Leaked GeV CRs from a Broken Shell: Explaining 9 Years of Fermi-LAT Data of SNR W28

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Abstract

Supernova remnant (SNR) W28 is well known for its classic hadronic scenario, in which the TeV cosmic rays (CRs) released at the early stage of this intermediate-age SNR illuminate nearby molecular clouds (MCs). Overwhelming evidence has shown that the northeastern part of the SNR (W28-North) has already encountered the MC clumps. Through this broken shell W28-North, CRs with an energy down to < 1 GeV may be able to be injected into nearby MCs. To further verify this hadronic scenario, we first analyze nine years of Fermi-LAT data in/around W28 with energies down to 0.3 GeV. Our Fermi-LAT analysis displays a 10–200 GeV skymap that spatially matches the known TeV sources HESS J1801–233 (W28-North) and HESS J1800–240 A, B, and C (240 A, 240 B, and C) well. At low energy bands, we have discovered a 0.5–1 GeV blob located to the south of 240 A and C, and a low flux of 0.3–1 GeV at 240 A. A hadronic model is built to explain our analysis results and previous multiwavelength observations of W28. Our model consists of three CR sources: the run-away CRs escaped from a strong shock, the leaked GeV CRs from the broken shell W28-North, and the local CR sea. Through modeling the SNR evolution and the CR acceleration and release, we explain the GeV–TeV emission in/around SNR W28 (except for 240 A) in one model. The damping of the magnetic waves by the neutrals and the decreased acceleration efficiency are both taken into account in our model due to the intermediate age of SNR W28.

Key words: acceleration of particles – cosmic rays – diffusion – gamma rays: ISM – ISM: supernova remnants

1. Introduction

For intermediate-age/old supernova remnants (SNRs), the released TeV cosmic rays (CRs) mostly come from the run-away CRs during the early stage of the SNR, and they are expected to fill the nearby environment almost homogeneously at the present time. This hypothesis has been well supported in the case of SNR W28 (Aharonian et al. 2008): H.E.S.S. data along with the NANTEN 12CO data have shown that the TeV sources HESS J1801–233 (W28-North) and HESS J1800–240 A, B, and C (240 A, 240 B, and C) well spatially match their molecular cloud (MC) counterparts well. These counterparts are an MC northeast of the SNR (MC-N) and MCs to the south of the SNR (MC-A, MC-B, and MC-C). Subsequent Fermi observations of SNR W28 by Abdo et al. (2010) have found GeV counterparts of W28-North and 240 B, and further Fermi analysis work by Hanabata et al. (2014) provided a more detailed GeV spectrum of the southern counterparts. These two works suggest that this intermediate-age SNR likely releases its GeV CRs into nearby MCs. Considering the relatively low diffusion coefficient of GeV CRs and their relatively late releasing time when compared to TeV CRs, it is not surprising to find that only some of these MCs (possibly due to the shorter distance to the SNR) are brightly illuminated in the Fermi-LAT skymap of Abdo et al. (2010).

From the multiwavelength view of W28, Very Large Array (VLA) 90 cm radio image from Brogan et al. (2006) has shown a clear shell structure, which provides us the location (R.A. 18h01m42.2 s, decl. –23°20′6″0″) and the radius (0′34′′) of SNR W28. The ROSAT/ASCA study by Rho & Borkowski (2002) has discovered thermal X-ray emission at the SNR center, and the estimated X-ray emitting mass is only 20–25 M\(_{\odot}\). The lack of nonthermal X-ray emission suggests that this intermediate-age SNR can no longer accelerate fresh super-TeV electrons. Interestingly, there is a bright feature northeast of the SNR that is bright in both radio and thermal X-rays. This bright feature, which spatially coincides with W28-North, indicates that SNR W28 has already encountered nearby MCs, i.e., MC-N, and shocked the gas there (Rho & Borkowski 2002; Nakamura et al. 2014; Zhou et al. 2014). This shock-MC encounter scenario is also supported by other observational evidence: the northeast region of SNR W28 contains a rich concentration of 1720-MHz OH masers (Frail et al. 1994; Claussen et al. 1999; Hewitt & Yusef-Zadeh 2009), with velocity of local standard of rest (VLSR) in the range of 5–15 km s\(^{-1}\), and near-IR rovibrational H\(_2\) emission (Reach & Rho 2000; Neufeld et al. 2007; Marquez-Lugo & Phillips 2010). The velocity dispersion distribution of the NH\(_3\) emission line in this NE region suggests an external disruption from the W28 SNR direction (Nicholas et al. 2011, 2012). More multiwavelength observations of W28 can be found in Section 3.1.

So far, the releasing process of the GeV CRs from intermediate-age SNRs is still an open question. In previous works on W28, see, e.g., Gabici et al. (2010), Li & Chen (2010), Ohira et al. (2011), and Tang (2017), run-away CRs with energies down to \(\leq 1\) GeV are able to escape the shock during the SNR evolution history. Ohira et al. (2011) has studied the case in which a fast shock sweeps and passes small clumps, and neither the dynamical evolution of the system nor the shock environment that confine CRs is affected by the small clumps. Additionally, Ohira et al. (2011) have also explored a
scenario in which the entire SNR shell is embedded inside MC clumps, and the GeV CRs used to be trapped at the acceleration region become the run-away CRs immediately after the shock-MC encounter. SNR W28 has clearly only partially collided with MC-N, and the shock cannot simply “pass” MC-N unchanged because of the large size of MC-N.

In our work, we explore the hypothesis that most of the escaped $\lesssim10$ GeV CRs come from the broken shell at W28-North. When parts of the SNR W28-North encounter dense MC clumps, MC-N, the shock is significantly slowed or stalls (see, e.g., the shock stalled by dense clumps in case of RX J1713.7−3946; Sano et al. 2010; Gabici & Aharonian 2016) and the magnetic turbulence in both the upstream and downstream of the shock will be damped by the high-density neutrals. This slowed or stalled shock together with the damping of the magnetic turbulence allow all the GeV CRs in the acceleration region to escape (see, e.g., Ohira et al. 2011), and also allow the CRs behind the shock to be carried or be diffused into MC-N. We note that based on a magnetohydrodynamics (MHD) simulation of the shock-MC encounter, Inoue et al. (2012) suggested a shell of amplified magnetic turbulence at the location of the stalled shock. This shell would prevent GeV CRs from entering the MC clumps. However, this shell from Inoue et al. (2012) requires a fast shock ($2500 \text{ km s}^{-1}$) to hit the MC clump, and it can only last for a relative short time of $\lesssim10^3$ year. For the intermediate-age SNR W28, the leakage of GeV CRs at W28-North is also supported by the millimeter observations reported by Vauprê et al. (2014) and Maxted et al. (2016): ionization evidence has been found only at MC-N and is very likely due to the leaked $0.1$–$1$ GeV CRs from the broken shell. A detailed model of the leaking process at W28-North is described in Section 3.2.3. Additionally, we do not rule out that the run-away CRs from the entire SNR (most parts of the SNR have not encountered MC clumps yet, and they display a shock velocity of $\sim100 \text{ km s}^{-1}$) are able to reach a very low energy of $1$ GeV and contribute significantly to the $\lesssim1$ GeV $\gamma$-ray emission at MC-N. A more detailed discussion of this hypothesis can be found in Section 3.3.3.

Triggered by the idea that GeV CRs leaked from W28-North probably dominate the GeV emission in/around W28, in the first part of our work (Section 2), using nine years of Fermi-LAT data, we reanalyze the previously discovered GeV sources in/around W28 with spectral energies down to $0.3$ GeV. In the second part (Section 3), we deliver a hadronic explanation for the GeV–TeV emission in/around W28, involving the leaked CRs from the broken shell W28-North.

2. Fermi-LAT Data Analysis

2.1. Data Preparation

We performed a series of binned maximum-likelihood analyses for a $20^\circ \times 20^\circ$ region of interest (ROI) centered at R.A. = $18^h00^m30^s00^s$, decl. = $-23^\circ26'00''00''$ (J2000), which is approximately the radio position of W28. We used the data obtained with the LAT between 2008 August 4 and 2017 April 4. The data were reduced and analyzed with the aid of the Fermi Science Tools v10r0p5 package. In view of the complex environment of the Galactic plane regions, we adopted the events classified as Pass8 “Clean” class for the analysis so as to better suppress the background. The corresponding instrument response function (IRF) “P8R2 CLEAN V6” was used throughout the investigation.

