# Time-Dependent Spectra of Cosmic Rays Escaping from Type Ia and Core-Collapse Supernova Remnants

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**Abstract:** Supernova Remnants (SNRs) are thought to be the main sources of Galactic cosmic rays (CRs) up to the "knee". The soft CR spectrum observed at Earth, and also soft gamma-ray spectra observed from a number of SNRs interacting with molecular clouds (MCs), challenge current theories of non-linear particle acceleration that predict harder slopes. However, one should keep in mind that the CRs at Earth as well as the CRs producing gamma-rays by interaction with MCs surrounding SNRs are actually particles that escaped from the parent SNRs. During the SNR evolution the bulk of the CRs is confined within the SNR shell. The highest-energy particles leave the system continuously, while the rest of the adiabatically cooled particles are released when the SNR has sufficiently expanded and slowed down to the point that the magnetic field (MF) at the shock is no longer able to confine them. We study how the spectrum of escaped particles depends on the time-dependent acceleration history in young type-Ia and core-collapse SNRs by combining numerical simulations of SNR evolution with a solution of the CR transport equation in test-particle mode. Having explored the significance of particles accelerated at the reverse shock (RS) for the emission from the SNR, we calculate the time-dependent gamma-ray spectra from MCs illuminated by the escaping CRs.

**Keywords:** Supernova Remnants - Molecular Clouds - Cosmic Rays

## 1 Introduction

Supernova Remnants are now widely considered to be sources of Galactic cosmic rays. Diffusive Shock Acceleration (DSA) theory [1, 2, 3, 4] and its non-linear modification (NDSA) [5] predict a power-law distribution $N(E) \propto E^{-s}$ of relativistic particles with index $s = 2$ ($s < 2$ for the high-energy tail in NDSA). Despite recent advances in DSA and NDSA it is still unclear why we observe soft ($s > 2$) CR spectra at Earth [6] and soft gamma-ray spectra from a number of SNRs (see [7], [8] and ref. therein).

A number of recent studies [9, 10, 11], triggered by Fermi observations, attempt to explain the soft gamma-rays from MC-SNR systems by escaped CRs[1]. These studies are mostly based on analytical models developed in [13, 14, 15]. The analytical models are usually based on assumptions about i) The SNR evolution, which is generally considered as either stationary or Sedov-like, and ii) particle acceleration, which is often considered to be quasi-instantaneous compared with the CR diffusion time. In addition, the source of CRs is considered a point-like, i.e., the SNR radius is much smaller than the distance to MC.

The analytical studies show that to explain observations, the diffusion coefficient in the SNR vicinity must be roughly two orders of magnitude smaller than the average Galactic value, supporting an early claim [16] that the diffusion coefficient might be reduced due to the presence of plasma waves which scatter particles. Recently, using a simple model of SNR evolution and Monte-Carlo simulations of CR diffusion, [17] showed that particles are indeed trapped around the SNR for a significant time. These findings may be considered in line with the conclusions of [18] who argue that beyond some critical value, $L$, which they call the free escape boundary, the number density of CRs falls significantly. The position of $L$ is dictated by the level of excited MHD turbulence. For test-particle case it is found to be comparable to the SNR radius [19].

In this paper our aim is to understand how the spectrum of escaped particles depends on the time-dependent acceleration history in young type-Ia and core-collapse SNRs, as well as on the diffusion coefficient in the vicinity of the SNR. These calculations are based on realistic models of the hydrodynamic evolution of SNR. We consider acceleration at both shocks, study type-Ia and core-collapse SNRs with Wolf-Rayet (WR) progenitors, and place a target MC at close distance to the SNR (a few SNR radii). Using two different diffusion models for CR particles upstream of the

1. A more general analytical study on CR escape is given in [12]

forward shock (FS), we calculate the spectra of CRs at the MC location and their hadronic gamma-ray emission.

