SPECTRA OF COSMIC-RAY PROTONS AND HELIUM PRODUCED IN SUPERNOVA REMNANTS

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ABSTRACT

Data obtained in the Advanced Thin Ionization Calorimeter (ATIC-2), Cosmic Ray Energetics and Mass (CREAM), and Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) experiments suggest that the elemental interstellar spectra of cosmic rays below the knee at a few times $10^6$ GeV are not simple power laws, but that they experience hardening at a magnetic rigidity of about 240 GV. Another essential feature is the difference between proton and helium energy spectra, such that the He/p ratio increases by more than 50% in the energy range from $10^2$ to $10^4$ GV. We consider the concavity of the particle spectrum resulting from the nonlinear nature of diffusive shock acceleration in supernova remnants (SNRs) as a possible reason for the observed spectrum hardening. The increase of the helium-to-proton ratio with energy can be interpreted as a consequence of cosmic-ray acceleration by forward and reverse shocks in SNRs. The contribution of particles accelerated by reverse shocks makes the concavity of the produced overall cosmic-ray spectrum more pronounced. The spectra of protons and helium nuclei accelerated in SNRs and released into the interstellar medium are calculated. The derived steady-state interstellar spectra are in reasonably good agreement with observations.

Key words: acceleration of particles – ISM: supernova remnants – shock waves

1. INTRODUCTION

High-accuracy measurements have revealed deviations of cosmic-ray spectra from plain power laws at energies of $10^{-10^5}$ GeV nucleon$^{-1}$. This refers, in particular, to the Advanced Thin Ionization Calorimeter (ATIC-2; Panov et al. 2009), Cosmic Ray Energetics and Mass (CREAM; Ahn et al. 2010; Yoon et al. 2011), and Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA; Adriani et al. 2011) experiments; see Lavalle (2011) for additional references. The general conclusions from these measurements are that the hardening is present in the spectra of protons, helium, and probably heavier nuclei at a magnetic rigidity of about 240 GV and that there is an increase in the He/p ratio in the above energy range.

A number of explanations for these results have been suggested: the hardening may reflect the contribution of two distinct populations of cosmic-ray sources (Zatsepin & Sokolskaya 2006); the action of numerous sources with the dispersion of source injection spectra (Yuan et al. 2011), fluctuations produced by local cosmic-ray sources (Thoudam & Hörandel 2012), specific conditions of cosmic-ray transport in the local bubble (Erlykin & Wolfendale 2012), interstellar diffusion with a diffusion coefficient that is not separable in energy and space (Tomassetti 2012), or the combination of diffusion in the cosmic-ray-induced turbulence and the background turbulence (Blasi et al. 2012). The energy-dependent He/p ratio may be due to acceleration by shock propagating through the medium with varying chemical composition, including the helium wind of a Wolf–Rayet star (Ptuskin et al. 2010), the stratified material of a bubble (Ohira & Ioka 2011), or the rate of ionization (Drury 2011), and the specifics of thermal ion injection in the process of shock acceleration (Malkov et al. 2012). Biermann et al. (2010) suggested that the spectral hardening and enrichment in heavy nuclei is due to the contribution of a polar cap cosmic-ray component produced by supernova explosions in winds of massive progenitor stars. The consideration of various interpretations of the observed cosmic-ray spectral peculiarities can be found in the paper by Vladimirov et al. (2012).

In the present work, we further develop our model of cosmic-ray acceleration in supernova remnants (SNRs; Ptuskin et al. 2010, hereafter Paper I) to explain both of the required features. To a good approximation, the model in Paper I explains the overall spectrum of cosmic rays observed in a wide range of energies up to about $10^9$ GeV. An important improvement of the code used in Paper I was made in our work (Zirakashvili & Ptuskin 2011, hereafter Paper II), such that particle acceleration by a reverse (backward) shock moving through the material of supernova ejecta was included in the calculations. This is in addition to the acceleration by the forward shock moving through the circumstellar medium studied in Paper I. The code described in Paper II was used by Zirakashvili (2011) and Zirakashvili & Aharonian (2011) for modeling particle acceleration in SNRs RXJ1713.7−3946 and Cas A.

It is worth noting that similar numerical models of the nonlinear production of cosmic rays in SNRs, where time-dependent cosmic-ray transport equations are solved together with gas-dynamic equations in spherical symmetry were developed by two other groups of authors: Berezhko et al. (1994) and Berezhko & Völk (2007), and Kang & Jones (2006). They give results analogous to our model for particle acceleration by forward SNR shocks, but they do not include acceleration by reverse shocks. Cosmic-ray acceleration by reverse SNR shocks was earlier considered by Berezhinskii & Ptuskin (1989). The process was recently analyzed by Telezhinsky et al. (2012) in a test particle approximation.