We further filtered the data by accepting only the good time intervals where the ROI was observed at a zenith angle smaller than $90^\circ$ so as to reduce the contamination from the albedo of Earth.

To subtract the background contribution, we included the Galactic diffuse background (gl_iem_v06.fits), the isotropic background (iso_P8R2 CLEAN V6 PSF3 v06.txt for “PSF3” data, iso_P8R2 CLEAN V6 FRONT v06.txt for “FRONT” data or iso_P8R2 CLEAN V6 v06.txt for a full set of data), and all other point sources cataloged in the most updated Fermi-LAT catalog (3FGL; Acero et al. 2015) within $25^\circ$ from the ROI center in the source model. Based on the $>10 \text{ GeV}$ morphological studies presented in Section 2.2.1, we refined the source configuration in the W28 complex, which is spatially associated with HESS J1801−233 and HESS J1800−240 A B and C. We set free the spectral parameters of the sources within $6^\circ$ from the ROI center in the analysis. The spectral parameters of sources beyond $6^\circ$ from the ROI center were fixed at the catalog values.

In spectral and temporal analysis, we required each energy bin and time segment to attain a signal-to-noise ratio $>3.0\sigma$ (equivalently, a TS value $>9$ and a chance probability $<0.3\%$) for a robust result. For each energy bin or time segment that did not meet this requirement, we placed a $2.5\sigma$ upper limit on its flux.

2.2. Morphological Analysis

2.2.1. $>10 \text{ GeV}$

We investigate the morphology of the W28 complex region in the $10$–$200 \text{ GeV}$ regime. The test-statistic (TS) map of this field is shown in Figure 1, where all 3FGL catalog sources except for 3FGL J1801.3−2326e (the northeastern part of W28), 3FGL J1800.8−2402, 3FGL J1758.8−2402, and 3FGL J1758.8−2346 are subtracted. The peak detection significance is $\sim20\sigma$ and is in the northeastern part.

In the source model, we proceeded to replace 3FGL J1800.8−2402 and 3FGL J1758.8−2402 with three point sources at the positions of 240 A, B, and C, respectively. In order to revise the morphology of 3FGL J1801.3−2326e (originally a uniform disk with a $0.39^\circ$ radius in the northeastern part), we followed the scheme of a likelihood ratio test adopted by Yeung et al. (2016, 2017). Since its centroid is exactly at the center of 3FGL J1801.3−2326e, we varied only the radius of the extension and left the center unchanged. We assigned it a simple power law (PL). The $-\ln$(likelihood) of different radii in $10$–$200 \text{ GeV}$ is tabulated in Table 1, and the most likely radius is determined to be $0.345^\circ$. We therefore adopted this morphology for the northeastern part of W28 in the subsequent analysis, and we refer to it as Fermi J1801.4−2326 to avoid confusion with 3FGL J1801.3−2326e.

We furthermore re-created the TS map with all sources in the revised model except for 3FGL J1758.8−2346 (the western clump) subtracted, and this is presented in Figure 2. We thus revised the position of 3FGL J1758.8−2346 to be $(269^h47917$, $-23^\circ820494)_2000$, which is the centroid determined on this map, and we renamed it “Source-W.” Here, we finalized the source model for the spectral analysis.

2.2.2. $<10 \text{ GeV}$

Motivated by the LAT spectra of 240 B and C presented in Section 2.3, we also investigated their morphology in lower energy bands. We created TS maps in which all sources except...
240 B and C are subtracted (Figure 3) in 1–50 GeV (left) and 0.5–1 GeV (right). We adopted PSF3 data to optimize the spatial resolution.

In 1–50 GeV, the excess shown in the map is coincident with 240 B and C, but the excesses from these two spatial components are hardly resolved. In 0.5–1 GeV, the excesses from 240 B and C, if any, are buried below the PSF wing of a brighter blob (the southern blob) whose centroid is at (269°73584, −24°268803)J2000. The detection significance of this southern blob is $\gtrsim 30\sigma$.

The diffuse background that is mainly caused by the CR sea interacting with the interstellar medium is particularly high at $<10$ GeV band. As seen in Figure 4, the southern blob is located inside a bright background region, therefore it is also possible that the southern blob is caused by an imperfect background reduction.

### 2.3. Spectral Analysis

To construct the binned spectra of our five target sources, we performed an independent fitting of each spectral bin. For each spectral bin, we assigned PL models to all target sources. Considering that we include photons with energies below 1 GeV and that we are investigating crowded regions in the Galactic plane, we find it not appropriate to adopt a full set of

| Radius of Extension (deg) | $-\ln(\text{likelihood})$ |
|--------------------------|----------------------------|
| 0.1                      | 85302.65878385              |
| 0.2                      | 85281.5689407               |
| 0.3                      | 85250.41629475              |
| 0.33                     | 85247.72361                 |
| 0.34                     | 85247.39720513              |
| 0.345                    | 85247.3959966               |
| 0.35                     | 85247.3950346               |
| 0.36                     | 85247.81674768              |
| 0.4                      | 85249.53678938              |

Figure 1. TS map of the entire W28 region at 10–200 GeV, with right ascension/declination as x/y axis. The radio boundary of SNR W28 is marked as a white dashed circle. The H.E.S.S. morphology contour is presented as green lines (4, 5, and 6σ), and the TeV sources HESS J1801–233 (W28-North) and HESS J1800–240 A, B, and C (A, B, and C) are indicated in green as well. The 3FGL catalog sources are marked as a cyan circle and crosses. The newly discovered GeV sources, Source-W and the southern blob, are marked as green boxes and cross. Source-W was first discovered by Hanabata et al. (2014), and its position reported by Hanabata et al. (2014) is marked as a solid green box with the label “HKJ2014.” More details about Source-W and the southern blob can be found in Figures 2 and 3 and in the text.

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data whose large PSF (e.g., a 68% containment radius of \( \sim 2.3 \) at 0.3 GeV; cf. SLAC\(^5\)) leads to severe source confusion. In addition, adopting only PSF3 data is also discouraged in spectral fittings because of the large systematic uncertainties that are induced by the severe energy dispersion. For FRONT data in 0.3–1 GeV, the FWHM of its PSF is \(<75\%\) of that for a full set of data, and its energy dispersion is greater than that for a full set of data by only \(<1\%\) of the photon energy (cf. SLAC\(^5\)). Therefore, we adopted only FRONT data in order to achieve a compromise between a small PSF and lower energy dispersion.

The 0.3–250 GeV spectral energy distributions (SEDs) are shown in Figure 5. We examined how well each spectrum can be described by a simple PL

\[
\frac{dN}{dE} = n_0 \left( \frac{E}{E_b} \right)^{-1}\Gamma,
\]

and a broken power-law (BKPL)

\[
\frac{dN}{dE} = \begin{cases} 
  n_0 \left( \frac{E}{E_b} \right)^{-1}\Gamma & \text{if } E < E_b \\
  n_0 \left( \frac{E}{E_b} \right)^{-1}\Gamma_1 & \text{otherwise.}
\end{cases}
\]

For the BKPL, we fixed the spectral break at \( E_b = 1 \) GeV because it cannot be properly constrained. The results of the spectral fitting are tabulated in Table 2.

For Fermi J1801.4–2326, the likelihood ratio test indicates that a BKPL is preferred over a PL by \( >13\sigma \). A BKPL model yields a photon index \( \Gamma_1 = 2.10 \pm 0.03 \) below the spectral break \( E_b = 5 \) GeV and a photon index \( \Gamma_2 = 2.63 \pm 0.02 \) above the break. In view of the apparent bump above 30 GeV, we repeated this test without the 0.3–1 GeV data. It turns out that the 1–250 GeV spectrum of Fermi J1801.4–2326 is satisfactorily described by a PL with \( \Gamma = 2.64 \pm 0.02 \), while the additional parameters of a BKPL are not strongly required (only \( \sim 1.5\sigma \)). The fitting parameters are tabulated in Table 3.

