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Origin of Spectral Hardening and Softening of Secondary Cosmic-Ray Nuclei

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We discuss the production, acceleration, and escape of cosmic-ray (CR) nuclei in a supernova remnant (SNR). Especially, we take into account the spallation of CR nuclei inside the interstellar medium (ISM) or circumstellar medium (CSM) surrounding the SNR, as well as the acceleration and escape of secondarily produced CR nuclei such as Li, Be, and B. We find that if the SNR is surrounded by a dense CSM with a wind-like density profile ($\propto r^{-2}$), the spectra of the escaping secondary nuclei are harder than those of the escaping primary nuclei. If we consider the CRs from such an SNR located in the vicinity of the Earth ($\lesssim 2$ kpc) in addition to the average Galactic CRs, we can reproduce the spectral hardening of CRs around ~ 200 GV and softening around ~ 10 TeV, as well as the flattening of the B/C ratio above $\sim$ TeV/n.

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1. Introduction

It is widely believed that supernova remnants (SNRs) are the origin of Galactic cosmic-rays (CRs). Strictly speaking, SNRs are considered to accelerate primary CRs such as protons, helium, carbon, oxygen, and so on, via the diffusive shock acceleration (DSA) mechanism. On the other hand, secondary CRs such as lithium, beryllium, and boron, and so on, are produced via spallation of heavier primary CR nuclei during their propagation in the interstellar medium (ISM). According to this picture, the amount of secondary CR nuclei produced per primary CR nuclei should be proportional to the grammage traversed by the primaries until their escape from the Galaxy, and the observed CR spectra as well as the energy dependence of secondary-to-primary ratios are broadly consistent with this scenario.

However, thanks to AMS-02, DAMPE, and CALET, the fine structures of CR spectra are revealed with greater precision, which are significantly deviated from what the conventional scenario predicts. For example, the spectra of CR protons, helium, carbon, and oxygen nuclei show hardenings above $\sim$ 200 GeV [1–5]. Similar hardenings are observed also in the spectra of secondary CR nuclei by AMS-02 [6]. What is remarkable in the secondary nuclei hardenings is that their spectra harden above $\sim$ 200 GeV even more than the primary CRs. Recently, the CR proton and helium spectra in the energy range of $\gtrsim$ TeV have been investigated in detail by DAMPE and CALET, and it is shown that they are softened above $\sim$ 10 TeV [7–10]. As for secondary CRs, the boron-to-carbon ratio in the $\gtrsim$ 100 GeV range has been investigated by DAMPE and CALET, and it is suggested that its energy dependence shows a slight hardening above $\sim$ 100 GeV/n [11, 12]. Several scenarios have been discussed to account for these anomalies: the effect of propagation, reacceleration of secondary CRs, contribution from different kinds of sources, etc. In this work, we propose a scenario to account for the spectral hardening and softening simultaneously by assuming a local CR source (i.e., SNR), in which not only primary but also secondary CRs are produced and accelerated. How the model with a local SNR can explain the observed CR structures can be understood in the following way: the observed CRs consist of the superposition of the background CRs coming from the entire Galaxy, whose energy spectra are well-approximated by a single power-law, and the CRs from a nearby SNR, which appear in the observed CR spectra as a bumpy structure (i.e., the combination of hardening in the lower energy and softening in the higher energy). In the following sections we describe our model and the results (for the detail of our model, see [13]).

2. Model

In the context of the diffusive shock acceleration theory [14], particles in the vicinity of the shock front are scattered by the turbulent magnetic field and, going back and forth across the shock, they would gain more energy. During the acceleration of primary CRs, they can interact with ambient medium and produce secondary CRs by spallation. If these secondaries have energetic enough to cross the shock front diffusively, they also can be accelerated as primaries. Although such processes have already been discussed in some papers [15, 16], their energy-dependent escape into the interstellar space 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 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, respectively. From numerical MHD calculations, it had been shown that l should be the same order as the radius of the SNR, $R_{\rm sh}$. Since D, $u_{\rm sh}$, and $R_{\rm sh}$ evolve with time, the condition (1) is not only energy-dependent but also time-dependent. In the next subsection, we describe the equations to derive the distribution functions of primary and secondary CRs taking into account this condition.