## 2 Method

We treat CRs as test particles in gas-flow profiles given by numerical simulations of the hydrodynamical evolution of an SNR [20, 21]. The method, described in detail in [7], is based on a numerical solution of the CR transport equation in a grid co-moving with the shock wave. To ensure sufficient resolution near the shock, the spatial coordinate is substituted with a new coordinate, $x_*$, for which a uniform grid is used when solving the particle transport equation:

$$(x-1) = \left(\frac{r}{R_{sh}} - 1\right) = (x_* - 1)^3 \qquad (1)$$

As mentioned in [7], a coarse grid in $x_*$ transforms into a very fine grid in $x$ close to the shock, where the high resolution is needed to properly account for acceleration of newly injected particles. At the same time, the above transformation allows us to significantly extend the grid far into the ISM ($x \gg 1$) with only little extension in $x_*$. Although the resolution deteriorates with distance from the shock, the mean free path of the particles in the ISM is orders of magnitude larger than in the shock vicinity, thus permitting a moderate resolution.

## 3 Magnetic Field and Diffusion Models

We assume that the MF in the shock vicinity is non-resonantly amplified [25]. Non-resonant amplification probably dominates in the early stages of SNR evolution. The field is calculated as [27]:

$$B_0(t) = \sqrt{2\pi\rho_u(t)\left(\frac{V_s(t)^3}{c}\right)\xi(t)} \qquad (2)$$

where $\rho_u(t)$ is the density upstream of the shock, $V_s(t)$ is the shock speed, $c$ is the speed of light, and $\xi(t)$ is the ratio of cosmic-ray to ram pressure. In our calculations $\xi(t) \approx 0.05$ with small deviations over the simulation time. We parametrize the MF inside and outside the SNR. The scaling inside follows the time-dependent density distribution, $B(r,t) = \sigma B_0(t)\rho(r,t)/\rho(R_{FS},t)$, where $\sigma = \sqrt{11}$ is the compression ratio of the turbulent MF. We assume that the MF falls off exponentially to the interstellar field (5 $\mu$G), or circumstellar MF (CMF) for core-collapse SNR, at 0.05 $R_{\rm FS}$ ahead of the FS [26], and likewise down to the very small ejecta field (0.01-0.1 $\mu$G) at 0.05 $R_{\rm RS}$ toward the interior of the SNR. The tangential component of the stellar MF dominates in the wind zone; $B_c(R) = B_s R_{\rm WR}/R$, where $B_s \approx 100$ G is the MF at the surface of the WR star, $R_{\rm WR} = 8R_\odot$ is the WR radius, and $R$ is the distance from the star. Beyond the wind zone, the MF is interstellar. The evolution of the MF profiles in the two cases is shown in Fig. 1.

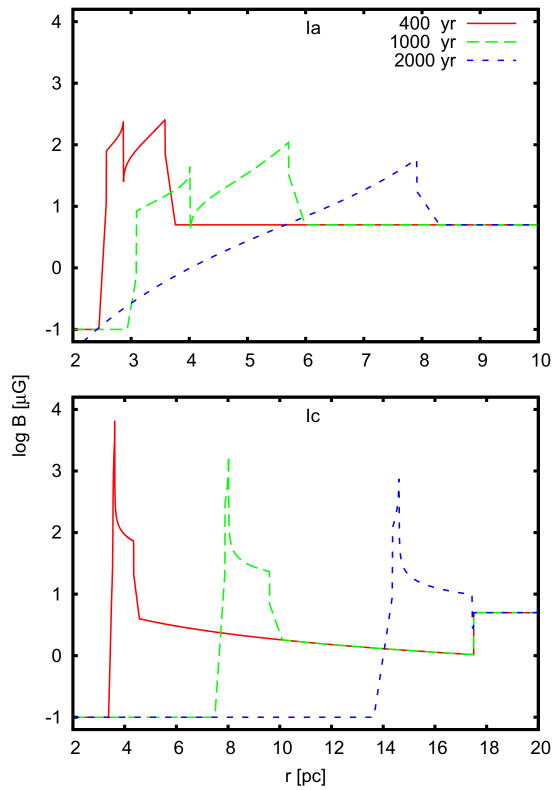


Figure 1: Time dependence of magnetic-field profiles for Type-Ia (top) and Type-Ic (bottom) SNRs.