For the GeV counterpart of 240 A, a BKPL is preferred over a PL by \( \sim 3.3\sigma \). A BKPL model yields a photon index \( \Gamma_1 = 0.53 \pm 0.72 \) below 1 GeV and a photon index \( \Gamma_2 = 2.37 \pm 0.09 \) above 1 GeV. For Source-W, a BKPL is preferred over a PL by \( \sim 4.3\sigma \). In the BKPL model, the photon indices below and above 1 GeV are \( \Gamma_1 = -0.09 \pm 0.85 \) and \( \Gamma_2 = 2.42 \pm 0.10 \), respectively.

For 240 B and C, each of their LAT spectra appears to contain a flux discontinuity, which means that the PL and BKPL models both fail to describe their spectral shapes (i.e., each of them might be decomposed into two spectral components). We therefore considered their spectral shapes separately in two mutually exclusive energy bands decoupled at around the termination point of the first component (0.75 GeV and 1 GeV for 240 B and C, respectively). The results of the spectral fitting are tabulated in Table 3.

It turns out that in 0.3–250 GeV, a two-component scenario (a model with discontinuous flux) is preferred over a single-component scenario (a model with continuous flux) by \( >10\sigma \) for both 240 B and C. For each source, we compared the sum of the PL TS values in the two decoupled energy bands with the BKPL TS value in 0.3–250 GeV. Since a two-independent-PL model can be reduced to a BKPL model by uniting the prefactors, the number of additional d.o.f. is only 1. The first LAT component of 240 B has a photon index \( \Gamma = 2.15 \pm 0.39 \). Its second LAT component starts with \( \Gamma_1 = 1.77 \pm 0.15 \) at 0.75 GeV, and then softens (at a \( \sim 3.2\sigma \) significance) to \( \Gamma_2 = 2.47 \pm 0.09 \) above a break energy \( E_b = 2780 \pm 837 \) MeV. 240 C has its first LAT component with \( \Gamma = 2.11 \pm 0.21 \), and its second LAT component starts at 1 GeV with a photon index \( \Gamma = 2.24 \pm 0.10 \). A spectral break is not required at all for its second component. The 0.3–1 GeV emissions detected at 240 B and C probably mostly originate from the southern blob (see Figure 3). With regard to this, the 0.3–1 GeV data points of 240 B and C can only serve as upper limits in our final results.

When compared with previous Fermi-LAT analysis work, as shown in Figure 6, we deliver similar spectral results of the relatively brighter GeV sources W28-North and 240 B, while our GeV fluxes of 240 A and C are lower than those from Hanabata et al. (2014). In Figure 6, we also plot a simple hadronic fitting (with a PL CR population) for each \( \gamma \)-ray source. The CR PL indices in the fitting of W28-North, 240 A, B, and C are set as 2.7, 2.2, 2.4, and 2.3, respectively. Because of the low \(<1\) GeV emission at 240 A and B, minimum cutoffs of the CR population of 5 and 9 GeV are used in the fitting of 240 A and B, respectively.

Source-W is ignored in this simple fitting and in the hadronic model below, because it has neither distinct MC counterparts nor TeV counterparts (it does have a radio counterpart). Here we do not exclude the possibility that Source-W could be explained by CRs released from the SNR as well. Hanabata et al. (2014), for instance, have presented a successful hadronic model for Source-W, in which they have used a mass of the MC at Source-W of \( 3.5 \times 10^{18} M_{\odot} \) and a distance of \( 16 \sim 25 \) pc to the SNR. However, under one SNR model and one diffusion coefficient, it seems difficult to explain why the GeV flux from Source-W is almost comparable to those from 240 A, B, and C, as seen in Hanabata et al. (2014). In order to compensate for the relatively lower mass of the MC counterpart.

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\(^5\) Fermi LAT Performance: http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm.
of Source-W, a much higher total CR energy is adopted in the Source-W model when compared to those adopted in their models of 240 A, B, and C. More complex hadronic scenarios could help solve this problem, e.g., by introducing a magnetic tube connecting the SNR and Source-W, or by introducing an asymmetric SNR expansion, that the shock can carry GeV CRs all the way to Source-W, as discussed by Hanabata et al. (2014). This scenario can also explain the extended radio structure southwest (Source-W) of the SNR. Additionally, Hanabata et al. (2014) have also discussed the other possible explanations (pulsar and blazar) for Source-W.

3. The Hadronic Model

3.1. The Physical Constraints from Multiwavelength Observations of W28

Based on the observational data introduced above, SNR W28 is obviously an intermediate-age SNR and can no longer accelerate fresh super-TeV electrons, and it has already encountered MC-N, part of the CRs trapped in behind the shock are able to be released. Further constraints of our physical parameters by multiwavelength observations are listed below.

1. **Distance to Earth**, ~2 kpc and **SNR radius**, ~13 pc. SNR W28 is located inside a complex star-forming region, where HII regions M 20 (d ~ 1.7 kpc; Lynds & O'Neil 1985) and M 8 (d ~ 2 kpc; Tothill et al. 2002) are seen. Nonetheless, there is no solid evidence to link these H II regions to SNR W28. Velázquez et al. (2002) suggested the distance of SNR W28 to be ~1.9 kpc, assuming it is associated with a 70$M_{\odot}$ HI feature detected in the SNR region. This HI feature is also seen as evidence of the interaction between SNR W28 and its surrounding gas.

2. **The density of pre-SN circumstellar medium**, ~5 cm$^{-3}$. Through near-IR and millimeter-wave observation, Reach et al. (2005) found that the different morphologies of W28 at different wavelengths can be explained by the highly nonuniform structure of giant molecular clouds, with a low-density inter-clump medium (ICM) ($n_1 \sim 5$ cm$^{-3}$) occupying most (90%) of the volume, moderate-density clumps ($n_1 \sim 10^3$ cm$^{-3}$) occupying most of the rest of the volume, and dense cores. Velázquez et al. (2002) has derived H I density upper limits of $n_1 \sim 1.5 ~ 2$ cm$^{-3}$, which is in accordance with the ICM density mentioned above, assuming that the observed mass (swept-up H I gas around the SNR) is evenly distributed inside a bubble with a 20 pc radius.

3. **Shock velocity at the present time**, ~100 km s$^{-1}$. Through observing the neutral hydrogen around the SNR, a H I...
cloud is detected by Velázquez et al. (2002) near $V_{LSR} = +37 \text{ km s}^{-1}$, overlapping the center of W28. This expanding H I cloud is likely to be a swept-up thick H I shell surrounding the SNR. The velocity dispersion of this H I cloud might therefore be lower than the intrinsic shock velocity. A more accurate method is directly measuring the forbidden lines at the shock downstream. Bohigas et al. (1983) estimated shock velocities of W28 between 60 and 90 km s$^{-1}$ using the line strength ratio of O III $\lambda 5007$/H$\alpha$, while Long et al. (1991) derived velocities higher than 70 km s$^{-1}$ from the line strength ratio of N II/H$\alpha$ and S II/H$\alpha$.

4. The time of the shock-MC encounter at W28-North. The detailed XMM study of W28 by Zhou et al. (2014) has found a soft component ($\sim 0.3 \text{ keV}$, $\sim 1 M_\odot$) and a hard component ($\sim 0.6 \text{ keV}$, $\sim 0.2 M_\odot$) in the NE shell (W28-North) whose ionization timescales are estimated to be $>7.5 \text{ kyr}$ and 10–40 kyr, respectively. In our model below, the shock-MC encounter time is set at 25 kyr after the SN explosion (12 kyr ago from the present time).
Table 2
0.3–250 GeV Spectral Properties

| Fermi J1801.4–2326 | 240 A | 240 B | 240 C | Source-W |
|-------------------|-------|-------|-------|---------|
| **PL** | | | | |
| $\Gamma$ | 2.422 ± 0.009 | 2.164 ± 0.061 | 2.209 ± 0.036 | 2.455 ± 0.070 | 2.133 ± 0.059 |
| Flux ($10^{-9}$ cm$^{-2}$ s$^{-1}$) | 315.816 ± 2.965 | 8.282 ± 1.066 | 21.188 ± 1.267 | 15.920 ± 1.379 | 8.456 ± 0.998 |
| TS | 19007.8 | 164.7 | 642.1 | 236.5 | 168.0 |