2.1 Equations

Hereafter 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

$$\begin{aligned} u(x)\frac{\partial f_i}{\partial x} &= \frac{\partial}{\partial x}\left[D_i(p)\frac{\partial f_i}{\partial x}\right] + \frac{p}{3}\frac{du}{dx}\frac{\partial f_i}{\partial p} \\ &\quad -\Gamma_i f_i + q_i + u_- Q_i \delta(x)\delta(p - p_0), \end{aligned} \tag{2}$$

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 a nuclei i with momentum p, Γ_i is the total spallation rate of a nuclei i, q_i is the source term due to the spallation of parent nuclei, and Q_i is the injection rate of a nuclei i at the shock front (the injection momentum is p_0). In solving these equations, we impose a boundary condition for the free escape of CR particles from the outer boundary, i.e.,

$$\lim_{x \to -l} f_i = 0. \tag{3}$$

We here focus on the CR nuclei of proton, helium, lithium, beryllium, boron, carbon, nitrogen, and oxygen. We solve eight 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 evolve with time. Note that, as for secondary CR nuclei (Li, Be and B) the injection term Q_i should be zero.

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. Fig. 1 depicts the schematic picture of our scenario.

3. Results

In the following results, we adopt the phenomenological model proposed by [17] 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 Sedov phase, and at the later time the threshold energy for a CR particle to escape the SNR decreases gradually.

Fig. 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

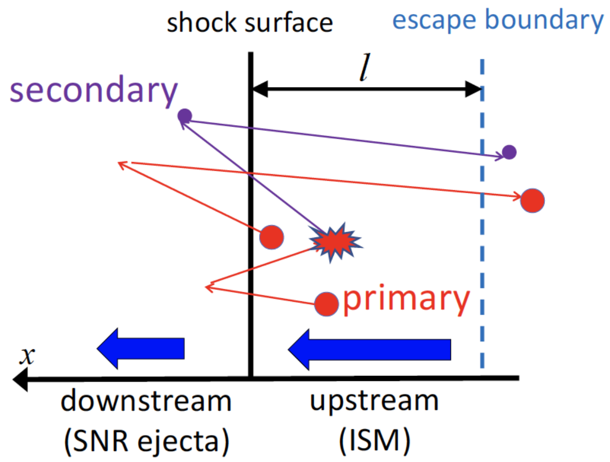

Figure 1: Schematic picture of secondary CR production, acceleration, and escape processes in our scenario. Here l is the distance from the shock surface to the escape boundary in the upstream.

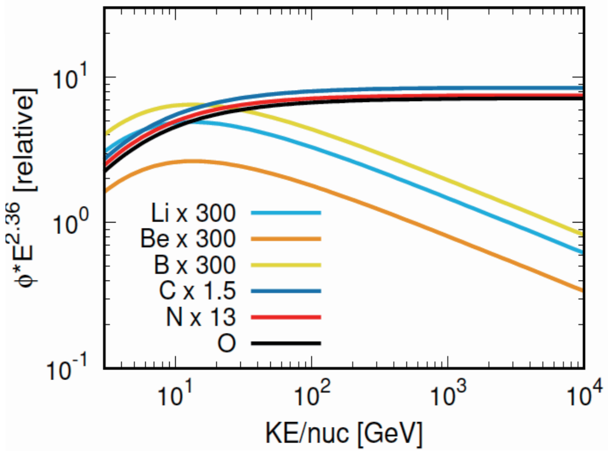

Figure 2: Time integrated energy spectra of CR nuclei escaping the SNR surrounded by a uniform ISM (n = 0.1 cm^{-3}).

result can be interpreted in the following way. In our scenario higher energy CRs can escape the SNR at earlier times, so they have shorter time to interact with ambient medium to produce secondary CRs. Therefore, the number of secondary CRs with higher energy would be smaller than those with lower energy, which have a long time enough to produce secondaries before the escape. This means that the spectra of secondary CRs would be steeper than those of primary CRs.