We consider two models of CR diffusion outside the SNR. The diffusion coefficient in model D1 is defined as:

$$D(r) = \begin{cases} D_B & r \leq L \\ D_G & r > L \end{cases} \qquad (3)$$

where $D_B$ is the Bohm diffusion coefficient, $D_G = 10^{28}\,(E/10\,\text{GeV})^{\alpha}\,(B/3\mu\text{G})^{-\alpha}$ cm$^2$/s is the Galactic diffusion coefficient [15], $E$ is the CR energy, and $L = 2R_{SNR}$ is the escape boundary. We take $\alpha = 1/3$. Model D2 assumes a less abrupt transition,

$$D(r) = \begin{cases} D_B & R_{SNR} \leq r \leq 1.05R_{SNR} \\ \chi D_G & 1.05R_{SNR} < r \leq L \\ D_G & r > L \end{cases} \qquad (4)$$

where $\chi = 0.01$.

## 4 Results

We calculated CR spectra at the MC location at times 400, 1000, and 2000 years, for both Type Ia and core-collapse SNe. As shown in [7] for Type-Ia SNRs, the contribution from the RS becomes marginal after 1000 years. Therefore, after 1000 years we may approximate the plasma flow profiles with a Sedov solution [24]. The SNR evolution is

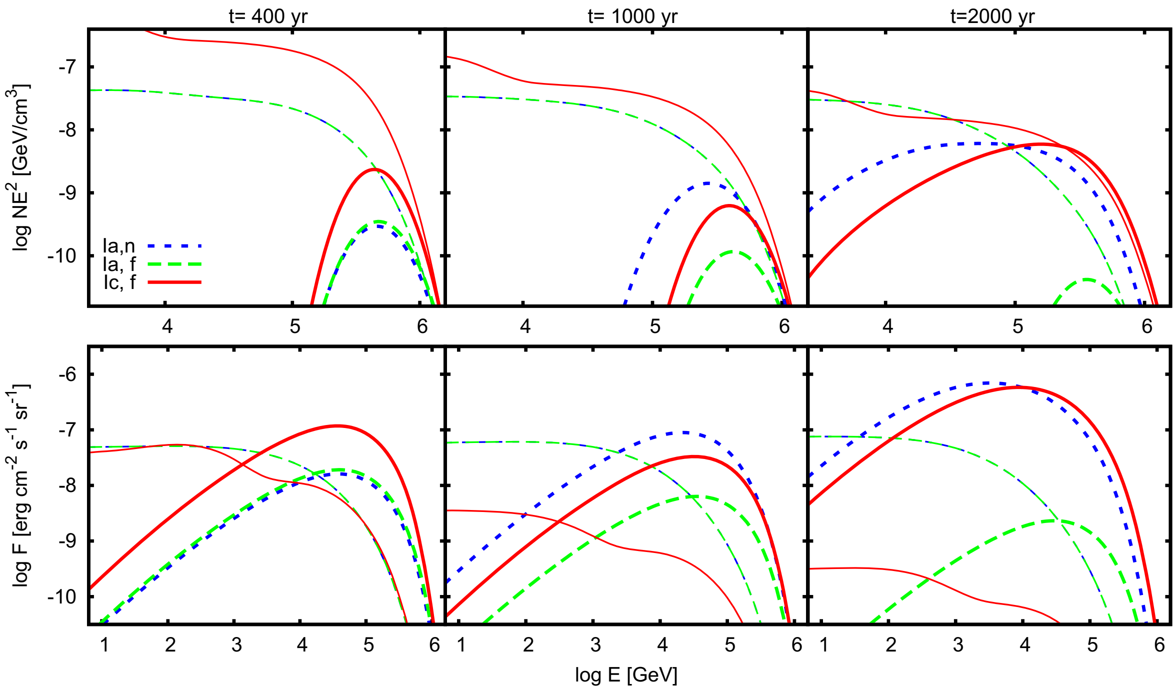


Figure 2: Results for diffusion model D1. For Type-Ia SNR we show both the "near" (Ia,n) and the "far" (Ia,f) case. Core-collapse SNR (Ic,f) spectra are multiplied by a factor 100. Upper panel: the time evolution of the spectra of escaped particles at the location of the MC (thick lines) and of CRs confined inside the SNR (thin lines). Lower panel: the corresponding gamma-ray emission from the MC (thick lines) and the SNR (thin lines).

tracked for 2000 years, at which time the FS radius is about 8 pc. For core-collapse SNR we considered a WR star expanding into a steady wind with constant mass-loss rate parameters, whose density decreases as $r^{-2}$ [21]. For simplicity we have assumed the steady wind stretches out to 17.5 pc without interacting with the surrounding medium, so that the shock continues to expand in the wind for 2000 years.

