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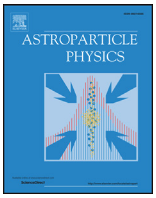

Diffusion of cosmic rays in a multiphase interstellar medium swept-up by a supernova remnant blast wave

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ABSTRACT

Supernova remnants (SNRs) are one of the most energetic astrophysical events and are thought to be the dominant source of Galactic cosmic rays (CRs). A recent report on observations from the Fermi satellite has shown a signature of pion decay in the gamma-ray spectra of SNRs. This provides strong evidence that high-energy protons are accelerated in SNRs. The actual gamma-ray emission from pion decay should depend on the diffusion of CRs in the interstellar medium. In order to quantitatively analyse the diffusion of high-energy CRs from acceleration sites, we have performed test particle numerical simulations of CR protons using a three-dimensional magnetohydrodynamics (MHD) simulation of an interstellar medium swept-up by a blast wave. We analyse the diffusion of CRs at a length scale of order a few pc in our simulated SNR, and find the diffusion of CRs is precisely described by a Bohm diffusion, which is required for efficient acceleration at least for particles with energies above 30 TeV for a realistic interstellar medium. Although we find the possibility of a superdiffusive process (travel distance $\propto t^{0.75}$) in our simulations, its effect on CR diffusion at the length scale of the turbulence in the SNR is limited.

1. Introduction

Supernova remnants (SNRs) have long been believed to be the source of hadronic Galactic cosmic rays (GCRs) up to energies of the 'knee', near 5×10^{15} eV, of the cosmic ray (CR) spectrum. Supernova explosions forming collisionless shock waves induce the shocked gas and relativistic particles (hereafter cosmic rays) that produce multi-wavelength thermal and nonthermal emission. Diffusive shock acceleration (DSA) is the most promising mechanism for converting the kinetic energy of a supernova explosion into energetic particles [1–4] and plays an important role in nonthermal emission during the overall process (e.g., [4–6]).

In the framework of DSA, an individual charged particle experiences many collisions with background electromagnetic waves and gains energy by shock crossing. This leads to a nonthermal CR spectrum of the power-law form $N(\varepsilon) \sim \varepsilon^{-2}$. Shock acceleration by DSA in SNR shocks is associated with transport processes, and some of the highest energy CRs eventually escape from their acceleration sites by a so-called diffusion process due to interactions with turbulent magnetic fields. To analyse the diffusion process we have to determine the effective diffusion coefficient $D(\mathbf{r}, \mathbf{p})$, and the understanding of $D(\mathbf{r}, \mathbf{p})$ is necessary to interpret many astronomical observations.

Several studies of escaping CRs have already been done and a strong spatial correlation between TeV emission and the molecular gas distribution at the Galactic Center has been observed [7–9]. The pion-decay signature in SNRs is believed to be evidence for protons accelerated in middle-aged SNRs interacting with molecular clouds [10–16]. Recent observations suggest that gamma-ray emission and CO+HI emission are spatially correlated in young SNRs *RX J1713.7-3946* and *RX J0852.0-4622* ([17,18], see also [19–21].

Nevertheless, the identification of pion-decay gamma rays is difficult because high-energy electrons also produce gamma rays via bremsstrahlung and Inverse Compton scattering (leptonic model) [10]. X-ray observations show that electrons are accelerated to highly relativistic energies in SNR shocks [23]. Therefore, in order to understand the acceleration sites of CRs, it is crucial to distinguish GeV–TeV emission from Inverse Compton scattering by CR electrons and the decay of neutral pions produced by inelastic collisions between CR protons and ambient thermal nuclei.

In this paper, we investigate the diffusion of CRs using a hydrodynamics simulation of a strong shock wave propagating in a realistic multiphase interstellar medium and a one-phase medium. The organization of the paper is as follows. In Section 2, we describe the three-dimensional hydrodynamics simulations and the resulting configuration of electromagnetic field used. We also briefly introduce the

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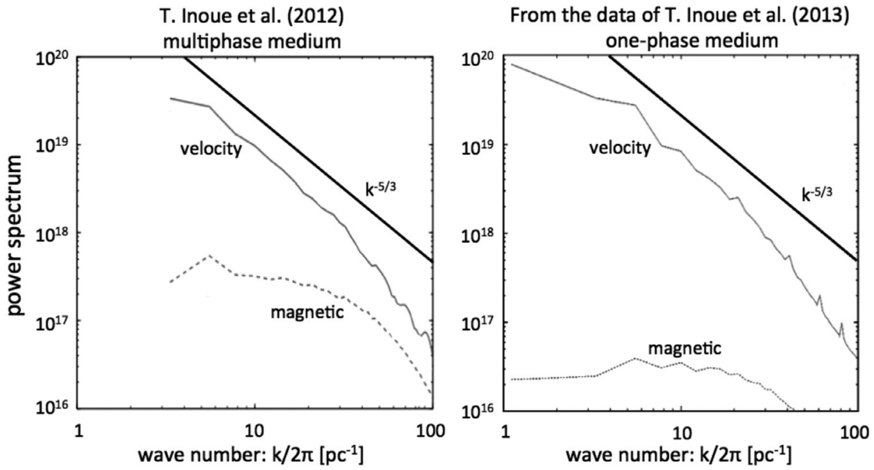

Fig. 1. Fourier power spectrum of SNR turbulence. Figures on left and right indicate for multiphase and one-phase medium, respectively. The upper thin solid line in figure indicates the velocity field and dashed line indicates the magnetic field. The uppermost thick solid line in figure represents the Kolmogorov law $k^{-5/3}$.

process of Bohm Diffusion. The results of test particle simulations performed in these environments are shown in Section 3. We investigate the properties of escaping CRs in terms of the diffusion coefficient in both energy and configuration space, and finally we summarize and discuss our findings in Section 4.