However, the situation is different in the case with a wind-like CSM. Fig. 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, by contrast with the previous case, the spectra of secondaries are harder than those of primaries. This can be interpreted in the following way. Since the density of the ambient medium is higher in the inner region, higher energy primaries, which would escape the shock when the SNR radius is still small, have more chance to interact with the CSM and produce many secondaries even if the interaction timescale is shorter. As a result, the number of secondary CRs with higher energy

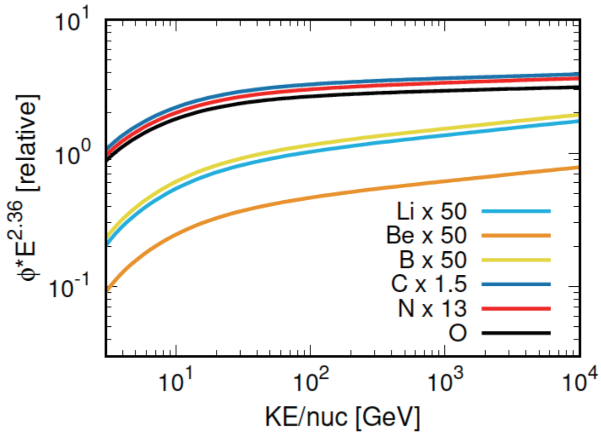

Figure 3: Time integrated energy spectra of CR nuclei escaping the SNR surrounded by a wind-like ISM ($\dot{M} = 3 \times 10^{-3} M_\odot$ yr^{-1} and $v_w = 100$ km s^{-1}).

would be larger than those with lower energy, which makes the spectra of secondaries harder than those of primaries.

Based on the results shown above, we propose that the hardening and softening observed in CR spectra are produced by the contribution from a local supernova that exploded in a dense CSM. As stated above, a local CR source contribution on top of the background CR flux can naturally reproduce the hardening at a lower energy and the softening at a higher energy simultaneously. Moreover, a SN with a wind-like CSM can make a harder secondary CRs, so it is more relevant to assume this type of an SN as a local CR source to reproduce the observed spectra. Fig. 4 depicts the observed spectra of CR protons and helium predicted from our model. We also plot the observation data by AMS-02, CALET, and DAMPE. Here 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}. We can see that our model can fairly reproduce the recent observations. Fig. 5 depicts the observed spectra of CR carbon and oxygen, and show that there should be spectral softening at ~ a few 10 TeV in these spectra, which is one of the predictions of our model. Fig. 7 depicts the secondary CR spectra predicted from our model, and one can see that our model can fairly reproduce the spectral hardening of secondaries reported by AMS-02. Fig. 8 depicts the boron-to-carbon ratio predicted from our model, which shows flattening above ~ TeV. Actually we predicted this tendency well before the B/C results are reported by DAMPE and CALET [13], and one can see that our prediction is fairly consistent with recent DAMPE and CALET results.

To conclude, 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 local SNR surrounded by a dense CSM.

4. Summary

We investigated the effect of the production of primary and secondary CR nuclei at an SNR surrounded by the ISM or CSM, and predict the observed CR spectra expected when such an

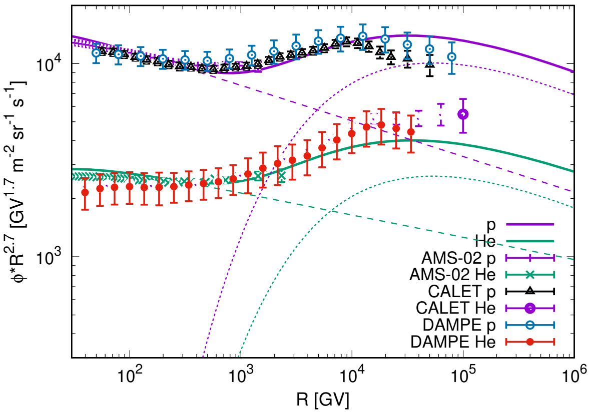

Figure 4: Comparisons of our model spectra of CR protons and helium with AMS-02, DAMPE, and CALET data. The background fluxes (dashed lines) and the contributions from our hypothetical past SN (dotted lines) are also shown.

