SLOW DIFFUSION OF COSMIC RAYS AROUND A SUPERNOVA REMNANT

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ABSTRACT

We study the escape of cosmic-ray protons accelerated at a supernova remnant (SNR). We are interested in their propagation in the interstellar medium (ISM) after they leave the shock neighborhood where they are accelerated, but when they are still near the SNR with their energy density higher than that in the average ISM. Using Monte Carlo simulations, we found that the cosmic rays with energies of $\lesssim$ TeV excite Alfvén waves around the SNR on a scale of the SNR itself if the ISM is highly ionized. Thus, even if the cosmic rays can leave the shock, scattering by the waves prevents them from moving further away from the SNR. The cosmic rays form a slowly expanding cosmic-ray bubble, and they spend a long time around the SNR. This means that the cosmic rays cannot actually escape from the SNR until a fairly late stage of the SNR evolution. This is consistent with some results of Fermi and H.E.S.S. observations.

Key words: cosmic rays – ISM: clouds – ISM: supernova remnants

Online-only material: color figures

1. INTRODUCTION

Most of the cosmic rays in the Galaxy are believed to be accelerated at the shock of supernova remnants (SNRs). Compared to cosmic-ray electrons that can be directly observed (e.g., Koyama et al. 1995), observational confirmation of accelerated protons is not easy. However, $\gamma$-ray observations have suggested that the protons illuminate molecular clouds around an SNR and produce $\gamma$-ray emission through $pp$ interaction (e.g., Aharonian et al. 2004, 2008; Abdo et al. 2009a). Hereafter, we treat cosmic-ray protons.

Recent $\gamma$-ray observations of molecular clouds around an SNR have given us information not only on the particle acceleration in the SNR but also on the escape of the particles from the SNR. By comparing a simple model with the latest Fermi and H.E.S.S. $\gamma$-ray observations, Fujita et al. (2009b) indicated that there are TeV cosmic rays around the hidden SNR in the open cluster Westerlund 2, and the old SNR W 28. They showed that the diffusion timescale of cosmic rays around the SNRs is much longer than that in the general region in the Galaxy. The diffusion coefficient is less than $\sim 1\%$ of that in the general region (see also Torres et al. 2008). This suggests an important fact. The typical diffusion coefficient in the general region is $D \sim 10^{30} \text{ cm}^2 \text{ s}^{-1}$ for particles with an energy of $\sim 1 \text{ TeV}$ (Berezinskii et al. 1990). If the coefficient is $1\%$ of that typical value or $D \sim 10^{27} \text{ cm}^2 \text{ s}^{-1}$, the timescale on which the particles cross the scale of an SNR ($R_{\text{sh}} \sim 15 \text{ pc}$) is $\sim R_{\text{sh}}^2/(6D) \sim 1 \times 10^4 \text{ yr}$. This is comparable to the time in which a shock with a velocity of $\sim 10^3 \text{ km s}^{-1}$ crosses that scale. This means that particles that can leave the shock neighborhood would not easily escape from the periphery of the SNR. Here, the shock neighborhood means the region where some nonlinear effects generate strong magnetic waves or cause strong amplification of magnetic fields (Lucek & Bell 2000; Bell 2004). In that region, the particle diffusion would follow the so-called Bohm diffusion and the particles are efficiently accelerated.

In this Letter, we theoretically investigate particle diffusion in the interstellar medium (ISM) outside this shock neighborhood. We show that cosmic-ray streaming generates Alfvén waves around the SNR, which scatter the particles and make the particle diffusion in the ISM around the SNR significantly slow. We also show that the cosmic rays actually cannot easily escape from the periphery of the SNR. In contrast with previous studies (e.g., Ptuskin & Zirakashvili 2003; see also Lee et al. 2008), we consider the time evolution of the diffusion coefficient and the effect of cosmic-ray diffusion in the ISM before being affected by the streaming. We use Monte Carlo simulations to study the diffusion, while at the same time we calculate the evolution of the SNR and the excitation of Alfvén waves based on a simple model. We consider the diffusion in the ISM around an SNR that are highly ionized, because ion neutral friction does not significantly affect the growth of the Alfvén waves. Observed molecular clouds that are bright in the $\gamma$-ray band may be immersed in the ionized ISM. In Fujita et al. (2009b), it was not specified whether the observed slow diffusion of cosmic rays is happening inside or outside the molecular clouds. In this study, we take the latter stance.