2. Methods

2.1. Setup of background interstellar medium

2.1.1. Multiphase medium

The interstellar medium (ISM) is an open system in which radiative cooling and heating are effective. It is an inhomogeneous, multiphase system in which gases of different temperatures, densities, and ionization fractions can coexist in approximate pressure equilibrium. Diffuse warm gas (diffuse intercloud gas) with $T \simeq 10^4$ K and HI clouds (interstellar clouds) with $T \simeq 10^2$ K are approximately in pressure equilibrium in a typical ISM environment. As a consequence of the thermal instability driven by external compressional events such as shock waves due to expanding HII regions or very late phase SNRs, unstable gas evolves into diffuse gas and HI clouds [24–26]. Therefore, inhomogeneities inevitably emerge and remain ubiquitous in the ISM. The characteristic length scale of an inhomogeneity can be expressed in terms of the "Field length", which is the critical wavelength of the thermal instability [27,28]. The Field length depends on density and temperature and can be smaller than 1 pc. A blast wave generated by supernova expansion sweeps up the dense and clumpy HI clouds of the multiphase ISM, which eventually generates strong velocity shear in the magnetic fields. Magnetic fields undergo amplification from their typical strength of μG to mG due to the turbulent dynamo in the post-shock region ([22,29–31]). This process may explain the existence of magnetic fields of mG strength investigated by Uchiyama et al. [32].

Inoue et al. [22] performed ideal three-dimensional magnetohydrodynamic (MHD) simulations of a strong shock wave ($v_{\rm sh} \sim 2500$ km s^{-1}) propagating in a realistic multiphase ISM as the pre-shock region. We use the data for the perpendicular shock of Inoue et al. [22] at $t = 750$ years as the background ISM to set up the electromagnetic field for our microscopic particle simulations.

To generate a multiphase ISM, Inoue et al. [22] solved the ideal MHD equations including cooling, heating, and thermal conduction, which determine the unstable scale of thermal instability. They considered a net cooling function and photoelectric heating, and generated an inhomogeneous medium via thermal instability. The simulation considered ideal gas and used an adiabatic index of $\Gamma = 5/3$. The mean number density, initial thermal pressure, and initial magnetic field strength were taken to be $\langle n_0 \rangle = 2.0$ cm^{-3}, $p/k_B = 2887$ K cm^{-3}, and $B_{0y} = 5.0$ μG, respectively, at the $x = 0$ boundary plane. For the density, they imposed random density fluctuations with a thermally unstable state in the range 10 K $\leq T \leq 10^4$ K for effective cooling and heating. In the resulting clumpy cloud, they induced a high Mach number shock wave using a hot plasma with $p_h/k_B = 10^9$ K cm^{-3} and $\langle n_h \rangle = 0.1$ cm^{-3}.

2.1.2. One-phase medium

Inoue et al. [30] performed ideal three-dimensional magnetohydrodynamic (MHD) simulations to investigate the interaction between blast wave ($v_{\rm sh} \sim 1800$ km s^{-1}) and interstellar density fluctuations. They investigated the magnetic field amplification and the magnetic field distribution of turbulent SNRs driven by the Richtmyer–Meshkov instability (RMI). They assumed an adiabatic gas with adiabatic index $\Gamma = 5/3$ and used a high Mach number shock wave. Density fluctuations superposed by sinusoidal functions were included and followed an isotropic power-law spectrum with random phases. The power spectrum of the density fluctuations was shown to be described by an isotropic power law for the wavenumber k in the inertial range of turbulence: $P(k) = \rho_k^2 k^2 \propto k^{-5/3}$, where ρ_k is the Fourier component of the density. The mean number density, the initial thermal pressure, and the initial magnetic field strength were taken to be $\langle n_0 \rangle = 0.5$ cm^{-3}, $p/k_B = 4 \times 10^3$ K cm^{-3}, and $B_0 = 3.0$ μG, respectively. The parameters represent typical values in the diffuse ISM [33,34]. To induce the blast wave, a hot plasma is set up as follows: $p_h/k_B = 2 \times 10^8$ K cm^{-3}, $\langle n_h \rangle = 0.05$ cm^{-3}, and $B_{0y} = 3.0$ μG at the $x = 0$ boundary plane. This creates the primary shock wave whose normal vector is perpendicular to the mean magnetic field. The SNR is modelled as a young SNR (age $= 10^3$ years) with a late with velocity of 1800 km s^{-1}. We used the data for the perpendicular shock on model 1 in [30] at $t = 700$ years as the background ISM.

A simulation box with size $L_{\rm box} = 2$ pc is used, and the system resolution is $\Delta x = L_{\rm box}/(\text{number of grid cells}) = 1.95 \times 10^{-3}$ pc, where the number of uniform grid cells is 1024^3. Periodic boundary condition is used for the yz-plane. The above simulation resolution and boundary condition are applied for both media. The Fourier power spectra of SNR turbulence for both media are given in Fig. 1 (for more details see [22,30].)

2.2. Test particle simulations

The magnetized turbulent medium flows along the (positive) x-direction. We calculate the trajectories of CR particles using