Two effects considered below in the frameworks of our model of particle acceleration in SNRs are of particular importance: the nonlinear shock modification that leads to the concave spectrum of accelerated particles with a pronounced hardening; and the acceleration of supernova ejecta material that is poor in hydrogen by a reverse shock that leads to the difference between the overall proton and helium spectra and increases their concavity.
2. MODELING OF COSMIC-RAY ACCELERATION IN SUPERNova REMNANTS

Cosmic-ray acceleration in shell SNRs proceeds through the diffusive shock acceleration mechanism, which is a version of the first-order Fermi acceleration in the shock vicinity, where the gas with a frozen magnetic field is compressing. The fast, charged background particles are scattered by random magnetohydrodynamic (MHD) waves and inhomogeneities, and they gain energy crossing the shock; see, e.g., Malkov & O’C Drury (2001) for a review. The process of efficient acceleration should be modeled simultaneously with the SNR hydrodynamics because the pressure of accelerated particles modifies the gas flow and the shock structure that affects the particle spectrum. Also, the current of accelerated particles results in the streaming instability that amplifies the background MHD waves. These waves in turn determine the value of particle spatial diffusion.

Hydrodynamical equations for the gas density $\rho(r,t)$, gas velocity $u(r,t)$, gas pressure $P_g(r,t)$, and the equation for the isotropic part of the cosmic-ray proton momentum distribution $N(r,t,p)$ in the spherically symmetric case take the form (see also Paper II)

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2} \frac{\partial}{\partial r} r^2 u \rho,$$  \hspace{1cm} (1)

$$\frac{\partial u}{\partial t} = -\frac{\partial u}{\partial r} + \frac{1}{\rho} \left( \frac{\partial P_g}{\partial r} + \frac{\partial P_e}{\partial r} \right),$$  \hspace{1cm} (2)

$$\frac{\partial P_g}{\partial t} = -u \frac{\partial P_g}{\partial r} - \frac{\gamma_p P_g}{r^2} \frac{\partial^2 u}{\partial r^2} - (\gamma_p - 1)(w - u) \frac{\partial P_e}{\partial r},$$  \hspace{1cm} (3)

$$\frac{\partial N}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 D(p,r,t) \frac{\partial N}{\partial r} - w \frac{\partial N}{\partial r} + \frac{\partial N}{\partial \rho} \frac{p}{\rho} \frac{\partial^2 w}{\partial r^2} \rho \frac{\eta^4 (p - p_f)}{4 \pi p_f^2 \rho^3} \delta(R_f + 0,t) \frac{\partial}{\partial r} \left( R_f - u(R_f + 0,t) \right) \delta(r - R_f(t))$$

$$+ \frac{\eta^4 (p - p_b)}{4 \pi p_b^2 \rho^3} \rho \frac{\partial R_b - 0,t}{} \left( u(R_b - 0,t) - \dot{R}_b \right) \delta(r - R_b(t)).$$  \hspace{1cm} (4)

Here, $P_e = 4\pi \int p^2 dp \rho N/3$ is the cosmic-ray pressure, $w(r,t)$ is the advective velocity of cosmic rays, $\gamma_p$ is the adiabatic index of the gas, and $D(r,t,p)$ is the cosmic-ray diffusion coefficient. It was assumed that the diffusive streaming of cosmic rays results in the generation of MHD waves. Cosmic-ray particles are scattered by these waves. That is why the cosmic-ray adveotive velocity $w$ may differ from the gas velocity $u$. In our modeling they differ in the value of the radial component of the Alfvén velocity calculated in the isotropic random magnetic field: $w = u + \xi_A V_A/\sqrt{3}$, $V_A = B/\sqrt{4\pi \rho}$. Here, the factor $\xi_A$ describes the possible deviation of the cosmic-ray drift velocity from the gas velocity. The values $\xi_A = 1$ and $\xi_A = -1$ are assumed upstream of the forward and reverse shocks, respectively, where the Alfvén waves are generated by the cosmic-ray streaming instability and propagate in the corresponding directions. The damping of these waves heats the gas upstream of the shocks (McKenzie & Voelk 1982), which is described by the last term in Equation (3), and limits the total compression ratios by a number close to 6. In addition, we use the value $\xi_A = -1$ downstream of the shocks because the cosmic-ray gradient is positive in this region. The Alfvén drift here strongly influences the slope of the particle momentum spectrum, since the magnetic fields are compressed downstream of the shocks, and the gas velocity in the shock frame falls below the sound speed. This leads, in particular, to a noticeable steepening of the particle spectrum at the forward shock; see Paper I.

