Collisonless shocks have long been regarded as efficient cosmic ray accelerators in the universe \cite{1}. In fact, observations of supernova remnants (SNRs) provide the evidence that electrons and ions are accelerated to highly relativistic energy \cite{2}. However, shock structures and injection to the shock acceleration have not been understood completely. Previous studies by particle simulations have addressed only shocks in fully ionized plasmas.

The interstellar medium is not always fully ionized plasmas. The existence of neutral particles around collisionless shocks has been identified in many SNRs from observations of H\alpha emission \cite{3}. Recently, some authors proposed important effects of the neutral particles on particle acceleration and collisionless shocks \cite{4-5}.

In this Letter, we present the first hybrid simulations of collisionless perpendicular shocks propagating into partially ionized plasmas. In the hybrid simulation code, ions are treated as particles and electrons are a mass-less fluid to satisfy the charge quasi-neutrality. The hybrid code computes the motion of ions as coupled to Maxwells equations in the low-frequency limit \cite{6}. In addition, we solve ionization of hydrogen atoms and the motion of hydrogen atoms as the free streaming in this Letter.

We consider charge exchange with protons and collisional ionization with electrons, protons and hydrogen atoms as ionization processes, and we take into account the velocity dependence of their cross sections \cite{10}. At each time step, we calculate ionization of each hydrogen atom with particles in the same cell.

The ratio of the ionization frequency, $\nu_{\text{ion}} = n \sigma_{\text{ion}} v_{\text{rel}}$ to the cyclotron frequency, $\Omega_{\text{cp}}$, is given by

$$\frac{\nu_{\text{ion}}}{\Omega_{\text{cp}}} \approx 10^{-5} \left( \frac{\sigma_{\text{ion}} v_{\text{rel}}}{10^{-7} \ \text{cm}^3/\text{s}} \right) \left( \frac{n}{1 \ \text{cm}^{-3}} \right) \left( \frac{B}{3 \ \mu\text{G}} \right)^{-1}$$

(1)

where $n$, $\sigma_{\text{ion}}$, $v_{\text{rel}}$ and $B$ are the number density, the ionization cross section, the relative velocity, and the magnetic field strength, respectively. The reaction rate coefficient, $\sigma_{\text{ion}} v_{\text{rel}}$ is normalized by the typical value for $v_{\text{rel}} = 2000 \ \text{km/s}$, and the number density and the magnetic field strength are normalized by typical values of the interstellar medium. In order to reduce the computational cost, we set $\nu_{\text{ion}}/\Omega_{\text{cp}} \approx 10^{-2}$, that is, the cross sections of ionization or $n/B$ are enhanced by a factor of $10^3$, but the ionization frequency is still much smaller than the cyclotron frequency.

We set a two-dimensional simulation box in the $xy$ plane with the periodic boundary condition in the $y$ direction and particles are injected at the left boundary, $x = 0$, and reflect at the right boundary, $x = 20000 \ (c/\omega_{\text{pp}})$, where $c$ and $\omega_{\text{pp}}$ are the speed of light and plasma frequency of protons, respectively. The simulation box size is $L_x \times L_y = 20000 \ (c/\omega_{\text{pp}}) \times 400 \ (c/\omega_{\text{pp}})$. The cell size and time step are $\Delta x = \Delta y = 0.5 \ (c/\omega_{\text{pp}})$ and $\Delta t = 0.0125 \ \Omega_{\text{cp}}^{-1}$, respectively. Initially, the number of simulation particles are 16 in each cell for protons and hydrogen atoms and the magnetic field is taken to be spatially homogenous, pointing in the $y$ direction, $\vec{B} = B_0 \vec{e}_y$. We have also performed a simulation for the case of the uniform magnetic field of the $z$ direction, $\vec{B} = B_0 \vec{e}_z$. Because the results are essentially the same as that of $\vec{B} = B_0 \vec{e}_y$, we show only the case of $\vec{B} = B_0 \vec{e}_y$. The plasma parameters are as follows: The upstream ionization fraction is 0.5, the drift velocity of the $x$ direction is $v_{\text{d}} = 10 \ v_{A}$, where $v_{A} = B_0/\sqrt{4\pi \rho_{p,0}}$ is the Alfvén velocity and $\rho_{p,0}$ is the proton mass density in the upstream region, the ratio of the particle pressure to the magnetic pressure is $\beta_\text{p} = \beta_\text{H} = 0.5$ for protons and hydrogen atoms, the electron temperature is assumed to be zero because the electron heating in the collisionless perpendicular shock has not been understood yet \cite{11}. We have to specify the velocity scale to calculate ionization processes, so that we set $v_{\text{d}} = 10 \ v_{A} = 2000 \ \text{km/s}$ to reproduce the typical shock velocity of young SNRs.