Given the difference in the surrounding medium density profiles, the radius of the Type-Ia SNR is nearly two times smaller than that of core-collapse SNR. Therefore we have considered two distances to the MC in the vicinity of Type-Ia SNR. In the "near" case the center of MC is at 12 pc from the center of SNR and in the "far" case it is at 21.5 pc, the same as for core-collapse SNR. We considered only CR protons and their radiation via pion decay [22]. Emission from the wind-swept shell for the core-collpase SN, which could contribute [23], was not considered.

The upper panels of Fig. 2 and Fig. 3 present the evolution of spectra for CRs escaped from the SNR (at the location of the MC) in comparison to CRs confined inside the SNR. Their intensities are a few orders of magnitude higher than the Galactic CR background, which is not shown here. One can clearly notice the difference between D1 and D2 diffusion models. In D1 models, Bohm diffusion operates up to the escape boundary. In that case, the particles are indeed trapped around the SNR, and only the particles with the highest energy can leave the system. After 2000 years the MC is inside the escape boundary for core-collapse and the "near" case of Type-Ia SNRs. Therefore, we observe a broadening of the spectra towards lower energies and an increase in intensity. This is in stark contrast to the "far" case of Type-Ia SNR, for which the MC remains outside of the escape boundary. If we assume (as in the D2 model) that strong MHD turbulence and MF amplification occurs only close to the shock (5% of its radius), we still observe trapping of particles, but the efficient diffusion further out permits quite a few low-energy particles to escape. In both models of diffusion and both types of SNRs, the large MF at the contact discontinuity does not permit particles accelerated at the RS to diffuse out of the SNR. Finally, one should note that the increase in diffusion coefficient within the escape boundary in D2 models does not seem to have any serious impact on the maximum energy attained by CRs. It is also worth noting that in all diffusion models and SNR types one can clearly observe the dilution, i.e. the decrease in CR intensity upstream of the FS, introduced by the spherical geometry of the SNR.

The gamma-ray emission from MCs is moderately affected by the diffusion model. However, the MC emission shows broader and flatter spectra in D2 models, which may help inferring the diffusion coefficient in the vicinity of SNR. Obviously, the intensity of the gamma-ray emission is also strongly dependent on the cloud parameters. Here we assume a cloud with density $n = 100$ cm$^{-3}$ and mass $1000 M_\odot$.

