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Escape-limited maximum energy at perpendicular shocks in the interstellar magnetic field

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We investigate the maximum energy limited by the escape from a perpendicular shock region of a spherical shock in the interstellar medium (ISM), and the size of the rapid acceleration region. The perpendicular shock of supernova remnants (SNRs) has been expected to be PeVatrons without a magnetic field amplification in the upstream region. We perform test particle simulations, showing that the escape-limited maximum energy in the perpendicular shock is about a few 10 TeV for the typical type Ia SNRs. In addition, we show that, in the free expansion phase, the rapid perpendicular shock acceleration realizes in about 20% area of the whole shock surface, which is much larger than the superluminal shock region.

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1. Introduction

Supernova remnants (SNRs) are the plausible candidate of a PeVatron, and are believed to be the source of Galactic cosmic rays (CRs). The diffusive shock acceleration (DSA) is the probable mechanism to accelerate CRs to PeV scale [1–4]. The HAWC observation reported PeVatron candidates in our galaxy [5–7]. An evidence of PeVatrons near the Galactic center was found by the HESS observation [8]. The Tibet ASγ observation observed the sub-PeV diffuse gamma rays and found a potential PeVatron SNR in our galaxy [9, 10]. The LHAASO observation recently reported some PeVatron candidates in our galaxy [11–13]. However, we have not fully understood what types of SNRs can be PeVatrons. It is claimed that DSA in SNRs cannot accelerate CRs to PeV in the interstellar medium (ISM) magnetic field, which is about a few μG. To accelerate CRs to PeV in SNRs, a magnetic field amplification to about 100 μG in the upstream region are needed. Some magnetic amplification mechanisms have been proposed and studied by several simulations [14–17]. However, it is still unknown that whether or not a sufficient magnetic field amplification in the upstream region can be realized.

It was suggested that the perpendicular shock can rapidly accelerate CRs to PeV without an upstream magnetic field amplification. In addition, it was claimed that the momentum spectrum in the perpendicular shock becomes softer than that of the standard DSA prediction, $p^2 dN/dp$, when the magnetic turbulence is assumed to be weak both in the upstream and downstream region to realize the rapid acceleration [18]. The strong downstream turbulence is recently reported by some observations and simulations [20–23]. Thus, we considered the weak upstream turbulence and the strong downstream turbulence. Under this condition, the rapid acceleration and the canonical spectrum are simultaneously realized [19]. However, it is still unknown the size of the acceleration region that CRs are rapidly accelerated.

It was recently pointed out that the maximum energy of CRs can be limited by the escape process from accelerators [24–26]. In addition, the spectral index of escaped CRs is determined by the time evolution of the escape-limited maximum energy [26]. Therefore, the escape process and the escape-limited maximum energy are vital issues to understand the maximum energy and the observed energy spectrum of CRs. To reveal the escape process and the escape-limited maximum energy, previous studies applied the diffusion approximation that neglects the gyro motion in the magnetic field. However, the gyro motion can be important to realize the rapid acceleration in perpendicular shocks [19]. Thus, the escape process from the perpendicular shock region and the escape-limited maximum energy have not been investigated without the diffusion approximation. In this work, we first investigate the escape process from perpendicular shocks and the escape-limited maximum energy for a spherical shock wave in the ISM magnetic field.

In this work, we consider type Ia SNRs because surroundings of typical type Ia SNRs are believed to be the ISM. It is believed that the shock wave of core collapse SNRs also propagates the ISM after about 10^4 years. However, for $t \gtrsim 10^4$ yr, the radiation cooling in the shocked ISM region becomes important [28]. In addition, the shock velocity for $t \gtrsim 10^4$ yr is too slow to accelerate CRs to PeV. Therefore, in this work, we consider only type Ia SNRs.

2. Simulation

The shock evolution of type Ia SNRs is given by [27]. Here, we assume the explosion energy, $E_{\rm SN} = 10^{51}$ erg, the ejecta mass, $M_{\rm ej} = 1 M_{\odot}$, and the mass density , $\rho = 1.67 \times 10^{-24}$ g cm^{-3} . We consider two types of the upstream magnetic field configuration, $\vec{B}_1$: an uniform magnetic field, $\vec{B}_1 = \vec{B}_0$ and the uniform magnetic field with a turbulent magnetic field, $\vec{B}_1 = \vec{B}_0 + \delta\vec{B}$. The uniform magnetic field strength is set to be 3 μG. The turbulent magnetic field is represented by the summation of static plane waves [30]. The injection scale, the amplitude, and the spectrum of the turbulence are set to be 1 or 100 pc, the isotropic Kolmogorov spectrum, and $|\delta\vec{B}| = |\vec{B}_0|$.