The phase space at time $t = 2000 \ \Omega_{\text{cp}}^{-1}$ is shown in Fig 1. The shock is located at $x = 12700 \ (c/\omega_{\text{pp}})$ and propagating into the $-x$ direction with velocity $3.61 \ v_{A}$ in the downstream rest frame, so that the shock velocity is $v_{\text{sh}} = 13.61 \ v_{A} = 2722 \ \text{km/s}$ in the upstream rest frame and the total compression ratio is about 3.77. Note that if we redefine the Alfvén velocity as $B_0/\sqrt{4\pi \rho_{p,0} + \rho_{\text{H,0}}}$, the shock velocity becomes $19.25 \ v_{A}$ in the upstream rest frame, where $\rho_{\text{H,0}}$ is the upstream hydrogen mass density. The total compression ratio of 3.77 is somewhat smaller than 3.93 that based on the Rankine-Hugino relations for $v_{\text{sh}} = 19.25 \ v_{A}$ and $\beta_\text{p} + \beta_\text{H} = 1$. This is because the simulation box is two-dimensional space or because the behavior of pickup ions produced by ionization of hydrogen atoms is not that of gas with the adiabatic index of 5/3.

Some hydrogen atoms leak into the upstream region

Simulations of Collisionless Perpendicular Shocks in Partially Ionized Plasmas

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FIG. 1. Phase space plots of protons (top) and hydrogen atoms (bottom) at $t = 2000 \Omega_{cp}^{-1}$. The color shows the phase space density in logarithmic scale.

FIG. 2. Velocity distribution of hydrogen atoms in the downstream region, $12700 \leq x \leq 17000 \ (c/\omega_{pp})$, at time $t = 2000 \Omega_{cp}^{-1}$. The red, blue, and black lines show $v_x$, $v_y$ and $v_z$ components of the velocity distribution, respectively.

FIG. 3. Shock structures averaged over the $y$ direction at $t = 2000 \Omega_{cp}^{-1}$. The red, blue, and black lines show the proton density normalized by 10 times the far upstream value, the proton mean velocity normalized by the far upstream value and the ionization fraction, respectively.

FIG. 4. Magnetic field strength and density structures at $t = 2000 \Omega_{cp}^{-1}$. The top figures show structures of the magnetic field strength, $|B/B_0|$ in the upstream (left) and downstream (right) regions, respectively. The bottom figures show structures of the proton density, $n_p/n_{p,0}$ in the upstream (left) and downstream (right) regions, respectively. Note that the spatial scale of right figures is smaller than that of left.

from the downstream region. The leakage neutral particles are originated in downstream hot neutral particles produced by charge exchange between downstream hot protons and downstream hydrogen atoms. The number density of the leakage hydrogen atoms is about 7% of that of upstream hydrogen atoms at the shock and the mean velocity of leakage hydrogen atoms is $v_{z,\text{leak}} = -3.1 \ v_A = -620 \ km/s$ in the shock rest frame. The leakage neutral particles are ionized by upstream electrons, protons and hydrogen atoms in the upstream region. Then, the ionized particles are picked up by the upstream flow and become pickup ions. In addition, upstream neutral particles freely penetrate the shock front without deceleration and are ionized in the downstream region. As the result, upstream neutral particles also become pickup ions in the downstream region.

In Fig 2, we show the velocity distribution of neutral
FIG. 5. Energy spectra of protons (red) and hydrogen atoms (blue) in the downstream region, $12700 (c/\omega_{pp}) \leq x \leq 17000 (c/\omega_{pp})$, at time $t = 2000 \Omega_{cp}^{-1}$.