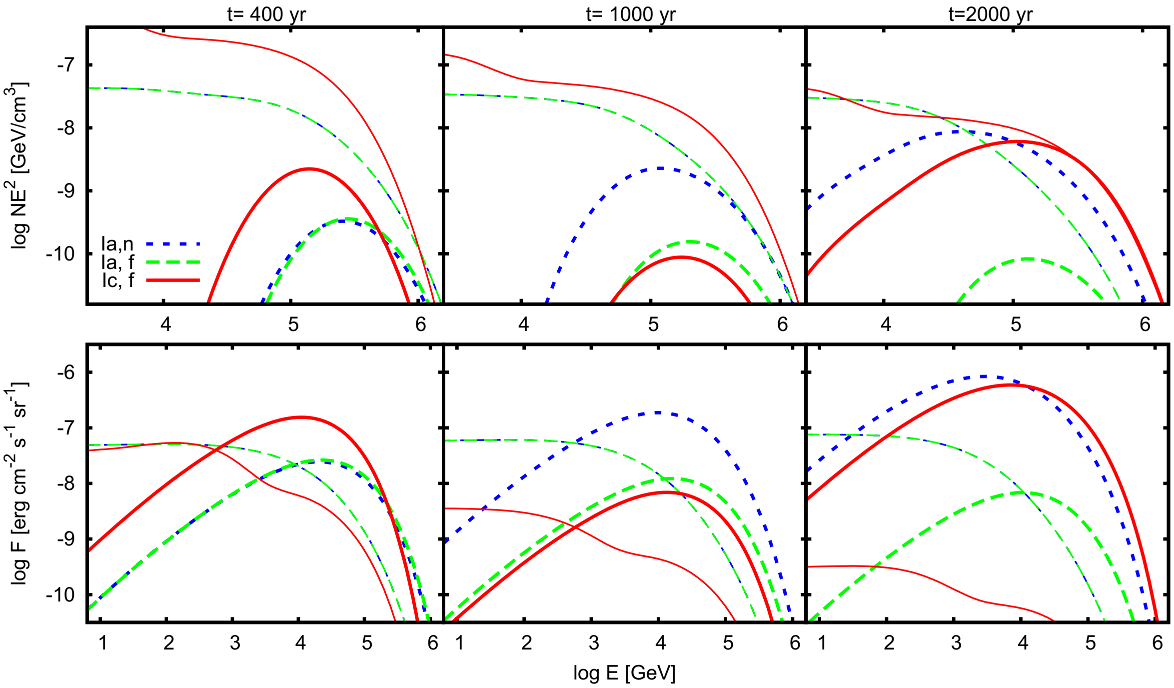


Figure 3: Same as in Fig. 2, but for diffusion model D2.

## 5 Conclusions

We modified the method developed in [7] to efficiently trace escaping CRs up to distances far from the SNR. Our approach combines a realistic treatment of SNR evolution with test-particle calculations of CR acceleration by both the reverse and the forward shock. We show that the spectra of escaped particles depends strongly on the efficiency of diffusion in the vicinity of the SNR. If Bohm diffusion operates out to the escape boundary, CRs are strongly trapped around the SNR and only the highest-energy particles leave the system. If the diffusion coefficient ahead of the FS is larger than Bohmian, then the spectra of escaped CRs, and consequently of the gamma-ray emission from nearby MCs broaden towards lower energies. We also find that the increase in diffusion coefficient beyond the SNR precursor does not significantly affect the maximum energy of CRs.

## References

[1] W. I. Axford, E. Leer, G. Skadron, in: International Cosmic Ray Conference, Vol. 11 of International Cosmic Ray Conference, 1977, pp. 132-137.
[2] G. F. Krymskii, Akademiia Nauk SSSR Doklady 234, 1977, 1306-1308.
[3] A. R. Bell, MNRAS 182, 1978, 147-156.
[4] R. D. Blandford, J. P. Ostriker, ApJL 221, 1978, L29-L32.
[5] M. A. Malkov, L. OC Drury, Reports on Progress in Physics 64, 2001, 429-481.
[6] M. Ave, et al. ApJ 697, 2009, 106-114.
[7] M. Pohl, V. Dwarkadas, I. Telezhinsky, ICRC32.
[8] D. Caprioli, arXiv:1103.2624v2
[9] Y. Fujita et al., ApJ 707, 2009, L179–L183.
[10] H. Li, Y. Chen, MNRAS 409, 2010, L35–L38.
[11] S. Gabici et al., in Proc. of the Ann. Meeting of the French Society of Astron.& Astroph., 2010, 313–317.
[12] D. Caprioli, E. Amato, P. Blasi, APh. 23, 2010, 160-168.
[13] A. M. Atoyan, F. A. Aharonian, H. J. Voelk, Phys. Rev. D 52, 1995, 3265.
[14] F. A. Aharonian, A. M. Atoyan, A&A 309, 1996, 917.
[15] S. Gabici, F. A. Aharonian, S. Casanova, MNRAS 396, 2009, 1629–1639.
[16] D.G. Wentzel, ARA&A 12, 1974, 71.
[17] Y. Fujita, Y. Ohira, F. Takahara, ApJ 712, 2010, L153-L156.
[18] B. Reville, J. G. Kirk, P. Duffy, ApJ 694, 2009, 951-958.
[19] V. N. Zirakashvili, V. S. Ptuskin, ApJ 678, 2008, 939-949.
[20] V. V. Dwarkadas, R. A. Chevalier, ApJ 497, 1998, 807.
[21] V. V. Dwarkadas, ApJ 630, 2005, 892-910.
[22] C. Huang, et al., APh. 27, 2007, 429439.
[23] D. Ellison, A. Bykov, ApJ 731, 2011, art.id.87.
[24] D.P. Cox, J. Franco, ApJ 251, 1981, 687-.
[25] A. R. Bell, MNRAS 353, 2004, 550-558.
[26] V. N. Zirakashvili, F. A. Aharonian, ApJ 708, 2010, 965980.
[27] D. Caprioli, P. Blasi, E. Amato, MNRAS 396, 2065–2073.