The two last terms in Equation (4) correspond to the injection of thermal protons with momента $p = p_f$, $p = p_b$, and mass $m$ at the fronts of the forward and reverse shocks at $r = R_f(t)$ and $r = R_b(t)$, respectively. The indices $f$ and $b$ are used for quantities corresponding to the forward and reverse shocks, respectively. The dimensionless parameters $\eta_f$ and $\eta_b$ determine the injection efficiency. The magnetic energy density is relatively small, so it does not appear explicitly in Equation (2).

Shocked ejecta and interstellar gas are separated by the contact discontinuity at $r = R_c$. The spatial dependence of the magnetic field at $r > R_c$ is taken in the form

$$B(r,t) = \sqrt{\frac{4\pi \rho R_f}{\rho_0 M_A}} \sqrt{1 + \left( M_A V_A / R_f \right)^2}, \quad r > R_c,$$  \hspace{1cm} (5)

where $\rho_0$ is the gas density of the circumstellar medium, $V_A$ is the Alfvén velocity there, and $M_A$ is some constant. We employ the results of Völk et al. (2005) in their analysis of X-ray radiation from young SNRs, and we assume that the magnetic energy density $B^2/8\pi$ downstream of the shock is 3.5% of the ram pressure $\rho_0 R_f^2$ that determines the constant $M_A = 23$. According to Equation (5), the far upstream energy density of the amplified magnetic field is a small part (0.5/$M_A^2$) of the ram pressure. Note that this relation is consistent with modeling of the cosmic-ray streaming instability in young SNRs (Zirakashvili & Ptuskin 2008). We assume that the magnetic field is compressed in accordance with the plasma density upstream and downstream of the forward shock. We also assume that there is no decay of the magnetic field in the downstream region. The magnetic amplification is weak in old remnants with the forward shock speed $R_f < M_A V_A$. The magnetic field strength $B$ is close to the interstellar value $B_0$ in these SNRs (see Equation (5)). We assume that the magnetic field does not depend on the radius downstream of the reverse shock at $R_b < r < R_c$, but depends on the density similar to Equation (5) upstream of the reverse shock, $r > R_b$.

The diffusion coefficient is of the form

$$D = \kappa D_B.$$  \hspace{1cm} (6)

Here, $D_B = \nu pc/(3ZeB)$ is the so-called Bohm diffusion coefficient for particles of charge $Ze$ and velocity $v$ ($c$ is the speed of light). The function $\kappa = (1 + (M_A V_A / R_f)^2)^3$ at $r > R_c$, and $\kappa = 3$ at $r < R_c$, approximates the dependence of the diffusion coefficient on shock velocity. It corresponds to the case where the MHD turbulence in the shock vicinity is amplified by cosmic-ray streaming instability, which is balanced by the Kolmogorov-type nonlinearity; see Ptuskin & Zirakashvili (2005) and Paper II for details. We assume that the diffusion coefficient is close to its Bohm limit in young SNRs when the shock velocity exceeds $\sim 700$ km s$^{-1}$. This slightly-underestimates the diffusion coefficient of particles at the very end of the energy spectrum. This is because these particles are scattered by small-scale magnetic inhomogeneities generated by the non-resonant streaming instability and their diffusion coefficient is several times higher than the Bohm diffusion
coefficient (Zirakashvili & Ptuskin 2008). The value of $D$ grows with time because the wave generation becomes less efficient as the shock velocity decreases.

The equation for ions is similar to Equation (4). For ions with mass number $A$ and mass $M = Am$, it is convenient to use the momentum per nucleon $p$ and the normalization of the ion spectra $N_i$ to the nucleon number density. Then, the number density of ions $n_i$ is $n_i = 4\pi A^{-1} \int p^2 dp N_i$. The ion pressure $P_i = 4\pi \int p^2 dp p N_i/3$ is also taken into account in the total cosmic-ray pressure $P_c$.