In this work, the downstream magnetic field strength, B_2, is assumed to be amplified from the shock compressed value. We assumed that a fraction of the energy flux of the upstream kinetic energy is converted to the downstream magnetic energy flux.

$$B_2 = \sqrt{16\pi\varepsilon_B \rho} u_{\rm sh} \ , \tag{1}$$

where ε_B is the conversion fraction, and $u_{\rm sh}$ is the shock velocity in the ISM rest frame. In this work, we use $\varepsilon_B = 10^{-2}$. As for the velocity profile inside the spherical shock, we use an approximate solution of $u_2(r) = (3u_{\rm sh}/4)(r/R_{\rm sh})$, where r is the radial distance from the explosion center [29].

We use different methods to solve the particle motion in the upstream and downstream regions. In the downstream region, we solve random work by the Monte-Carlo method because we assume the highly turbulent downstream magnetic field, and the isotropic particle scattering in local fluid rest frame. As for the downstream diffusion, we set the Bohm limit in the downstream magnetic field. On the other hand, in the upstream region, we solve the particle trajectory in the upstream magnetic field, $\vec{B}$. We use the Bunemann-Boris method to solve the equation of motion for upstream particles [31]. Particles are impulsively injected into the equatorial plane at $t_{\rm inj} = 40, 100, 200, 660, 2000, 6600$, and 20000 yr. The energy of injected particles at $t_{\rm inj} = 20000$ yr is 100 GeV, and 1 TeV for the other injection times. The particle splitting method is applied to improve statistics of the number of high energy particles.

3. Simulation results

In Figure 1, we show the maximum energy of particles. The horizontal axis and the vertical axis show the SNR age and the maximum energy of particles, respectively. The black dotted line is the age-limited maximum energy, $E_{\rm max,age}$, given by the condition that the acceleration time, $t_{\rm acc}$ (see Equation (5) in [19]), is equal to the SNR age, $t_{\rm age}$. The age-limited maximum energy in this work is

$$E_{\rm max,age} = \left(\frac{u_{\rm sh}}{v}\right)^2 \left(\frac{B_2}{B_1}\right) \left\{\pi \left(\frac{u_{\rm sh}}{v}\right) \left(\frac{B_2}{B_1}\right) + \frac{16}{3}\right\}^{-1} ZeB_1 v t_{\rm age} \ , \tag{2}$$

where v is the particle velocity, Ze is the particle charge. In our acceleration model, we assume that the upstream and downstream particle motions are the gyration and the Bohm diffusion, respectively. The blue filled and open squares are simulation results for the uniform and turbulent magnetic field with the injection scale of 100 pc, respectively. Simulation results are extracted as follows. First, we make the momentum spectrum of escaping CRs, $p^2 dN/dp$. The peak momentum is estimated at

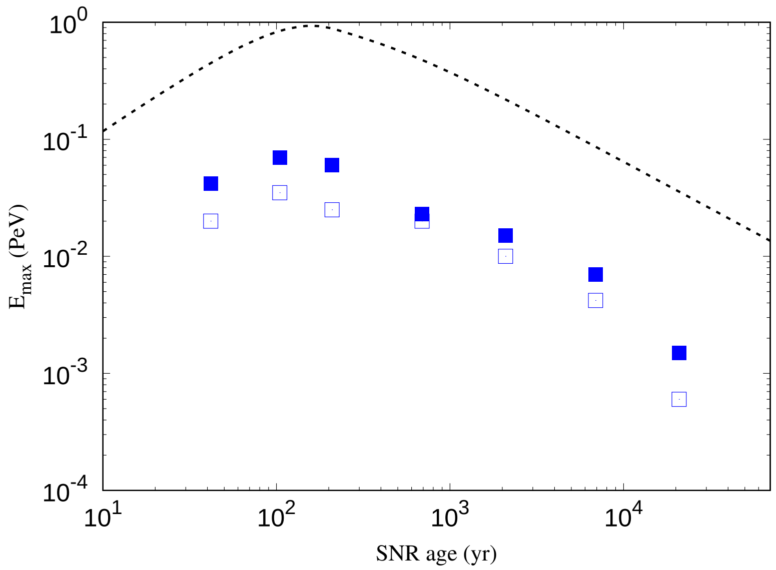

Figure 1: Maximum energy of particles accelerated in the perpendicular shock of type Ia SNRs. The black dotted line are the age-limited maximum energy (Equation (2)). The blue filled and blue open square are simulation results for the uniform and turbulent magnetic field with the injection scale of 100 pc, respectively.

