ORIGIN OF SPECTRAL HARDENING OF SECONDARY COSMIC RAY NUCLEI*

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We discuss the production, acceleration and escape of secondary cosmic-ray (CR) nuclei, such as lithium, beryllium, and boron, produced by spallation of primary CR nuclei at the shock in supernova remnants (SNRs). We find that if the SNR is surrounded by a dense circumstellar medium which has a wind-like profile, the spectra of the escaping secondary nuclei are harder than those of the escaping primary nuclei. We show that if there was a past supernova surrounded by a dense wind-like CSM at a distance of ~ 1.6 kpc, we could simultaneously reproduce the spectral hardening of primary and secondary CRs above ~ 200 GV that have recently been reported by AMS-02.

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1. Introduction

Galactic cosmic-rays (CRs) are conventionally classified into two categories: one is primary CRs, which are produced at the sources such as supernova remnants (SNRs) via the diffusive shock acceleration (DSA) mechanism, and the other is secondary CRs such as lithium, beryllium, and boron, which are produced via spallation of heavier primary CR nuclei such as carbon, nitrogen, and oxygen during the propagation in the interstellar medium (ISM). Since the amount of secondary CRs produced per primary CR nucleus is proportional to the grammage traversed by the primaries until their escape from the Galaxy, the fluxes and rigidity dependence of secondary CRs

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are regarded as a probe of the propagation of Galactic CRs. Although the rigidity dependence of the boron-to-carbon ratio measured by AMS-02 [1] is consistent with the Kolmogorov turbulence theory, the later measurement by AMS-02 reported that the spectra of CR lithium, beryllium, and boron deviate from a single power-law above 200 GV in an identical way and that they harden even more than the primary CRs [2], which have already been known to show hardenings [3–7]. Several scenarios have been discussed to account for this deviation: the effect of propagation, reacceleration of secondary CRs, a contribution from different kinds of sources, *etc.* In this work, we propose another scenario, in which CR lithium, beryllium, and boron nuclei are produced and accelerated inside the SNR, and propagate in the ISM as primary CRs. In the following sections, we describe our model and the results (see our published paper [8] for details).

2. Model

In the context of the diffusive shock acceleration theory [9], particles in the vicinity of the shock front are scattered by the turbulent magnetic field and, going back and forth across the shock, they can gain kinetic energy. During the acceleration of primary CRs, they can interact with ambient medium and produce secondary CRs by spallation. If these secondaries are energetic enough to cross the shock front diffusively, they can be accelerated as primaries. Although such processes have already been discussed in some papers [10, 11], their escape into the ISM has not been considered. The condition for a particle to escape the acceleration site is described as

$$\frac{D(p)}{u_{\rm sh}} \gtrsim l\,, \tag{1}$$

where $D(p)$, $u_{\rm sh}$, and l are, respectively, the diffusion coefficient as a function of the momentum of a particle p, the shock velocity, and the distance beyond which a particle can escape the shock without being trapped by turbulent magnetic fields. From the numerical MHD calculations, it had been shown that l should be of the same order as the radius of the SNR, $R_{\rm sh}$. In general, the escape condition above evolves with time as the SNR expands because the magnetic fields will decay and the shock will slow down with time. As a result, CR particles will escape the shock in an energy-dependent way. In the next subsection, we describe the equations to derive the distribution functions of primary and secondary CRs taking into account this effect.

2.1. Equations

In the following discussions, we assume that the CRs can be regarded as test particles during DSA in an SNR. Letting the shock front be at $x = 0$, we can describe the diffusion–convection equation for the distribution functions of CR nuclei $f_i(x,p)$ (i represents the type of nuclei) in a stationary case as

$$u(x)\frac{\partial f_i}{\partial x} = \frac{\partial}{\partial x}\left[D_i(p)\frac{\partial f_i}{\partial x}\right] + \frac{p}{3}\frac{\mathrm{d}u}{\mathrm{d}x}\frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i + u_- Q_i \delta(x)\delta(p-p_0)\,, \quad (2)$$

where $u(x)$ is the fluid velocity ($u(x) = u_- \equiv u_{\rm sh}$ for $x < 0$, and $u(x) = u_+ \equiv u_{\rm sh}/r$ for $x > 0$), $D_i(p)$ is the diffusion coefficient for nuclei i with momentum p, Γ_i is the total spallation rate of nuclei i, q_i is the source term due to the spallation of parent nuclei, and Q_i is the injection rate of nuclei i at the shock front (the injection momentum is p_0). In solving these equations, we impose some boundary conditions (see [8] for details), and the most important one is the condition for the free escape of CR particles from the outer boundary