| **BKPL** | | | | |
| $\Gamma_1$ | 2.095 ± 0.025 | 0.530 ± 0.721 | 2.245 ± 0.145 | 2.984 ± 0.182 | −0.086 ± 0.849 |
| $\Gamma_2$ | 2.629 ± 0.019 | 2.371 ± 0.092 | 2.200 ± 0.049 | 2.237 ± 0.088 | 2.416 ± 0.098 |
| $E_0$ (MeV) | 1000 | 1000 | 1000 | 1000 | 1000 |
| Flux ($10^{-9}$ cm$^{-2}$ s$^{-1}$) | 308.367 ± 3.021 | 5.912 ± 1.232 | 21.346 ± 1.417 | 17.081 ± 1.375 | 5.640 ± 1.083 |
| TS | 19216.0 | 178.3 | 642.1 | 245.8 | 190.2 |

| Table 3
Spectral Properties in Narrowed Energy Bands

| Fermi | J1801.4–2326 | 240 B | 240 C |
|-------|-------------|-------|-------|
| **PL** | | | |
| Energy band (GeV) | 1–250 | 0.75–250 | 1–250 |
| $\Gamma$ | $2.637 ± 0.021$ | $2.238 ± 0.045$ | $2.237 ± 0.101$ |
| Flux ($10^{-9}$ ph cm$^{-2}$ s$^{-1}$) | $61.092 ± 0.881$ | $7.540 ± 0.415$ | $2.263 ± 0.276$ |
| TS | 8413.9 | 572.5 | 111.0 |

| **BKPL** | | | |
| $\Gamma_1$ | $2.650 ± 0.022$ | $1.769 ± 0.149$ | $2.159 ± 0.203$ |
| $\Gamma_2$ | $2.123 ± 0.216$ | $2.469 ± 0.088$ | $2.371 ± 0.314$ |
| $E_0$ (MeV) | $33262 ± 2354$ | $2780 ± 837$ | $8686 ± 4896$ |
| Flux ($10^{-9}$ ph cm$^{-2}$ s$^{-1}$) | $61.138 ± 0.881$ | $6.978 ± 0.455$ | $2.212 ± 0.408$ |
| TS | 8418.0 | 585.8 | 111.3 |

5. **SN total energy**, $\sim 1 \times 10^{51}$ erg. This is the typical total energy for both core-collapse (CC) SNe and type Ia SNe, and it also satisfy the requirements of the derived circumstellar gas density and the observed shock velocity at the present time (see more details in the SNR evolution model below).

6. **Progenitor mass**, $8 M_\odot$. Massive stars that often end in CC SNe are likely to be born in clusters inside or near giant molecular clouds (Smartt 2009). Nonetheless, no central compact object has been found in SNR W28 so far, and this is not surprising when we consider the cooling of a neutron star (if it is a CC SN) at an age of $\sim$40 kyr (Yakovlev & Pethick 2004). The low X-ray emitting mass found in the center of the SNR could be due to the SNR expansion inside an empty pre-SN bubble or other processes, such as evaporation (Rho & Borkowski 2002; Zhou et al. 2014). In our model below, we adopt a CC SN scenario with a progenitor mass of $8 M_\odot$, and an ejecta mass of $6 M_\odot$. Discussions of other types of SNRs can be found in Section 3.3.

7. **Diffusion coefficient**. A diffusion coefficient of 10% of the Galactic standard ($D(E) = 10^{27}(E/10$ GeV)$^{\delta} \text{cm}^2 \text{s}^{-1}$, $\delta = 0.5$) is adopted for the entire space outside the SNR. This value is mainly based on the TeV spectrum fitting of all sources in or around W28, as well as on the GeV spectrum fitting of W28-North; see more details in Section 3.3.1. Similar values are also adopted by Gabici et al. (2010), who has used an approximation of a point CR source to explain the GeV–TeV emission in or around W28.

8. The masses of MC-N, A, and B are estimated as $5 \times 10^5 M_\odot$, $4 \times 10^5 M_\odot$, and $6 \times 10^4 M_\odot$, respectively, via NANTEN 12CO data (Aharonian et al. 2008; Gabici et al. 2010). We note that most components of these MCs are found to cover a broad velocity range from 10 to 20 km s$^{-1}$ which corresponds to a kinematic distance of approximately 2–4 kpc (Aharonian et al. 2008). In Section 3.3, we discuss a scenario in which the MC clumps are placed at 4 kpc to Earth rather than at 2 kpc. The mass of the MC-C is estimated as $1.4 \times 10^4 M_\odot$ by Nicholas et al. (2012), however, in our model below, we adopt $2 \times 10^4 M_\odot$ as the mass of MC-C for a better fitting.

9. The projected distances of HESS J1800–240 A, B, and C from the center of the SNR are $\sim$20 pc, assuming the distance of SNR W28 to Earth as 2 kpc (Aharonian et al. 2008).

3.2. Models

3.2.1. The SNR Evolution

For a CC SN with a minimum progenitor mass ($8 M_\odot$), the progenitor wind bubble can be neglected. Therefore, our SNR can directly expand into the ICM from the beginning. Our modeling results are only sensitive to the pre-SN environment (e.g., the progenitor wind bubble) but not to the ejecta mass, therefore a type Ia SNR scenario would deliver results similar to those shown below.

In our work, we adopt the analytical solutions for the ejecta-dominated stage and the Sedov–Taylor stage from Chevalier (1982), Nadezhin (1985), and Ostriker & McKee (1988), Bisnovatyi-Kogan & Silich (1995), and Ptuskin & Zirakashvili (2005), respectively. When the shock is further slowed, we...
adopt the analytical solution for the pressure-driven snowplow (PDS) stage derived by Cioffi et al. (1988). As shown in Figure 7, inside a homogeneous ICM with density $n_{\text{ISM}} = 6$ H cm$^{-3}$, the SNR spends its first $\sim 650$ years ($\sim 2.5$ pc) in the ejecta-dominated stage. At $\sim 14$ kyr ($\sim 9.3$ pc), it completes the Sedov–Taylor stage and enters the pressure-driven snowplow stage. When it finally reaches 13 pc at 37 kyr, the present shock velocity is 110 km s$^{-1}$. The escape energy of the run-away CRs, which is marked as blue lines in Figure 7, is derived from the CR acceleration theory below.

3.2.2. The CR Acceleration and Run-away CRs

Cosmic-ray acceleration in the SNR is well known as the first-order Fermi acceleration, which normally provides a PL CR spectrum at the shock with an index $\Gamma_{\text{CR}} \sim -2.0$ and a cutoff at the escape energy $E_{\text{max}}$. To explain the super-TeV CRs observed in many young SNRs, Bell (2004) and Zirakashvili & Ptuskin (2008) have developed the acceleration theory of nonresonant streaming instability, in which the magnetic turbulence at the shock upstream is quickly amplified by the CR streaming, and is finally able to boost the escape energy up to hundreds of TeV in a young SNR.

In a strong shock, only CRs with an energy higher than $E_{\text{max}}$ are able to escape from the upstream and propagate to the nearby environment with a flux $J_{\text{out}}$, while other CRs that are trapped at the shock follow a PL spectrum with an index $\Gamma_{\text{CR}} \sim -2.0$. For a young SNR with a high shock velocity $v_{\text{SNR}} \gtrsim 1000$ km s$^{-1}$, only these super-TeV CRs are expected to be released. These early escaped super-TeV CRs could explain the TeV emission from the MCs around intermediate-age SNRs well, e.g., SNR W28 (Gabici et al. 2010), and even around young SNRs, e.g., SNR HESS J1731–347 (Cui et al. 2016). With the Fermi-LAT observational study by Abdo et al. (2010), the discovered GeV emission from W28-North, which peaks at $\lesssim 0.3$ GeV, indicates alternative sources of CRs. Sticking to the run-away CR explanation, one would need to gradually decrease the escape energy to $\lesssim 1$ GeV, mainly by decreasing the shock velocity, decreasing the magnetic field in the upstream, and/or increasing the density of the neutrals in the upstream.