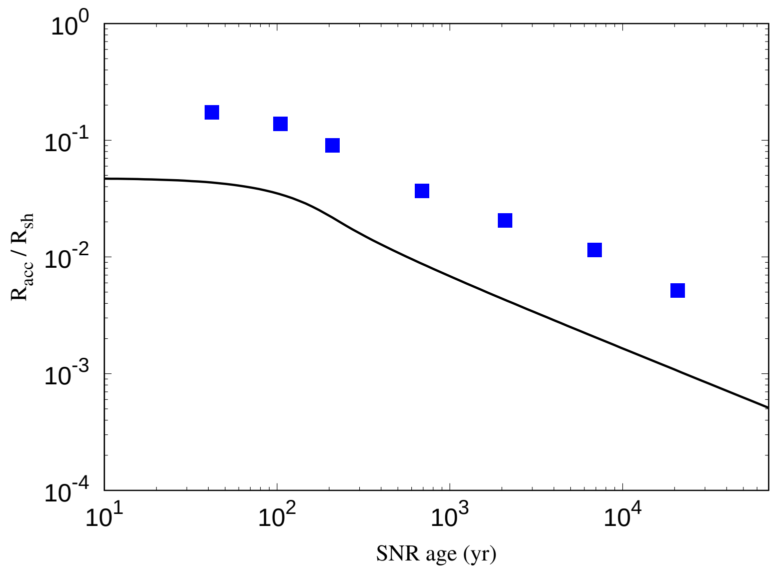

Figure 2: Size of the perpendicular shock acceleration region, $R_{\rm acc}$. The blue squares and the black solid line are the simulation results for the uniform magnetic field and the superluminal shock region, respectively.

every some time steps. We regard the particles as escaping particles when particles move more than 10% of the shock radius away from the shock surface. Next, we see the time evolution of the peak momentum of $p^2 dN/dp$ for escaping CRs. We identify the maximum value of the peak momentum as the escape-limited maximum energy. As one can see, simulation results are always at least ten times smaller than the age-limited maximum energy. The simulation results in the realistic model of the ISM magnetic field are not so different from the simulation results for the uniform magnetic field. The results for the turbulent magnetic field with the injection scale of 1 pc (not shown here) do not change significantly from that for 100 pc. Thus, the perpendicular shock in type Ia SNRs in the ISM cannot accelerate CRs to PeV.

In Figure 2, we show the size of acceleration region. The horizontal axis and the vertical axis show the SNR age and the size of the acceleration region, respectively. The black line and the blue squares show the superluminal shock region and simulation results for the uniform magnetic field. Simulation results are given by the averaged last shock crossing point of escaped particles. In Figure 2, the simulation results occupy about 20% area of the whole shock surface in the free expansion phase, and are larger than the size of the superluminal shock region ($R_{\rm acc}/R_{\rm sh} \approx u_{\rm sh}/v$). The theoretical estimations for the escape-limited maximum energy and the size of the acceleration are shown in Kamijima & Ohira 2021

4. Discussion

For core collapse supernovae, the initial progenitor mass is stripped by the stellar wind before the explosion. Thus, the explosion of core collapse supernovae occurs in the circumstellar medium (CSM). It is expected that the magnetic field configuration in the CSM is the Parker spiral structure. Then, large areas of SNR shocks in the CSM become perpendicular shocks, so that CRs could be accelerated to PeV. In the future, we are going to investigate the CR acceleration and the escape process in the Parker spiral magnetic field.

5. Summary

In this work, we first investigate the CR escape process from the perpendicular shock of the spherical shock in the ISM magnetic field. The perpendicular shock region in SNRs is expected to be PeVatron without an upstream magnetic field amplification, however, the escape process and the escape-limited maximum energy is still unknown. In addition, we have not fully understood how large area in the whole SNR shock surface is occupied by the rapid acceleration. We performed test particle simulations to reveal the escape-limited maximum energy and the size of the acceleration region. We showed that the size of the rapid acceleration region occupies about 20% of the SNR shock radius during the free expansion phase and the fraction decreases with time. We showed that the escape-limited maximum energy is about a few 10 TeV. Thus, we conclude that the maximum energy is not limited by the finite age, but always limited by the escape process. The perpendicular shock of type Ia SNRs in the ISM cannot accelerate CRs to PeV.

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