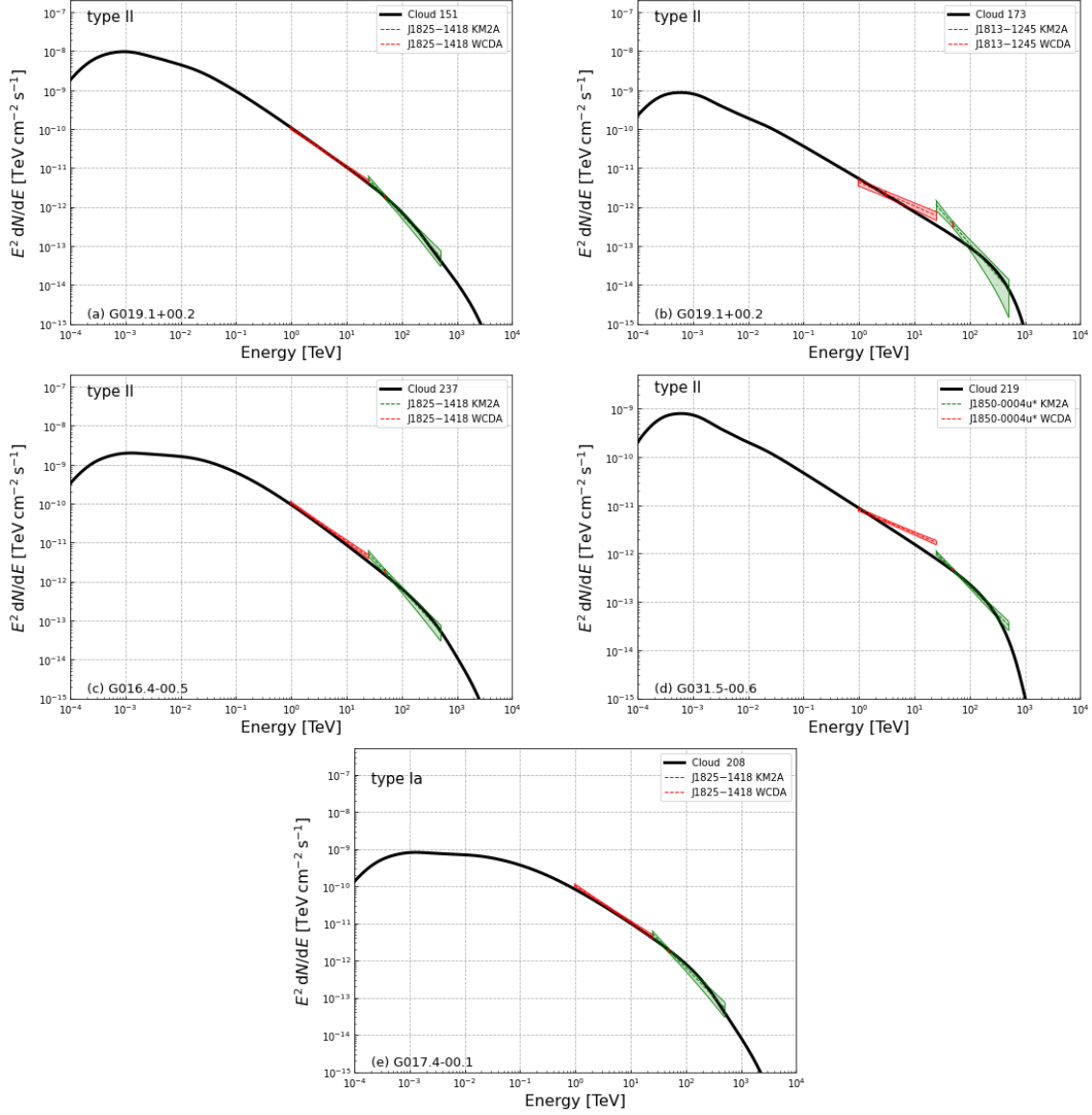


Figure 4. The γ -ray spectra of five SNR-MC systems. The relevant parameters are listed in Tables 2 and 3.

specified by the researchers and L_2 derived from L_1 . Taking as an example the SNR-MC system comprising SNR G019.1+00.2 and Cloud 151, which is described in Section 4.1. This system spatially coincides with the γ -ray source 1LHAASO J1825-1418. Figure 5(a) and (b) shows how the fitting curve varies with the SNR age (t_{age}) and the internal radius of the MC (L_1). Additionally, Figure 5(c), (d) and (e) illustrates the impact of the adjustable parameters χ , δ , and p_{cut} on the fitting curve.