When the shock velocity $v_{\text{SNR}}$ and the density of the nearby circumstellar medium are obtained, the CR acceleration processes can be calculated through the acceleration theory of nonresonant CR streaming from Zirakashvili & Ptuskin (2008). An analytical approximation of this theory derived by Zirakashvili & Ptuskin (2008) is adopted in our work. It provides the escape CR flux $J_{\text{out}}$, the CR density at shock $n_0$, and most importantly, the escape energy $E_{\text{max}}$; see more details in Zirakashvili & Ptuskin (2008) and Cui et al. (2016). A magnetic field of $B_0 = 5$ $\mu$G and an initial magnetic fluctuation...
Knowing the run-away CR spectrum $J_{\text{out}}$ at any given time, we can integrate the entire SNR history as well as the whole surface of the SNR, and eventually, we are able to derive the run-away CR density analytically at any location with a given diffusion coefficient; see details in Section 2.4.1 of Cui et al. (2016). By lowering the escape energy to 10 GeV, which is presented in our damping model (see Figure 8 and text below), a significant amount of GeV CRs can also be released via this run-away process during the late stage of the SNR evolution.

The damping of the magnetic waves upstream of the SNR, which is due to the presence of neutral atoms, becomes important in intermediate-age/old SNRs (Zirakashvili & Ptuskin 2017). Hence, in addition to the shock-MC encounter part of the SNR, W28-North, the other parts of this intermediate-age SNR are also likely to release GeV CRs. Both the damping model and the non-damping model are

Figure 7. SNR evolution profiles. The same SNR age/velocity profile adopted in both the damping and non-damping models is shown as the green and red line. Because of the different acceleration efficiencies and neutral densities adopted in the two models, two different evolution profiles of the escape energy (blue solid and dashed lines) are presented.

Figure 8. CR spectra of the two models. The spectrum of run-away CRs integrated until the present time (37 kyr) and the total leaked CRs from W28-North at 25 kyr are marked as solid and dashed lines, respectively. The leaked CRs consist of two parts, the PL ($\Gamma_{\text{CR}} = -2.0$) up to $E_{\text{max}}$, and the high-energy tail. The normalization for the dashed lines has been multiplied 10 times for graphical purposes.
explored in our work. In the non-damping model, the escape energy follows the analytical solution of the nonresonant CR streaming theory mentioned above. In the damping model, this same analytical solution only works during the early stage of the SNR, when the shock velocity drops to \( \sim 1000 \text{ km s}^{-1} \) \( (R_{\text{SNR}} = 4 \text{ pc}) \). The estimate of the escape energy in partially ionized medium of \( \chi = \frac{v_{\text{SNR}} n_{\text{i}}^{\frac{1}{2}} n_{\text{e}}^{-\frac{1}{2}}}{\Gamma_{\text{CR}} n_{\text{i}}^{\frac{1}{2}} n_{\text{e}}^{-\frac{1}{2}}} \) by O’C Drury et al. (1996) is adopted, which is in accordance with the simulation work by Zirakashvili & Ptuskin (2017). This number \( \sim 1000 \text{ km s}^{-1} \) also gives a smooth transition from the analytical solution by Zirakashvili & Ptuskin (2008) to the estimate by O’C Drury et al. (1996). Here \( n_{\text{e}} \) is the number density of neutrals, which is set to be \( 0.3 \text{ cm}^{-3} \) in our damping model.

For intermediate-age/old SNRs, the CR acceleration efficiency \( \eta \) is expected to decrease at a low Mach number shock \( (M_s \lesssim 50) \); see, e.g., the hydrodynamic estimation of the acceleration efficiency by Voelk et al. (1984). We note that the acceleration efficiency \( \eta \) used in this work is the ratio between the energy flux of run-away CRs and the kinetic energy flux of incoming gas onto the shock. In our work, both the sound speed and Alfvén speed in ICM are set to be \( 15 \text{ km s}^{-1} \) (Chevalier 2005). Here we adopt a relationship of \( \eta = \eta_0 \exp(-\frac{M_0}{M_s} \chi^2) \), where \( \eta_0 \) is the acceleration efficiency when the shock velocity is high. This is set to be 0.04 and 0.03 for the damping model and non-damping model, respectively. By choosing \( \Gamma_{\text{CR}} = 1.2-1.4 \) and \( M_0 = 4-5 \) in our models, this relationship is roughly consistent with the simulation results of \( 0^\circ < \theta < 45^\circ \) by Caprioli & Spitkovsky (2014), where \( \theta \) is the angle between the normal of the shock and the magnetic field. When \( \theta \gtrsim 45^\circ \), the acceleration efficiency drops significantly. These acceleration parameters adopted in our model are also constrained by the limitation of the total CR energy; see more information in Section 3.3.5.

3.2.3. When the Shock Encounters the MC Clumps at W28-North

The shock-MC encounter time is set at 25 kyr \( (R_{\text{SNR}} \sim 11.5 \text{ pc}) \) after the SN. Following the encounter, part \( (\chi) \) of the SNR shell located at W28-North is rapidly slowed down by the dense MC clump, and only very light gas is shocked (the estimated X-ray emitting mass at W28-North is only \( \sim 1 M_\odot \), according to Zhou et al. 2014) before the shock is fully stalled. In fact, the shocked gas mostly comes from the transition region between the diffuse gas and the dense clump. After the shock-MC encounter, a significantly slowed shock will continue to propagate inside the MC clump, but is unable to shock the dense gas there (Gabici & Aharonian 2016). Owing to the high density of the neutral gas, both the magnetic turbulence in the upstream and the downstream will be significantly damped, leaving the CRs confined at and behind this part of the shock, with a total number \( \sim N \) ready to be released, where \( N \) is the total number of CRs trapped inside the SNR. During the SNR evolution history, CRs are continually carried downstream into the interior of the SNR, with a flux \( J_{\text{in}} \sim n_{\text{SNR}} \chi E_{\text{max}} / 4 \). Some of these trapped CRs inside the SNR may re-enter the acceleration region and even escape from the upstream. We note that the CRs \( (E \lesssim E_{\text{max}}) \) confined inside the acceleration region are almost instantly released after the shock-MC encounter, see, e.g., Ohira et al. (2011), while the GeV CRs filling in the inner region of the SNR need to be carried into MC-N by gas flow/turbulence. Assuming a magnetic field of \( >10 \text{ } \mu\text{G} \) inside the SNR, which is consistent with the simulation results by Zirakashvili & Ptuskin (2017), the mean Bohm diffusion distance of a 1 TeV proton is merely \( \lesssim 0.3 \text{ pc} \) after 10 kyr. After the CRs cross the stalled shock and propagate into MC-N and beyond, they will enter an environment with a much higher diffusion coefficient, which is 10\% of the Galactic diffusion coefficient in our model.

Simulation work by Zirakashvili & Ptuskin (2012, 2017) has shown that the spatial distribution of the CRs inside the SNR is dependent on the SNR age and CR diffusion coefficient (CR energy). The intermediate-age/old SNRs tend to show a more homogeneous CR distribution inside the SNR, while the CRs inside young SNRs are mostly confined immediately behind the shock. The GeV CRs are more likely to “feel” the gas compression and are more concentrated immediately behind the shock, while super-TeV CRs fill the inside of the SNR more homogeneously. See also the radius profiles of CR pressure and gas density inside different SNRs by Zirakashvili & Ptuskin (2012).

In addition to the CRs in the acceleration region that are immediately released into MC-N after the shock-MC encounter, the GeV CRs located in the inner region of the SNR, which “feel” the gas compression, can also be carried into MC-N by the downstream flows/turbulence. In our model, the CRs released from W28-North (including both the CRs from acceleration region and the CRs carried by flow) are arbitrarily chosen as an instantaneous process. Hence, this release time (12 kyr ago) actually functions like an averaged release time, and the total energy of leaked CRs from W28-North is normalized later in our modeling.