The numerical procedure we use to solve Equations (1)–(4) was described in detail in Paper II. A finite-difference method is employed for Equations (1)–(4) upstream and downstream of the forward and reverse shocks. A non-uniform grid consists of a shock front, and the parameters of a Type I SNR, which freely expands after supernova explosions; $n_i = n$ allows one to resolve small scales of hydrodynamical quantities resulting from the pressure gradient of low-energy cosmic rays. The gases compressed at the forward and reverse shocks are separated by a contact discontinuity at $r = R_c$ between the shocks. An explicit conservative total variation diminishing scheme for hydrodynamical equations (1)–(3) and uniform spatial grid are used between the shocks.

### 3. SPECTRA OF COSMIC RAYS PRODUCED BY SUPERNova REMNANTS

To demonstrate a possible effect of acceleration by reverse shocks on cosmic-ray composition, we perform calculations for two classes of supernovae: Type I where hydrogen is absent in the outer layers of ejecta and Type II where hydrogen strongly prevails. The relative rates of these types of supernovae in the Galaxy are 0.46 and 0.54, respectively (Smith et al. 2011). The following characteristics of Type Ia and Type IIP SNRs as representative of these two classes of supernovae are accepted in the calculations.

Type Ia SNRs have kinetic energy of explosion $E = 10^{51}$ erg, number density of the surrounding interstellar gas $n = 0.1$ cm$^{-3}$, and mass of ejecta $M_{ej} = 1.4 M_\odot$. Also important for accurate calculations is the index $k$, which describes the power-law density profile $\rho \propto r^{-k}$ of the outer part of the star that freely expands after supernova explosions; $k = 7$ for Type Ia supernova. Type IIP SNRs have the parameters $E = 10^{52}$ erg, $n = 0.1$ cm$^{-3}$, $M_{ej} = 8 M_\odot$, and $k = 12$.

Figure 1 shows the overall spectra of relativistic nuclei produced in Type Ia and Type IIP SNRs during $10^5$ years of their evolution by forward (solid lines) and reverse (dashed lines) shocks. For illustration, it is assumed that the interstellar medium and the ejecta of Type II SNRs consist of protons; the ejecta of Type I SNRs consist of nuclei with mass number $A$ ($A > 1$) and charge $Z = A/2$. The accepted value of the interstellar magnetic field is $5 \mu G$. The pressure of the accelerated particles modifies the profiles of forward and reverse shocks that lead to the concave spectra of cosmic rays. The plotted function is defined as $Q(p) = 4\pi p^2 F(p)$, where $F(p)$ is the distribution of all accelerated nucleons injected into the interstellar medium over an SNR lifetime. The total number of accelerated nucleons is $\int Q(p)dp$. The procedure for calculating SNR evolution and simultaneous cosmic-ray acceleration was described in depth in Paper II. There, one can also find plots that show the calculated profiles of the gas density, velocity and pressure, and the cosmic-ray pressure in evolving SNRs.

The spectra of particles accelerated at reverse shocks are harder than the spectra at forward shocks, in spite of the same level of shock modification for both shocks. This is because the shocks propagate in the media with different properties. When the reverse shock reaches the flat part of the ejecta density distribution, it propagates in the medium density, which decreases with time. That is why the number of freshly injected ions is low in comparison with the number of higher energy particles accelerated earlier, thereby leading to spectral hardening. This effect is absent at the forward shock propagating in the medium with constant density.