5. Summary and Discussion

Based on the CRs diffusion model proposed by Ohira et al. (2011), we have provided a detailed description of the propagation and spatial distribution characteristics of CRs

during the expansion of SNRs. Furthermore, we have investigated the mechanisms responsible for the production of γ -rays in SNR-MC systems. Specifically, when a substantial number of MCs are present around an SNR, the escaping high-energy protons undergo p-p interactions with the dense medium within the MCs, leading to the generation of high-energy γ -rays.

This study uses the W51 complex, one of the most active star formation regions in the Galaxy, as the research sample (Cao et al. 2024b). Based on the ECPL model, we fitted the high-energy γ -ray spectrum of W51C and estimated the model parameters using the MCMC method. The best-fit parameters obtained are: cutoff momentum $p_{\text{cut}} \approx 0.9 \text{ PeV}/c$, diffusion

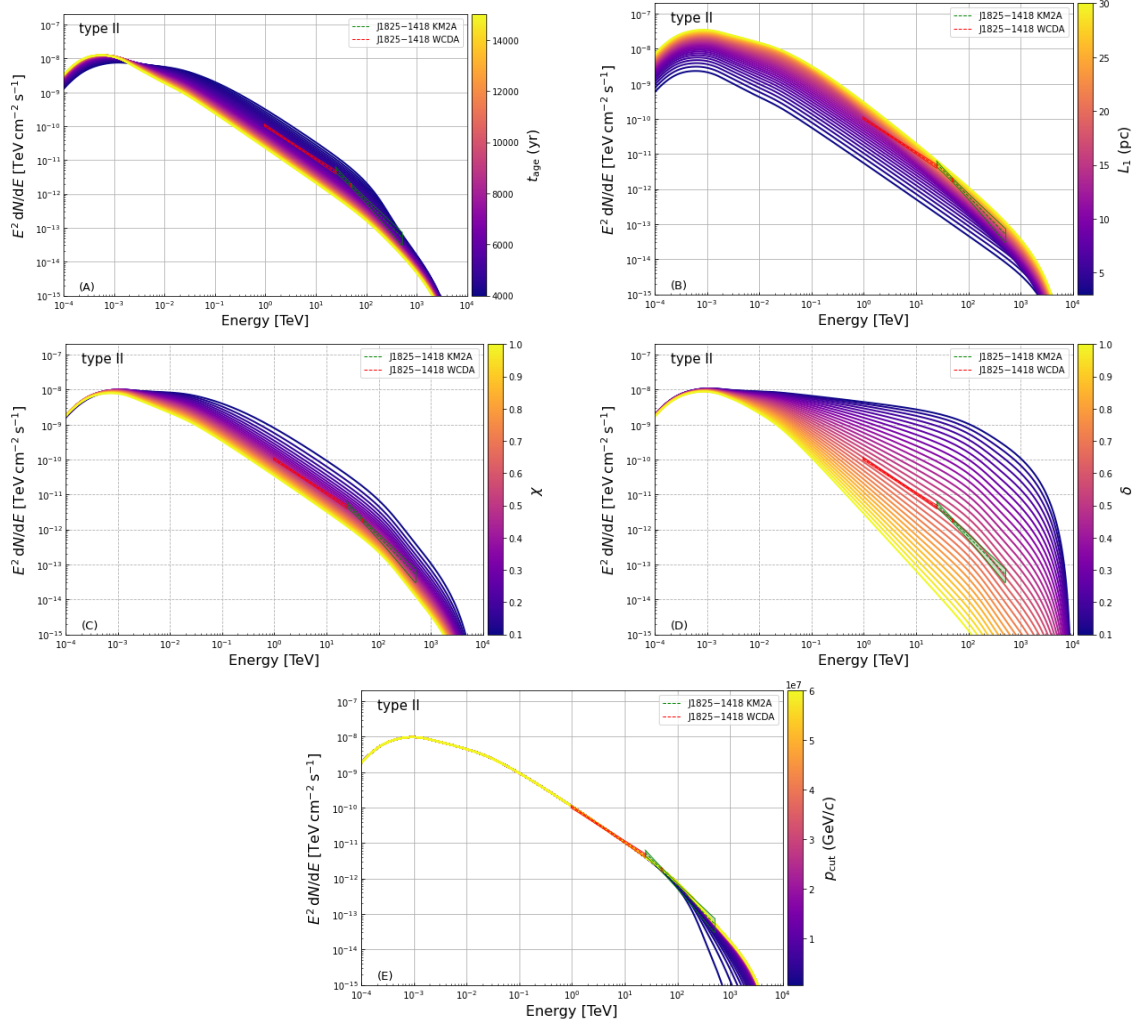


Figure 5. The influence of various parameters on the fitting curve: Cloud 151 irradiated by SNR G019.1+00.2.

index $\delta = 0.23$, and normalization coefficient $\chi = 0.13$. The fitting result yields a χ^2_ν value of 1.51, indicating that the model accurately reproduces the observational data. Compared to the study by Cao et al. (2024b), which employed a relatively simplified p-p interaction model for fitting the γ -ray spectrum, their approach did not fully account for the complex effects of CR escape and diffusion processes on the high-energy spectral features. As a result, the spectral cutoff energy obtained from their model was relatively low. In contrast, the present study explicitly incorporates the mechanisms of CR escape and diffusion into the model construction, with particular emphasis on the evolutionary stage of the SNR and the time-dependent evolution of the escape momentum. This improved modeling approach naturally accommodates higher particle cutoff energies, thereby yielding a spectral cutoff that exceeds that of previous studies and enhancing both the accuracy and