$$\lim_{x\to -l} f_i = 0\,. \quad (3)$$

We here focus on the CR nuclei of lithium, beryllium, boron, carbon, nitrogen, and oxygen, and solve six diffusion–convection equations simultaneously to obtain the escaping CR fluxes, $\phi_i(p) = -D_i(p)\left.\frac{\partial f_i}{\partial x}\right|_{x=-l}$, which are the function of time through the size of the escape boundary l. Since l is of the same order as $R_{\rm sh}$, its time evolution depends on the environment of the SNR. In the case where the SNR is surrounded by the uniform ISM, the SNR shell expands as $R_{\rm sh} \propto t^{2/5}$, while in the case where the SNR is surrounded by the circumstellar medium (CSM) with a wind-like profile, the shell expands as $R_{\rm sh} \propto t^{2/3}$. For these two cases, one can obtain the CR spectra emitted from a single SNR by integrating ϕ_i with time. Figure 1 depicts the schematic picture of our scenario.

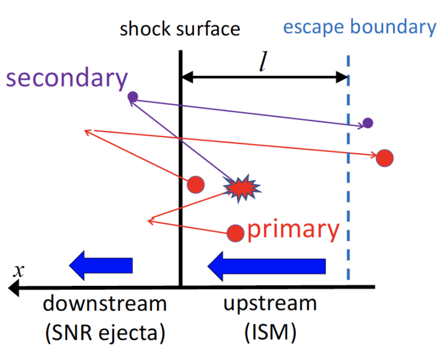

Fig. 1. Schematic picture of secondary CR production, acceleration, and escape processes in our scenario. Here, l is the distance from the shock surface to the escape boundary upstream.

3. Results

In the following results, we adopt the phenomenological model proposed by [12] for the time evolution of the escape energy of a CR particle. In this model, the CRs with knee energy ($\sim 10^{15.5}$ eV) escape at the beginning of the Sedov phase, and at the later time, the threshold energy for a CR particle to escape the SNR gradually decreases.

Figure 2 depicts the time-integrated spectra of CRs that have escaped the SNR surrounded by a uniform ISM. Here, the ISM density is assumed as 0.1 cm^{-3}. One can see that the spectra of secondary CRs (Li, Be, and B) are softer than those of primary CRs (carbon and oxygen). This result can be interpreted in the following way. Secondary CRs with higher energy are produced by the spallation of primary CRs, and in our scenario, higher energy CRs can escape the SNR at earlier times, so they have a shorter time for the interaction with the ambient medium. Therefore, the number of secondary CRs with higher energy would be smaller than those with lower energy, which means that the spectra of secondary CRs would be steeper than those of primary CRs.

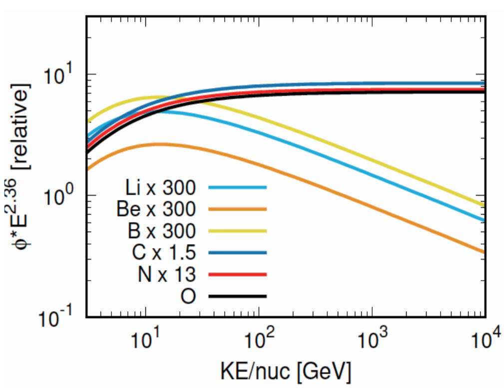

Fig. 2. Time integrated energy spectra of CR nuclei escaping the SNR surrounded by a uniform ISM ($n = 0.1$ cm^{-3}).

However, the situation is different in the case of a wind-like CSM. Figure 3 depicts the time-integrated spectra of CRs that have escaped the SNR surrounded by a wind-like CSM, where the mass loss rate and wind velocity are $3 \times 10^{-3} M_\odot$ yr^{-1} and 100 km s^{-1}, respectively. One can see that, in contrast with the previous case, the spectra of secondaries are harder than those of primaries. This can be interpreted in the following way. As in the previous case, primary CRs with higher energy would escape the SNR at an earlier time. However, since the CSM density is higher in the inner region, higher energy primaries have more chance to interact with the CSM and produce secondaries even if the interaction timescale is shorter. As a result, the number of secondary CRs with higher energy would be larger than those with lower energy, which makes the spectra of secondaries harder than those of primaries.

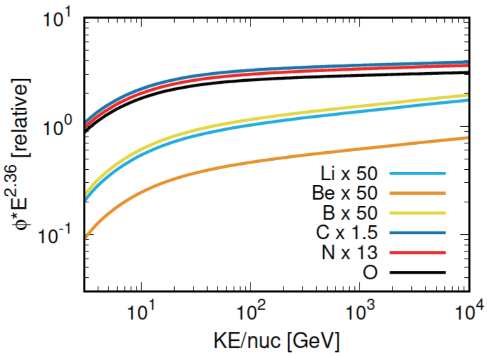

Fig. 3. Time integrated energy spectra of CR nuclei escaping the SNR surrounded by a wind-like ISM ($\dot{M} = 3 \times 10^{-3} M_\odot$ yr^{-1} and $v_{\rm w} = 100$ km s^{-1}).