2. MODELS

Cosmic rays are scattered by Alfvén waves generated by the streaming of the cosmic rays themselves. We treat the propagation of a cosmic-ray particle as a three-dimensional random walk. We assume that the diffusion coefficient depends on the position $r$, although the scattering is isotropic at each point. For a given diffusion coefficient $D(t, r, E)$, where $E$ is the energy of the particle, the mean free path of a particle is written as $l_m = 6D/v$, where $v$ is the velocity of the particle. The diffusion coefficient is given by

$$D_a = \frac{4}{3\pi} \frac{pvc}{eB\psi},$$

(1)

where $p$ is the momentum of the particle, $c$ is the speed of light, $e$ is the positron charge, $B$ is the magnetic field, and $\psi(t, r, E)$ is the energy density of Alfvén waves per unit logarithmic bandwidth (which are resonant with particles of energy $E$) relative to the ambient magnetic energy density $U_M$ (Bell 1978). At the rest frame and the outside of a shock,

$$\frac{\partial \psi}{\partial t} \approx \sigma - \Gamma \psi,$$

(2)
where $\Gamma$ is the damping rate (Bell 1978). The growing term is given by

$$\sigma(t, r, E) = \frac{4\pi v_A^2 v}{3 U_M} |\nabla f|,$$

where $v_A$ is the Alfvén velocity and $f(t, r, E)$ is the distribution function of cosmic rays (Skilling 1975; Bell 1978). For the damping, we consider the one owing to collisions between charged and neutral particles:

$$\Gamma = 8.4 \times 10^{-9} \left( \frac{n_H}{\text{cm}^{-3}} \right) \left( \frac{T}{10^4 \text{ K}} \right)^{0.4} \min\left(1, \frac{\rho_{\text{coh}}^2}{\rho^2} \right) \text{s}^{-1},$$

where $n_H$ is the neutral hydrogen density, $T$ is the temperature of the ISM, and

$$\rho_{\text{coh}} = 8 \left( \frac{n_H}{\text{cm}^{-3}} \right)^{-3/2} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.4} \left( \frac{B}{1 \mu \text{ G}} \right)^2 \text{GeV}$$

(Kulsrud & Cesarsky 1971; O’C Drury et al. 1996). For $p > \rho_{\text{coh}}$, neutrals participate in the coherent oscillations of the ions in the Alfvén wave, which decreases the damping rate.

The evolution of an SNR follows the Sedov solution for $t_{\text{sed}} < t < t_{\text{rad}}$:

$$R_{\text{sh}}(t) = R_{\text{rad}}(t/t_{\text{rad}})^{2/5},$$

where $t_{\text{SED}}$ is the starting time of the Sedov phase and $R_{\text{rad}}$ is the radius of the SNR when its radiative cooling becomes effective at $t = t_{\text{rad}}$. For particle acceleration in the shock neighborhood, we adopt a simple model. We assume that only particles with a maximum energy $E_{\text{max}}(t)$ can escape from the shock at a given time (see Ptuskin & Zirakashvili 2005; Ohira et al. 2010). We simply assume that $E_{\text{max}}(t) \propto t^{-\delta}$, where $\delta (> 0)$ is the parameter (Gabici et al. 2009). Since we are mainly interested in the particle diffusion outside the shock, we assume that the growth of Alfvén waves stops inside the shock for simplicity ($\psi = 0$).

We assume that $\psi = 0$ at $t = 0$. When $\psi$ is close to zero, the diffusion coefficient in Equation (1) diverges. Thus, we use a diffusion coefficient of $D = \min(D_t, D_s)$ in actual calculations, where $D_t$ is the standard value in the Galaxy at positions far away from SNRs:

$$D_t = 10^{28} \left( \frac{E}{10 \text{ GeV}} \right)^{0.5} \left( \frac{B}{3 \mu \text{ G}} \right)^{-0.5} \text{cm}^2 \text{s}^{-1}$$

(Gabici et al. 2009). We do not consider the cooling of particles and the reacceleration of particles that are caught up by the SNR.