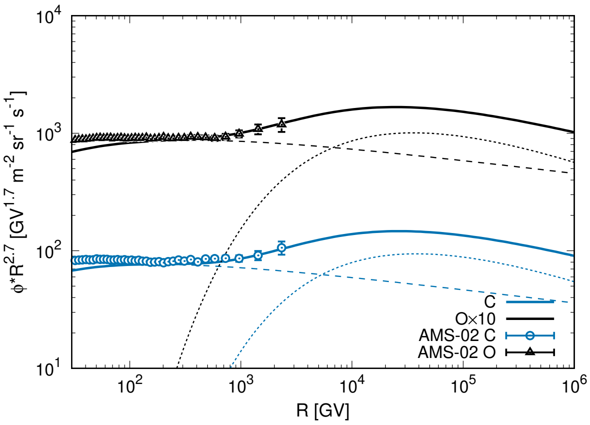

Figure 5: Comparisons of our model spectra of CR carbon and oxygen with AMS-02 data. The background fluxes (dashed lines) and the contributions from our hypothetical past SN (dotted lines) are also shown.

SNR is located in the vicinity of the Earth. Taking into account the acceleration of primary and secondary CRs and their escape, we predict their spectra being hardening around $\sim$ 200 GeV and softening around $\sim$ 10 TeV, and show that a local SNR with a wind-like CSM can reproduce the spectra measured by AMS-02/DAMPE/CALET in which secondary CRs harden above $\sim$ 200 GV even more than primary CRs. Future CR measurements by next-generation experiments with an extended high energy range will put this to the test.

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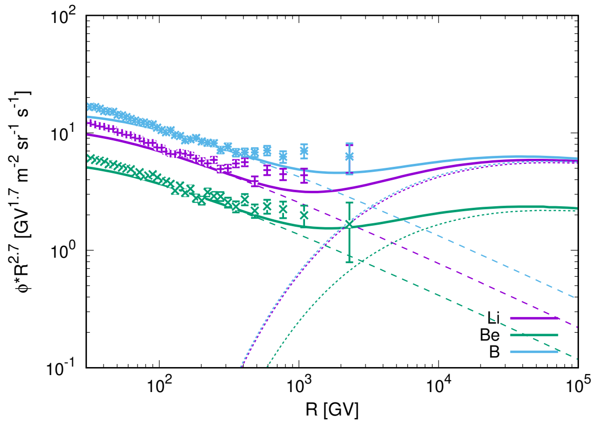

Figure 6: Comparisons of our model spectra of CR lithium, beryllium and boron with AMS-02 data. The background fluxes (dashed lines) and the contributions from our hypothetical past SN (dotted lines) are also shown.

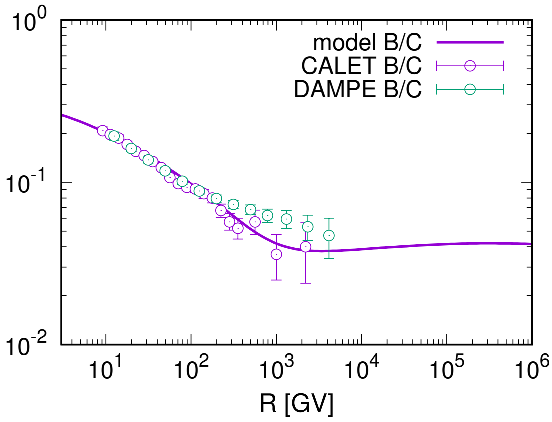

Figure 7: Boron-to-carbon ratio in the observed CRs reported by DAMPE and CALET along with our model prediction (solid line).

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