To account for the AMS-02 results, where secondary CRs harden more than primaries at ~ 200 GV, we introduce the CR contribution from a past local SN. Especially, an SN with a wind-like CSM can make a harder secondary CRs, thus it is more relevant to adopt this type of an SN as a local CR source to reproduce the AMS-02 spectra. Figures 4 and 5 depict the observed spectra of primary CRs and secondary CRs, respectively. In making these plots, we assume a local SN with the age of 1.6×10^5 yr^{-1}, the distance of 1.6 kpc, the total energy of 10^{51} erg, the ejecta mass of $3M_\odot$, the mass loss rate of $2.5 \times 10^{3} M_\odot$ yr^{-1}, and the wind velocity of 100 km s^{-1}. Such an

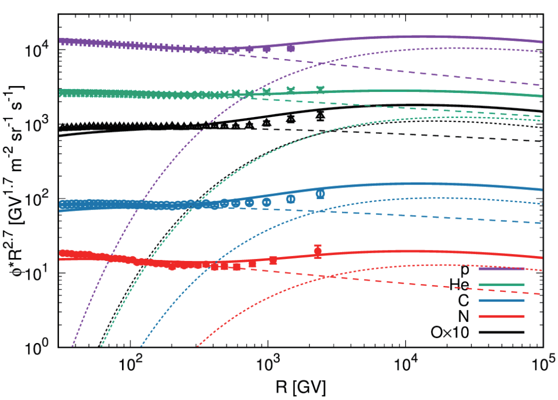

Fig. 4. Comparisons of our model spectra of CR protons, helium, carbon, nitrogen, and oxygen with AMS-02 data. The background fluxes (dashed lines) and the contributions from our hypothetical past SN (dotted lines) are also shown.

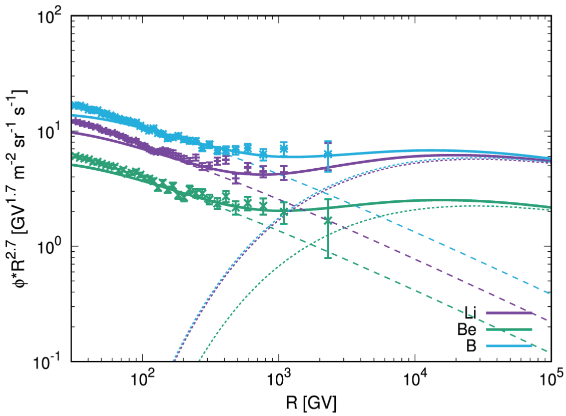

Fig. 5. Comparisons of our model spectra of CR lithium, beryllium, and boron with AMS-02 data. The background fluxes (dashed lines) and the contributions from our hypothetical past SN (dotted lines) are also shown.

SN may originate from the envelope stripping due to the binary interaction (*e.g.*, Roche lobe overflow). We can fit not only the spectra of primaries but also those of secondaries by taking into account the production, acceleration, and escape of secondary CRs inside a single SNR. We can test this model by the secondary-to-primary ratios (*e.g.*, boron-to-carbon ratio) at rigidity $\gtrsim$ 1 TeV (Fig. 6). In fact, the primary-to-secondary ratios would show flattening or rising with the energy within our scenario, and such a feature is never expected as long as we consider the ISM propagation effects as the origin of spectral hardening of CRs.

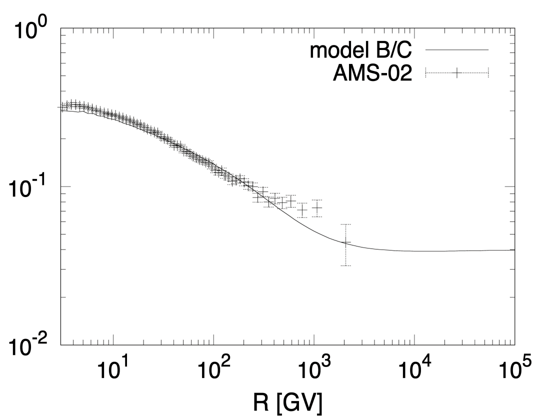

Fig. 6. Boron-to-carbon ratio in the observed CRs reported by AMS-02 along with our model prediction (solid line).

4. Summary

We investigated the effect of the production of secondary CR nuclei at an SNR by the DSA mechanism using an analytic approach. Taking into account the acceleration of secondary CRs and their escape, we predict their spectra and show that a local SN with a wind-like CSM can reproduce the AMS-02 spectra in which secondary CRs harden above $\sim$ 200 GV even more than primary CRs. Future CR measurements by next-generation experiments such as AMS-100 with an extended high energy range will put this to the test.

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