3. RESULTS

First, we consider cosmic-ray diffusion in the ISM that is completely ionized ($\Gamma = 0$). We assume that $R_{\text{rad}} = 15$ pc and $t_{\text{rad}} = 1 \times 10^4$ yr, which are close to those for Westerlund 2 and W 28 (Fujita et al. 2009a, 2009b). The strength of undisturbed magnetic field is $B = 10 \mu$ G. The mass density of ISM is $\rho = 8.35 \times 10^{-22}$ g cm$^{-3}$. The maximum energy $E_{\text{max}}$ decreases from 100 TeV ($t = t_{\text{SED}} = 215$ yr) to 1 GeV ($t = t_{\text{rad}}$), which leads to $\delta = 3$. For the calculations of $\psi$ (Equation (2)), we set the inner boundary at $r = 3.2$ pc, where the highest energy cosmic rays are injected ($E = 100$ TeV). We consider the gradient of $f$ only in the radial direction. The outer boundary is set at $r = 50$ pc. The innermost mesh has a width of $\sim 0.2$ pc, while the width of the outermost mesh is $\sim 6$ pc. The time step for the calculation of $\psi$ is taken as the time in which $E_{\text{max}}(t)$ decreases by a factor of 10$^{0.2}$, which is a factor of a few smaller than the duration in which particles with $E_{\text{max}}(t)$ are actually injected (Caprioli et al. 2009).

In Figure 1, we present the distribution of particles with an energy of $E = 1$ TeV at $t = 2.2 \times 10^3$ and $1 \times 10^4$ yr (or $t_{\text{rad}}$). The shock radius at those times is $R_{\text{sh}} = 8.1$ and 15 pc, respectively. The particles with that energy are injected at $t = 1 \times 10^3$ yr at $R_{\text{sh}} = 6.0$ pc. The number of the injected particles with that energy is 100,000. Immediately after the injection at $t = 1 \times 10^3$ yr, the particles rapidly leave the shock because of the large diffusion coefficient ($D = D_t$), until Alfvén waves grow enough to scatter the particles.

Figure 1 indicates that many of the particles are still wandering around the SNR at $t = 2.2 \times 10^3$ yr. Until this time, the streaming of the cosmic rays has generated Alfvén waves outside the SNR, and they are strong enough to scatter particles (but still $\psi \ll 1$). As a result, the diffusion coefficient has become much smaller than $D_t$ in Equation (7). In fact, at $r \sim 10$ pc, $D_t/D_s \sim 0.01$ for $E = 1$ TeV, which is consistent with the Fermi and H.E.S.S. results (Aharonian et al. 2007, 2008; Abdo et al. 2009b) as is discussed in Fujita et al. (2009b). Even at $t = t_{\text{rad}}$, a significant fraction of the particles remain around the expanding SNR. Because of the relatively high value of $\psi$ and the low value of the diffusion coefficient, cosmic rays cannot easily escape from the region peripheral to the SNR. At $t = t_{\text{rad}}$, 71% of the injected particles with $E = 1$ TeV are around the SNR ($r < 20$ pc). The number density does not decrease smoothly toward larger $r$ (Figure 1), because the diffusion becomes slow where the gradient of $f$ is large (Equation (3)), which tends to steepen the gradient further.