physical plausibility of the model in reproducing the observed high-energy γ -ray spectrum.

In conjunction with the results of Mitchell & Celli (2024), we conducted a systematic comparison of the fitting results with the 1LHAASO γ -ray source catalog to investigate whether UHE or UNID γ -ray sources could originate from the radiative emission of SNR-MC systems. By comparing the spatial overlap between SNRs and MCs with γ -ray sources observed by LHAASO, several potential counterparts were identified. This finding further supports the hypothesis that SNR-MC interaction systems could be candidates for “PeVatrons” within the Galaxy. We also systematically examined the influence of key model parameters, such as SNR age (t_{age}), the inner boundary radius of the MC (L_1), cutoff momentum (p_{cut}), and diffusion index (δ) on the γ -ray spectral morphology. The results show that variations in these

parameters can significantly alter the spectral features, particularly the shape and the position of the high-energy cutoff.

It should be noted that this model, when describing cosmic ray propagation, is based on the assumption of spherical symmetry and a uniform diffusion coefficient. These assumptions may have certain limitations in the real environment of the Galaxy. In reality, the magnetic field structure of the Galaxy is complex and subject to turbulent effects (Vladimirov et al. 2009), which can lead to an inhomogeneous distribution of CRs, potentially affecting the accuracy of γ -ray spectra. Moreover, observations indicate that the shape and density distribution of MCs are highly irregular, further complicating the p-p interaction regions. Future studies will need to more comprehensively consider asymmetric CR diffusion, magneto-hydrodynamic effects, and the cumulative impact of multiple supernova explosions to better approximate the true high-energy physical environment of the Galaxy.

Acknowledgments

This research is supported by NSFC grant No. 12393852 and the Yunnan Fundamental Research Project (grant No. 202501AS070068).