Similar to the spectrum of the CRs confined inside the SNR in the simulation work by Zirakashvili & Ptuskin (2017), the spectrum in our model (also the spectrum of leaked CRs), as seen in Figure 8, is arbitrarily made of two components: first, a low-energy part with a PL index of \( \Gamma_{\text{CR}} = -2.0 \) and a cutoff energy of \( E_{\text{max}} \), which represents the CR spectrum in/near the acceleration region, and second, a high-energy tail extending beyond \( E_{\text{max}} \) with a PL index of \( \Gamma_{\text{CR}} = -2.3(-2.5) \) and a cutoff energy of 10(5)TeV for the damping(non-damping) model. In our models, \( \chi \) represents the percentage of the SNR shell that is stalled by the MC-N at 25 kyr. After the MC-shock encounter, part \( (\chi) \) of the shock starts to release all its GeV CRs, while the other \( 1-\chi \) GeV CRs will mostly remain behind their local shock. \( \chi \) is a free parameter here, but it is constrained by the limitation of the total CR energy. By choosing \( \chi = 10\% \), for instance, we would derive a total CR energy in the SNR of \( \sim 4\%/11\% \ E_{\text{51}} \) 12 kyr ago in our damping/non-damping model.

At 25 kyr after the SN, the energy of TeV CRs trapped inside the SNR only accounts for \( \lesssim 1\% \) of the energy of the total trapped CRs in our models. Unlike the GeV CRs, all of the diffuse super-TeV CRs trapped in the entire SNR (rather than 10% of the SNR) are able to be gradually released through the leaking hole of W28-North. In our models, the run-away CRs from the early SNR stages dominate the higher energy \( \gamma \)-ray emission at the MC clumps. Therefore, for simplicity, part \( (\chi) \) of the TeV CRs is bound together with the GeV CRs and released instantaneously from W28-North.

3.2.4. Sea of the Galactic CR

The spatial distribution of Galactic sea CRs, especially the GeV sea CRs, could be quite inhomogeneous. Naturally, the GeV CRs are likely to be concentrated near the star-forming regions, e.g., the spiral arms. Through studying the Fermi-LAT
data and the gas density in the entire Galaxy, Acero et al. (2016) have derived a rough radius profile of CR density/spectrum in the Galactic plane. Considering that SNR W28 lies inside the Galactic plane with a distance to the Galactic center of ~5 kpc, using this radius profile, one can obtain the spectrum of its local CR sea (CR spectrum index $\Gamma_{\text{CR,sea}} \sim -2.55$ to $-2.72$, energy density $U_{\text{CR,sea}} \sim 1.1$ eV cm$^{-3}$), which is similar to the one detected on Earth. However, in our models, we explore scenarios with CR sea densities lower than the averaged local one mentioned above, in order to better fit the $\lesssim 1$ GeV observations (especially for 240 A).

3.3. Results and Discussions

In this work, we tried to reproduce the GeV–TeV spectrum at MC-N, MC-A, MC-B, and MC-C simultaneously in one model. To explain the GeV observation, the key strategy in our model is realized by introducing released GeV CRs from the broken shell at W28-North rather than decreasing the energy of run-away CRs down to 1 GeV. As seen in Figure 9, the GeV–TeV observations in/around W28 are explained, except for 240 A. In our models, the TeV emission in/around W28 is dominated by run-away super-TeV CRs released during the early stages of the SNR, while the leaked CRs from W28-North dominate almost the entire GeV band of W28-North and also contribute to the $\sim 3$–100 GeV emission at the distant MC clumps. The $\lesssim 3$ GeV emission at the distant MC clumps is explained by the local CR sea. For 240 B, the reproduced GeV flux at around 2 GeV is slightly lower than the observational data, and this can be due to the contamination from the southern blob. For 240 C, in addition to reducing the south blob, we could also use a higher density of CR sea to better fit the $\lesssim 1$ GeV emission (using the CR sea density detected on Earth, which is not shown in this paper). For 240 A, our reproduced GeV spectrum cannot fit the sharp peak of 2 GeV shown in the observational data, and 240 A is also spatially far away from this southern blob. More discussions of our model and results are listed in the following subsections.

3.3.1. The Diffusion Coefficient and Diffusion Distances

In the reproduction of the $\gamma$-ray emission at MC-N, MC-A, B, and C, the diffusion coefficient for the entire space outside the SNR is fixed as $D(E) = 10^{27}(E/10$ GeV)$^\delta$ cm$^2$ s$^{-1}$, $\delta = 0.5$, mostly based on the requirement of fitting the GeV data of W28-North and the TeV data of all the $\gamma$-ray sources. Thus the fine-tuning of the distances between these MC clumps and the CR sources is performed for a better fitting result, see Table 4. The three-dimensional distances between the MC clumps and the CR sources in our model satisfy the triangle relationship among the three objects: W28-North, SNR center, and each MC clump. For GeV CRs, their spatial distribution are sensitive to the distances to the CR sources. The distances of MC-A, B, and C to W28-North are about 25–35 pc in our model, and 25 pc is approximately the projected distance between W28-North and MC-B, C. Our model faces difficulties to efficiently bring $\lesssim 10$ GeV CRs from the SNR to MC-A and MC-B, which have shown $\gamma$-ray spectra peaks at 1.4 GeV and 2.8 GeV, respectively. Adding the CR sea could help moving the peaks of the reproduced $\gamma$-ray emission to lower energy; see the dotted and solid lines in Figure 9.

In the case of 240 A, when we place MC-A much closer to the SNR, e.g., 20 pc (the same effect as using a higher diffusion coefficient in the entire space), we could move the peak to a lower energy, but the reproduced 10–100 GeV flux will be too high to explain the observation as well. This overproduction of 10–100 GeV flux also occurs for MC-B and C. By modifying the diffusion coefficient, one solution for this situation is to introduce a diffusion coefficient with a smaller PL index (compared to 0.5 for a Galactic one), which allows the 1–100 GeV CRs to diffuse relative faster. Another solution would be introducing a diffusion coefficient spectrum with BKPLs: the PL index of the diffusion coefficient of 1–100 GeV CRs can be smaller than 0.5. Interestingly, the derived diffusion coefficients inside a Kolmogorov turbulence do show this type of a BKPLs, see, e.g., the numerical simulation results by Casse et al. (2002) and Fatuzzo et al. (2010). However, a PL index of the diffusion coefficient smaller than 0.5 would require a softer spectrum of the leaked GeV CRs ($\Gamma_{\text{CR}} < -2.0$) to explain the GeV spectrum of W28-North. Furthermore, an anisotropic or/and inhomogeneous diffusion environment could also help our modeling, e.g., fast-diffusing tubes based on the large magnetic structure. Overall, these alternative diffusion scenarios, which may need a total modification of our model, including the acceleration and releasing of the GeV–TeV CRs, will be left to future work.

3.3.2. An Inhomogeneous CR Sea Near W28?

Owing to the long distances from W28-North to MC-A, B, and C (20 pc), 1–100 GeV CRs leaked from W28-North are not able to efficiently reach these MC clumps at the present time with the diffusion coefficient used in our model. Hence, the CR sea is expected to dominate the $\lesssim 10$ GeV $\gamma$-ray emission at these three MC clumps. The density of the CR sea (5 kpc from Galactic center) observed by Acero et al. (2016) contradicts our Fermi-LAT discovery; the non-detection of $\lesssim 1$ GeV $\gamma$-rays at MC-A. These observed MC clumps cover a distance to Earth ranging from 2 to 4 kpc, see Aharonian et al. (2008), but placing them farther from Earth (e.g., 4 kpc instead of 2 kpc; power sources other than W28 could be introduced as well to explain the higher energy band) only leads to a situation in which the MC clumps are placed closer to the Galactic center (3–4 kpc), where a CR sea density higher by about three times than is detected on Earth is suggested by Acero et al. (2016). Noticeably, the diffuse background in the Fermi analysis is very important at this low-energy band, and we cannot rule out that our non-detection of $\lesssim 1$ GeV $\gamma$-ray at MC-A could be the result of an excessive background reduction; see our background in Figure 4.

In summary, if the low $< 1$ GeV flux at 240 A is true, an inhomogeneous distribution of the $< 10$ GeV CR sea becomes necessary. The CR sea density adopted in Figure 9 is half of the averaged local one, except for 240 A, for which we adopt a much lower one of 14% of the averaged local one.