Figure 2 shows the spectrum of cosmic rays at $t = t_{\text{rad}}$. We assume that the total energy of cosmic rays accelerated for $t_{\text{SED}} < t < t_{\text{rad}}$ is $10^{50}$ erg. Although we give the same number of particles for a given energy in the calculations, we give them weights so that the distribution function of all the particles that are accelerated at the shock is $f_0 \propto E^{-2}$. Figure 2 indicates that $f \propto E^{-2.75}$ for $E \gtrsim 10$ TeV regardless of positions. The index ($-2.75$) is the one when particles have already prevailed beyond the region considered (Aharonian & Atoyan 1996; Fujita et al. 2009b). For this energy range, Alfvén
waves are not much excited, because Equation (7) indicates that the diffusion coefficient when $\psi \approx 0$ ($D = D_s$) is large, and because the particles rapidly escape from the SNR without making a gradient of $f$ large enough to excite Alfvén waves (Equation (3)). On the other hand, the diffusion coefficient when $\psi \approx 0$ is smaller for $E \lesssim 3$ TeV (Equation (7)). Alfvén waves are generated through the gradient of $f$ in this energy range. As a result, cosmic rays in this energy range are well scattered by the Alfvén waves, and spread only slowly as a cosmic-ray bubble. Thus, the spectrum follows the original form of $f \propto E^{-2}$, and the value of $E^2f$ is distinctively large at $r \lesssim R_{sh}$ (= 15 pc) compared to the one at $r > R_{sh}$. The position of the cutoff in the spectra ($\sim$3 TeV) depends on the diffusion coefficient of the unperturbed ISM (Equation (7)). This indicates the need to study the escape of cosmic rays globally, not locally around the shock. At $r = 32$–36 pc, the spectrum is harder than $E^{-2}$ at $E \lesssim 3$ TeV, because most of the low-energy particles have not reached that region. It is to be noted that the wave energy does not exceed the background magnetic energy around the SNR in this energy range ($\psi < 1$). This is different from the shock neighborhood mentioned in Section 1, where $\psi \gtrsim 1$ is expected. The retained cosmic rays may be released at $r \gtrsim t_{\text{rad}}$ when the SNR can no longer hold them.

The spectra are different when the ISM is not completely ionized. In Figure 3, we assume that the ISM temperature is $T = 10^4$ K, and the neutral hydrogen density is $n_H = 0.1$ cm$^{-3}$ (Equations (4) and (5)). We chose these parameters because the neutral damping is marginally effective, and we can see the effect clearly. Other parameters are the same as those studied above. In Figure 3, the neutral damping is effective for $E < 1$ TeV at $r \gtrsim 16$ pc. Around the SNR or $r \sim 12$–16 pc, the generation of Alfvén waves overwhelms the damping at $E \sim 1$ TeV because of the large gradient of $f$. At $r \sim 12$–16 pc, particles that are recently injected are seen at $E \lesssim 10$ GeV.

4. SUMMARY AND DISCUSSION

We have shown that cosmic rays with energies of $\lesssim$ TeV excite Alfvén waves in the ISM around an SNR even after they leave the shock neighborhood where they are accelerated. The particles are scattered by the waves, which makes the diffusion of the particles slow. As a result, the particles remain around the expanding SNR for a long time. This means that even if the particles are accelerated in an early stage of the SNR evolution, they cannot actually escape from the SNR until a fairly late stage.

The ISM must have been well ionized for the cosmic rays to be held around the SNR, because the neutral damping of Alfvén waves is not effective. For Westerlund 2 and W 28, Fujita et al. (2009b) indicated that the supernova exploded in a hot cavity, which had been created through activities of the progenitor star and/or explosions of other supernovae. Therefore, the ISM might have been ionized. While the maximum energy of protons around the SNR is $\sim$2.7 TeV for W 28, it is $\sim$47 TeV for Westerlund 2 (Fujita et al. 2009b), which is larger than that predicted in Figure 2 ($\sim$3 TeV). However, the maximum energy increases to $\gtrsim$10 TeV if the magnetic field in the ISM is $B \sim 20$ $\mu$G and the ISM is fully ionized.

Recent H.E.S.S. and Fermi observations showed that $\gamma$-rays are produced in molecular clouds adjacent to SNRs (e.g., Aharonian et al. 2004, 2008; Abdo et al. 2009a). In molecular clouds, Alfvén waves may totally disappear through neutral damping. If this is the case, they may be illuminated by cosmic rays in the ionized ISM surrounding the clouds. The $\gamma$-rays may be generated through $pp$ interaction in the clouds. The cosmic rays that enter the clouds may quickly pass the clouds unless some other disturbers such as turbulence scatter the cosmic rays. In our study, the cosmic rays are confined around an SNR on a scale of the SNR itself (Figure 1). Thus, molecular clouds that are bright in the $\gamma$-ray band may not be found in the region beyond this scale.

If cosmic rays continue to be held by an SNR, they may be affected by adiabatic cooling as the SNR expands. Moreover, some of the cosmic rays engulfed by the SNR would be reaccelerated. These may affect the cosmic-ray spectrum in the Galaxy.

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