Particles accelerated in the numerous SNRs are injected into interstellar space, diffuse in galactic magnetic fields, interact with interstellar gas, and finally escape through the cosmic-ray halo boundaries into intergalactic space, where cosmic-ray density is negligible. We employ the plain diffusion model with a flat cosmic-ray halo (Ginzburg & Ptuskin 1976; Strong et al. 2007) for calculations of cosmic-ray propagation in the Galaxy. The leaky-box approximation to the diffusion model can be used for our purpose—the determination of proton and helium intensities; see Ptuskin et al. (2009). The cosmic-ray intensity obeys the relation $I \propto v_{an} Q(X_e^{-1} + \sigma/m_a)^{-1}$, where $X_e$ is the escape length (the average matter thickness traversed by cosmic rays before they exit from the Galaxy), $\sigma$ is the nuclear spallation cross section for a given type of relativistic nuclei moving through the interstellar gas, and $m_a$ is the mean interstellar atom mass. The escape length is determined from the relative abundance of secondary nuclei (primarily from the boron-to-carbon ratio) in cosmic rays. The approximation formula $X_e = 19\beta^3$ g cm$^{-2}$ at $R \leq 3$ GV and $X_e = 19\beta^3(R/3$ GV)$^{-0.6}$ g cm$^{-2}$ at $R > 3$ GV was given in Ptuskin et al. (2009); here $R$ is the particle magnetic rigidity and $\beta = v/c$. According to the last equation, the resulting spectrum is steeper than the source spectrum by 0.6 at high enough energies, but the uncertainty in the last value is about 0.1, and statistically accurate measurements of the boron-to-carbon ratio are not available at energies above $\sim 30$ GeV nucleon$^{-1}$. In the present calculations, we assume the dependence $X_e \propto R^{-0.7}$ at $R > 3$ GV up to a rigidity of $\sim 10^6$ GV. It corresponds to the
The processes of cosmic-ray acceleration by supernova shocks and the subsequent diffusion in interstellar magnetic fields at relativistic energy depend on the particle’s Larmor radius, so the spectra of different ions might be expected to have similar shapes when expressed as functions of particle magnetic rigidity. However, the data from the ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010; Yoon et al. 2011), and PAMELA (Adriani et al. 2011) experiments showed that the He/p ratio changes with energy at $10^{-10^5}$ GeV nucleon$^{-1}$. Also, the spectra of these ions demonstrate deviations from the plain power laws with hardening at about 240 GV. Thus, modern statistically accurate measurements confront the traditional power-law paradigm for the source spectrum and escape length of Galactic cosmic rays below the knee. A number of possible explanations for these experimental results were proposed in the papers cited in the Introduction, but a clear picture has not yet emerged.

In the present paper, our interpretation of both features (spectral hardening and changing of the He/p ratio) is provided in the framework of our model of cosmic-ray acceleration by SNR shocks, developed in Papers I and II (the first version of this work was presented in the conference paper Ptuskin et al. 2011). The hardening of the cosmic-ray spectrum mainly results from modification of gas flow in the shock precursor by the cosmic-ray pressure, which shapes the concave energy spectrum of cosmic rays. This effect is well known in the theory of diffusive shock acceleration; see, e.g., early papers Ellison & Eichler (1985) and Berezhko et al. (1994). It manifests itself here in the presence of Alfvén drift of accelerated particles and the strong dependence of cosmic-ray diffusion on shock velocity as a pronounced hardening at a rigidity of $\sim 240$ GV in the overall spectrum of accelerated particles produced by SNRs. Particle acceleration by a reverse shock moving through the supernova ejecta results in the production of an additional component of cosmic rays that has a specific hard energy spectrum and is depleted in hydrogen composition. This makes the hardening of the overall cosmic-ray spectrum more pronounced, and it produces the difference between the hydrogen and helium spectra.

The results of our calculations of the interstellar spectra of cosmic-ray hydrogen and helium shown in Figure 2 demonstrate good agreement with observations. It is assumed that reverse shocks only accelerate protons in Type II SNRs and only accelerate helium nuclei in Type I SNRs. Forward shocks accelerate interstellar protons and helium nuclei in both cases.

Clearly, more work is needed and planned to establish the adequacy of the suggested scenario. This refers to both a detailed analysis of the dispersion properties of SNRs (the SN explosion energy, the mass and complex composition of ejecta, the structure of circumstellar medium, etc.) and assumptions about the process of particle acceleration (the value of $M_A$, the parameterization of diffusion coefficient, etc.). Also, a single power-law dependence of cosmic-ray diffusion on rigidity in the interstellar magnetic fields, $D_{\text{ISM}} \propto v_R^{6.7}$, used in the present calculations in the entire range of rigidities from 10 to $10^9$ GV, is most probably a significant oversimplification. The explanation of low anisotropy of Galactic cosmic rays seems incompatible with such a strong dependence of diffusion on rigidity (Ptuskin et al. 2006; Blasi & Amato 2012).

In principle, the last difficulty could be relieved by decreasing $M_A$ from its $M_A = 23$ value taken from Paper I and accepted in the present calculations. This would lead to a steeper source spectrum and require weaker dependence of interstellar diffusion on rigidity to fit the observations of cosmic-ray spectra. Another possibility is a possible suppression of cosmic-ray anisotropy in the Local Bubble with enhanced turbulence where the solar system resides (Zirakashvili 2005).

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**Figure 2.** Calculated interstellar spectra of protons and helium are shown with thick gray lines. Data from the BESS, CAPRICE, AMS-01, ATIC-2, and CREAM experiments, corrected for solar modulation effects, are taken from the review of Lavalle (2011), where the corresponding references and a detailed description of observations can be found. The PAMELA experiment data are taken from the paper by Adriani et al. (2011) and corrected for solar modulation.
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