3.3.3. The Run-away GeV CRs

As described in the introduction section, considering the ionization evidence found at MC-N, we believe the CRs with energy down to $< 1$ GeV have already leaked through the broken shell at W28-North and dominate the GeV emission there. By lowering the escape energy, run-away CRs can also contribute significantly to the GeV emission at W28-North.
Nonetheless, in the damping theory, the ionization ratio in the ICM, which functions as a key factor on the escape energy, is unknown. With an ICM density of $10^{-3}$ cm$^{-3}$, an ICM temperature of $T \approx 10^4$ K, which is just above the ionization temperature of H, is needed to confine the dense clumps and to support the cloud against gravitational collapse (Blitz 1993; Chevalier 1999). Therefore, in our damping model, the neutral density of the upstream ICM is set as low as 0.3 cm$^{-3}$, and the

![Diagram of gamma-ray spectra for damping and non-damping models](image)

**Figure 9.** Broadband fit to the $\gamma$-ray emission from the sources HESS J1801–233 (W28-North) and HESS J1800–240 A, B, and C (top to bottom). The left and right panels are the fitting results of the damping and non-damping model, which are based on our own Fermi-LAT data points (red stars) and the H.E.S.S. data (blue circles). The observational data are marked in the same way as those in Figure 6. In each panel, the hadronic $\gamma$-ray produced via the run-away CRs from the shock, the released CRs from W28-North, the sea of Galactic CRs, and the total CRs are shown as dashed, dash–dotted, dotted, and solid lines, respectively. The density of the CR sea at 240 A (W28-North, 240 B and C) is modified to 14% (50%) of the one detected on Earth.
final escape energy of the 100 km s\(^{-1}\) shock at the present time is 10 GeV. To further decrease the escape energy to 1 GeV and allow the run-away CRs (from shocks other than W28-North) to dominate the <1 GeV \(\gamma\)-ray emission at MC-N, one requires a neutral density \(~3\ \text{cm}^{-3}\) in the ICM, following the estimation by O’C Drury et al. (1996). This requirement slightly contradicts the observed H\(I\) density upper limits of 1.5–2 \text{cm}^{-3}\) by Velázquez et al. (2002).

### 3.3.4. Progenitors Other than 8 \(M_\odot\)

In our SNR evolution model of W28, we have only explored a CC SN scenario that delivers a homogeneous pre-SN environment. This scenario has successfully explained the observed shock velocity at the present time and the measured gas density near the SNR. Here we discuss another three hypotheses that have more massive progenitors and more complex pre-SN wind environments.

1. **A large pre-SN wind bubble**, radius \(R_0 > 13\ \text{pc}\). Owing to the low shock velocity at the present and the lack of nonthermal X-ray, SNR W28 probably does not still evolve inside the pre-SN wind bubble, which has a typical density of \(\sim0.01\ \text{cm}^{-3}\).

2. **A medium pre-SN wind bubble**, radius \(13\ \text{pc} > R_0 > 10\ \text{pc}\). If SNR W28 were to have encountered the pre-SN bubble shell relative recently, we would more likely see a shell structure of thermal X-rays rather than the observed features: a diffused one in the center and a bright one at W28-North.

3. **A small pre-SN wind bubble**, radius \(R_0 \lesssim 10\ \text{pc}\). If SNR W28 has already swept the pre-SN bubble shell and is expanding in the ICM before it enters the radiation-dominated stage, a similar shock velocity \(v_{\text{SNR}} \approx 100\ \text{km s}^{-1}\) at the present time is expected (adopting the same SN energy \(E_{\text{ej}} = E_{s1}\)) because the final shock velocity during the Sedov stage is mostly sensitive to the total swept-up mass, but not to the radius distribution of the gas; see, e.g., the scenario 8 \(M_\odot\) and scenario 15 \(M_\odot\) in Cui et al. (2016). In this new SNR scenario, which is not explored in this work, the GeV CR leaking process that occurs after the sweeping of the pre-SN bubble shell is expected to be similar to that in our scenario, but the release of super-TeV CRs that mostly occurs in the early stage of the SNR evolution will be different.

#### 3.3.5. The Total Energy of Accelerated CRs at SNR W28

Since our SNR evolution history is fixed, the key normalization factor on the total accelerated CR energy becomes the acceleration efficiency, see Table 5. Adapting the \(\eta_{\text{esc}} = 0.04/0.03\) in our damping/non-damping model, at the shock-MC encounter time (25 kyr), the SNR has already released most of its run-away CRs with a total energy about 9.1%/6.6% \(E_{s1}\). After parts (\(\chi\)) of the SNR have encountered MC-N (25 kyr), about 0.4%/1.1% \(E_{s1}\) CRs are released from W28-North in the damping/non-damping model. If we follow the concept by Zirakashvili & Ptuskin (2012, 2017) that most of the accelerated CRs have escaped the SNR through run-away CRs for a intermediate-age/old SNR, then our total CR energy inside the SNR at 25 kpc should be lower than the one of run-away CRs, which leads to a \(\chi \geq 4.3%/16.7\%\) in the damping/non-damping model. After the shock-MC collision, only the other 1 – \(\chi\) part of the shell still releases run-away CRs. \(\chi\) is set ato be 10%/15% in our damping/non-damping model.

#### 3.3.6. The CR Leaking Process at W28-North

Based on the X-ray ionization time at W28-North by Zhou et al. (2014), we adopt an instantaneously releasing time (12 kyr ago from present) to set the CRs free at W28-North. In fact, as described in Section 3.2.3, only CRs from the acceleration region are released instantaneously, while the GeV/TeV CRs from the inner region are gradually injected into MC-N advectively/diffusively. After the shock-MC encounter, the tip of MC-N, which is buried inside the SNR, will keep being blown by a downstream wind (flow) with a velocity of \(v_{\text{flow}}\), where \(v_{\text{flow}}\) is slightly lower than the current shock velocity (at 25 kyr, \(v_{\text{flow}} \lesssim 150\ \text{km s}^{-1}\)). However, this advection-dominated injection of GeV CRs by the downstream flow will decrease with time, because first, the CR density gradually decreases from the region immediately behind the shock to the inner region of the SNR; see e.g., the simulation result of intermediate-age/old SNRs by Zirakashvili & Ptuskin (2012), whose CR density is halved at 10% \(R_{\text{SNR}}\) downstream from the shock front. Second, the flows that are falling onto MC-N will decrease when the gas pressure behind the stalled shock reaches a new balance and the eddies stirred by MC-N decay in several crossing times \(t_{\text{c}} = L_{\text{ed}}/v_{\text{flow}}\), where \(L_{\text{ed}}\) is the length of the eddies and should be comparable to the size of the MC-N tip that is embedded in the SNR (\(t_{\text{c}} = 10\) year when \(L_{\text{ed}} \sim 1\ \text{pc}\)). To fully unveil the leaking process at W28-North, an MHD simulation is required in future work, to obtain the flow/turbulence details as well as the diffusion environments in/around this shock-MC encounter region.

We note that this shock-MC encounter at W28-North could be a more complex process than our simple “colliding onto a flat wall” model, considering that the three-dimensional structure of this MC-N could be very complex. This complex encounter process could last for quite a long period, e.g., with an expanding velocity \(\sim 100\ \text{km s}^{-1}\), SNR W28 would need \(\gtrsim 10^5\) year to fully swallow MC-N, whose size is \(\gtrsim 1\ \text{pc}\).
4. Summary

This work is motivated by the exciting discovery of the GeV–TeV emission in/around SNR W28 several years ago, which seems to indicate a situation in which the super-TeV CRs released at early stages are evenly spread into the nearby environment and explain the spatial coincidence between the TeV emission and the molecular clouds well. Meanwhile, the GeV CRs released from W28-North (or from the entire SNR) are more highly concentrated near the CR releasing source, and this eventually explains why MC-N is the most brightly illuminated source in the Fermi-LAT skymap, with a peak energy down to \( \lesssim 0.3 \) GeV. To further support this scenario, we first reanalyzed the Fermi-LAT data of W28 and extended the GeV spectra at MC-A, B, and C down to 0.3 GeV, and second, we explored a hadronic model involving leaked GeV CRs from a broken shell. A detailed summary of these two steps is described below.