particles in the downstream region, $12700 (c/\omega_{pp}) \leq x \leq 17000 (c/\omega_{pp})$, at time $t = 2000 \Omega_{cp}^{-1}$. The red, blue and black lines show the proton density, the mean proton velocity of the $x$ direction, and ionization fraction, respectively. It is well known that the shock thickness is about the gyro radius of protons for perpendicular shocks in fully ionized plasmas, that is, $\approx 10 (c/\omega_{pp})$ for $v_{sh} \approx 10 v_A \ [12]$. For partially ionized plasmas, as shown in Fig 3, the velocity and density profiles have another scale length of the order of $10^3 (c/\omega_{pp})$ that corresponds to the ionization length scale. In the upstream and downstream regions, the plasma flow is gradually decelerated by the pressure of pickup ions produced in upstream and downstream regions. In this Letter, the ionization rate is enhanced by a factor of $10^3$ and $v_{sh} \approx 10 v_A$, so that the ionization length scale becomes about $10^2 (c/\omega_{pp})$ for young SNRs with $v_{sh} \approx 10^2 v_A$. Furthermore, in the shock rest frame, the velocity jump at the subshock with the length scale of $10 (c/\omega_{pp}) (x = 12700 (c/\omega_{pp})$) is 3.47 and smaller than the total compression ratio of 3.77. This is because the pickup ions produced in the upstream region make the Mach number small. The smaller velocity jump at the subshock makes the cosmic-ray spectrum soft and this can explain the observed gamma-ray spectra slightly steeper than the simplest prediction of the shock acceleration $\ [6,7]$. In Fig 4 we show the magnetic field strength and density structures in the upstream and downstream regions at time $t = 2000 \Omega_{cp}^{-1}$. In the upstream region (left figures), the magnetic field strength (top) is correlated with the density (bottom). This fast magnetosonic mode could be excited by the Drury instability $\ [13]$ or the following mechanism. Leakage neutral particles are more ionized in dense regions. Then, the dense regions are more decelerated by the leakage neutral particles in the upstream regions, so that the dense regions become more dense. Detailed linear analyses will be addressed in future works. Moreover, magnetic field structures of the $x$ and $z$ components, that are not shown in this Letter, show that the Alfvén mode is also excited in the upstream region. There is the pressure anisotropy of pickup ions, $P_x/P_\parallel > 1$, so that the Alfvén mode is excited by the ion cyclotron instability $\ [14]$, where $P_\perp$ and $P_\parallel$ are pressures perpendicular and parallel to the magnetic field, respectively. On the other hand, in the downstream region (right figures), the magnetic field strength (top) is anti-correlated with the density (bottom) and there is pressure anisotropy of pickup ions, $P_\perp/P_\parallel > 1$. Therefore, the downstream structure is due to the mirror instability $\ [14]$. The pickup ions could excite other instabilities for parallel shocks $\ [4]$. Furthermore, denser regions and larger magnetic field fluctuations could be produced for higher Alfvén Mach number shocks and the magnetic field could be amplify not only by plasma instabilities discussed above but also by turbulence $\ [15]$. Fig 5 shows energy spectra of protons and hydrogen atoms in the downstream region, $12700 (c/\omega_{pp}) \leq x \leq 17000 (c/\omega_{pp})$, at time $t = 2000 \Omega_{cp}^{-1}$. Some protons are accelerated to more than 10 times the initial

FIG. 6. Trajectories of three accelerated particles (red, blue and black lines). The left figure shows history of the kinetic energy. In the right figure, the background color shows the mean proton velocity normalized by the upstream value. The white and gray regions show upstream and downstream regions and the purple region shows the shock transition region including the precursor.

Fig 3 shows $y$-averaged shock structures at time $t = 2000 \Omega_{cp}^{-1}$.
kinetic energy. When leakage neutral particles are ionized and picked up by the upstream flow, their kinetic energy typically becomes 2.79 times the initial kinetic energy because the mean relative velocity between the upstream flow and the leakage neutral particles is 1.67 times the upstream flow velocity. When the pickup ions re-enter the downstream region, they are accelerated by adiabatic compression. Therefore, the typical energy of accelerated particles becomes about 10 times the initial kinetic energy. Because the cross section of charge accelerated particles becomes about 10 times the initial kinetic energy, effects of helium atoms are also important. The ionization fraction of helium in the upstream region depends on time because helium atoms are ionized by radiation from the downstream region [16]. Therefore, the injection of helium ions into the shock acceleration could depend on the age of SNRs. The cosmic-ray injection history of helium ions is important to understand the spectrum of cosmic-ray helium [17]. We have not solved electron dynamics in this Letter. Knock-on electrons produced by ionization of leakage neutral particles have a large velocity compared with that of upstream electrons, so that the Knock-on electrons are a promising candidate for injection particles into the shock acceleration. These issues will be addressed in future work.

In conclusion, we have investigated collisionless shocks propagating into partially ionized plasmas by a new hybrid simulation that solve ionization of hydrogen atoms, particle motions and Maxwells equations. We have demonstrated the followings: 1) Nearly 10% of upstream neutral particles leak into the upstream region from the shock downstream region. 2) The leakage neutral particles become pickup ions in the upstream region and they are preferentially accelerated by the shock. 3) The accelerated pickup ions make the temperature of the thermal component low. 4) Pickup ions modify the shock structure and excite plasma instabilities in the upstream and downstream regions. Hence, the ionization fraction is an important parameter to determine the injection efficiency of the shock acceleration, the spectral index of accelerated particles, magnetic field strength and the temperature of the thermal component. In addition, we have reproduce the velocity distribution of hydrogen atoms in the downstream region, that is observed as the Hα line profile of two gaussians.

Above quantitative values should be depend on the shock Mach number, ionization fraction, the shock velocity, the density, the magnetic field orientation, and so on. We have specified neutral particles as hydrogen atoms in this Letter. Because helium has about 25% of the shock kinetic energy, effects of helium atoms are also important. The ionization fraction of helium in the upstream region depends on time because helium atoms are ionized by radiation from the downstream region [16]. Therefore, the injection of helium ions into the shock acceleration could depend on the age of SNRs. The cosmic-ray injection history of helium ions is important to understand the spectrum of cosmic-ray helium [17]. We have not solved electron dynamics in this Letter. Knock-on electrons produced by ionization of leakage neutral particles have a large velocity compared with that of upstream electrons, so that the Knock-on electrons are a promising candidate for injection particles into the shock acceleration. These issues will be addressed in future work.

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