References

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, *ApJL*, **706**, L1
- Aharonian, F., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008, *A&A*, **483**, 509
- Aharonian, F., An, Q., Axikegu, et al. 2021, *ChPhC*, **45**, 025002
- Aharonian, F. A., & Atayan, A. M. 1996, *A&A*, **309**, 917
- Albert, A., Alfaro, R., Alvarez, C., et al. 2024, *ApJL*, **973**, L34
- Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, *A&A*, **541**, A13
- Alfaro, R., Alvarez, C., Arteaga-Velázquez, J. C., et al. 2024, *A&A*, **691**, A89
- Bell, A. R. 1978, *MNRAS*, **182**, 147
- Berezhko, E. G., Pühlhofer, G., & Völk, H. 2003, *A&A*, **400**, 971
- Blandford, R. D., & Ostriker, J. P. 1978, *ApJL*, **221**, L29
- Cao, Z., Aharonian, F., An, Q., et al. 2024a, *ApJS*, **271**, 25
- Cao, Z., Aharonian, F., Axikegu, et al. 2024b, *SciBu*, **69**, 2833
- Cao, Z., Aharonian, F., Axikegu, et al. 2025, *MNRAS*, **540**, 1860
- Caprioli, D., Kang, H., Vladimirov, A. E., & Jones, T. W. 2010, *MNRAS*, **407**, 1773
- Cardillo, M., & Giuliani, A. 2023, *ApSci*, **13**, 6433
- de Oña Wilhelmi, E., López-Coto, R., Aharonian, F., et al. 2024, *NatAs*, **8**, 425
- Fang, K., Kerr, M., Blandford, R., Fleischhack, H., & Charles, E. 2022, *PhRvL*, **129**, 071101
- Ferrand, G., & Safi-Harb, S. 2012, *AdSpR*, **49**, 1313
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
- Fujita, Y., Ohira, Y., Tanaka, S. J., & Takahara, F. 2009, *ApJL*, **707**, L179
- Gabici, S., Aharonian, F. A., & Casanova, S. 2009, *MNRAS*, **396**, 1629
- Gao, C., Zha, M., Yao, Z., Feng, C. & Lhaaso Collaboration 2024, 38th ICRC, **444**, 913
- Gelfand, J. D., Castro, D., Slane, P. O., et al. 2013, *ApJ*, **777**, 148
- Ginsburg, A. 2017, Star Formation Newsletter, arXiv:1702.06627
- Green, D. A. 2019, *JApA*, **40**, 36
- Guepin, C. & Poemma Collaboration Team 2022, APS April Meeting, 2022, Z03.004
- He, H. & Lhaaso Collaboration 2018, *RDTM*, **2**, 7
- Jogler, T., & Funk, S. 2016, *ApJ*, **816**, 100
- Kolmogorov, A. N. 1991, *RSPSA*, **434**, 9
- Koo, B.-C., Lee, J.-J., Seward, F. D., & Moon, D.-S. 2005, *ApJ*, **633**, 946
- Li, H., & Chen, Y. 2010, *MNRAS*, **409**, L35
- Li, H., & Chen, Y. 2012, *MNRAS*, **421**, 935
- Ma, X.-H., Bi, Y.-J., Cao, Z., et al. 2022, *ChPhC*, **46**, 030001
- Mitchell, A. M. W., & Celli, S. 2024, *JHEAp*, **44**, 340
- Ohira, Y., Murase, K., & Yamazaki, R. 2010, *A&A*, **513**, A17
- Ohira, Y., Murase, K., & Yamazaki, R. 2011, *MNRAS*, **410**, 1577
- Ohira, Y., & Takahara, F. 2010, *ApJL*, **721**, L43
- Ptuskin, V. S., & Zirakashvili, V. N. 2005, *A&A*, **429**, 755
- Rice, T. S., Goodman, A. A., Bergin, E. A., Beaumont, C., & Dame, T. M. 2016, *ApJ*, **822**, 52
- Sarmah, P., Chakraborty, S., & Joshi, J. C. 2023, *MNRAS*, **521**, 1144
- Tavani, M., Giuliani, A., Chen, A. W., et al. 2010, *ApJL*, **710**, L151
- Vecchi, M., Bueno, E. F., Derome, L., Génolini, Y., & Maurin, D. 2022, 37th ICRC, **395**, 174
- Vladimirov, A. E., Bykov, A. M., & Ellison, D. C. 2009, *ApJL*, **703**, L29
- Zabalza, V. 2015, *ICRC*, **34**, 922