1. The Fermi-LAT analysis of W28. Using nine years of Fermi-LAT data and the most updated Fermi Science Tools, the v10r0p5 package, we re-explored the GeV counterparts of HESS J1801–233, 240 A, B, and C, as well as the newly discovered GeV source west of W28, 3FGL J1758.8–2346 (Source-W). In the morphological study, our 10–200 GeV skymap is in accordance with the H.E.S.S. skymap, and the position of Source-W is slightly revised when compared to the one described in previous work. In the spectral study, the spectra of the southern GeV counterparts have shown discontinuities at \( \sim 1 \) GeV; a sudden flux increase at the \( \lesssim 1 \) GeV band of 240 B and C, and a non-detection at the \( \lesssim 1 \) GeV band of 240 A. Further morphological study triggered by these discontinuities discovered a 0.5–1 GeV blob (southern blob) located south of 240 B and C. This southern blob could be due to either an unknown GeV source or an unclean background reduction. Ultimately, only upper limits of the \( < 1 \) GeV band at 240 B and C are drawn in our final results.

2. The hadronic model involving leaked CRs from the broken shell. The main goal of our modeling work is to determine whether the \( \lesssim 10 \) GeV emission in W28 can be explained by the leaked CRs from the shock-MC collision, W28-North, rather than by run-away CRs with energy down to 1 GeV. Following the multwavelength observational constraints, a CC SN scenario with a progenitor mass of \( 8 \) M\(_{\odot}\) is adopted in our model, which derives a shock velocity of \( \sim 100 \text{ km s}^{-1} \) at the present time (37 kyr). Considering the intermediate-age of SNR W28, both the damping of the magnetic waves caused by neutral atoms and the decreasing acceleration efficiency caused by the low shock speed are taken into account in our model. The GeV–TeV emissions in/around W28, except for 240 A, are explained in our hadronic model. Our model consists of three CR sources: the run-away CRs escaped from upstream of strong shocks, the leaked CRs from the broken shell, W28-North, and the Galactic CR sea. The release of run-away CRs follows the nonresonant acceleration theory developed by Zirakashvili & Ptuskin (2008), which can provide the escape energy during entire the SNR history. The escape energy of run-away CRs ranges from \( \sim 50 \) TeV to 10 GeV/1 TeV in our damping/non-damping model. We assume that the SNR encountered MC clumps at W28-North 1.2 kyr ago, and following this encounter, the leaked CRs (most are GeV CRs with an energy lower than the escape energy) were released instantaneously. Because of the long distances of 240 A, B, and C to the SNR, their \( \lesssim 10 \) GeV emission is dominated by the local CR sea in our model. The finding of the non-detection of \( < 1 \) GeV emission at 240 A is sensitive to the diffuse background. If this finding is true, an inhomogeneous density of the CR sea (even if MC-A is 4 kpc away from Earth) is expected, which is necessary to provide a much lower CR sea density than the averaged one at a distance of 3–5 kpc to the Galactic center.

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References
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 718, 348
Ackero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Acero, F., Ackermann, M., Ajello, M., et al. 2016, ApJS, 223, 26
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2008, A&A, 481, 401
Bell, A. R. 2004, MNRAS, 353, 550
Bisnovatyi-Kogan, G. S., & Silich, S. A. 1995, RvMP, 67, 661
Blin, L. 1993, in Protostars and Planets III Giant Molecular Clouds, ed. E. H. Levy & J. I. Lunine (Tucson, AZ: Arizona Univ. Press), 125
Bohigas, J., Ruiz, M. T., Carrasco, L., Salas, L., & Herrera, M. A. 1983, RMxAA, 8, 155
Brogan, C. L., Gelfand, J. D., Gaensler, B. M., Kassim, N. E., & Lazio, T. J. W. 2006, ApJL, 639, L25
Caprioli, D., & Spitkovsky, A. 2014, ApJ, 783, 91
Casse, F., Lemoine, M., & Pelletier, G. 2002, PhRvD, 65, 023002
Chevalier, R. A. 1982, ApJ, 259, 302
Chevalier, R. A. 1999, ApJ, 511, 798
Chevalier, R. A. 2005, ApJ, 619, 839
Cioffi, D. F., McKee, C. F., & Bertchinger, E. 1988, ApJ, 334, 252
Claussen, M. J., Goss, W. M., Frail, D. A., & Desai, K. 1999, ApJ, 522, 349
Cui, Y., Pühlhofer, G., & Santangelo, A. 2016, A&A, 591, A68
Fatuzzo, M., Melia, F., Todd, E., & Adams, F. C. 2010, ApJ, 725, 515
Frail, D. A., Goss, W. M., & Slys, V. I. 1994, ApJL, 424, L11
Gabici, S., & Aharonian, F. 2016, in EPJ Web of Conferences, Vol. 121, Roma International Conf. on Astroparticle Physics 2014 (RICAP-14), ed. P. Piattelli et al. (Les Ulis: EDP Sciences)
Gabici, S., Casanova, S., Aharonian, F. A., & Rowell, G. 2010, in SF2A-2010: Proc. Annual meeting of the French Society of Astronomy and Astrophysics, ed. S. Boissier et al. (Paris: SF2A), 313
Hanabata, Y., Katagiri, H., Hewitt, J. W., et al. 2014, ApJ, 786, 145
Hewitt, J. W., & Yusef-Zadeh, F. 2009, ApJL, 694, L16
Inoue, T., Yamazaki, R., Inutsuka, S.-i., & Fukui, Y. 2012, ApJ, 744, 71
Li, H., & Chen, Y. 2010, MNRAS, 409, L35
Long, K. S., Blair, W. P., Matsui, Y., & White, R. L. 1991, ApJ, 373, 567
Lynds, B. T., & Onelli, E. J. Jr. 1985, ApJ, 294, 578
Marquez-Lugo, R. A., & Phillips, J. P. 2010, MNRAS, 407, 94
Maxted, N. I., de Witt, P., Rowell, G. P., et al. 2016, MNRAS, 462, 532
Nadezhdin, D. K. 1985, Ap&SS, 112, 225
Nakamura, R., Bamba, A., Ishida, M., et al. 2014, PASJ, 66, 62
Neufeld, D. A., Hollenbach, D. J., Kaufman, M. J., et al. 2007, ApJ, 664, 890
Nicholas, B., Rowell, G., Burton, M. G., et al. 2011, MNRAS, 411, 1367
Nicholas, B. P., Rowell, G., Burton, M. G., et al. 2012, MNRAS, 419, 251
O’C Drury, L., Duffy, P., & Kirk, J. G. 1996, A&A, 309, 1002
Ohira, Y., Murase, K., & Yamazaki, R. 2011, MNRAS, 410, 1577
Ostriker, J. P., & McKee, C. F. 1988, RevMP, 60, 1
Ptuskin, V. S., & Zirakashvili, V. N. 2005, A&A, 429, 755
Reach, W. T., & Rho, J. 2000, ApJ, 544, 843
Reach, W. T., Rho, J., & Jarrett, T. H. 2005, ApJ, 618, 297
Rho, J., & Borkowski, K. J. 2002, ApJ, 575, 201
Sano, H., Sato, J., Horachi, H., et al. 2010, ApJ, 724, 59
Smartt, S. J. 2009, ARA&A, 47, 63
Tang, X. 2017, arXiv:1707.00958
Tohill, N. F. H., White, G. J., Matthews, H. E., et al. 2002, ApJ, 580, 285
Vaupré, S., Hily-Blant, P., Ceccarelli, C., et al. 2014, A&A, 568, A50
Velázquez, P. F., Dubner, G. M., Goss, W. M., & Green, A. J. 2002, AJ, 124, 2145
Voelk, H. J., Drury, L. O., & McKenzie, J. F. 1984, A&A, 130, 19
Yakovlev, D. G., & Pethick, C. J. 2004, ARA&A, 42, 169
Yeung, P. K. H., Kong, A. K. H., Tam, P. H. T., et al. 2016, ApJ, 827, 41
Yeung, P. K. H., Kong, A. K. H., Tam, P. H. T., et al. 2017, ApJ, 837, 69
Zhou, P., Safi-Harb, S., Chen, Y., et al. 2014, ApJ, 791, 87
Zirakashvili, V. N., & Ptuskin, V. S. 2008, ApJ, 678, 939
Zirakashvili, V. N., & Ptuskin, V. S. 2012, ApJ, 767, 12
Zirakashvili, V. N., & Ptuskin, V. S. 2017, arXiv:1701.00844