Cosmic-ray helium hardening

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Abstract: Recent observations by the ATIC-2, CREAM and PAMELA experiments suggest that the spectrum of cosmic-ray (CR) helium is harder than that of CR protons below the knee energy and all CR spectra become hard at 100 GeV/nucleon. According to DSA theory, the spectrum of accelerated particles at a shock does not depend on CR elements, but depends only on the velocity profile of the shock. Thus, naively, recent CR observations seem to show that the acceleration site of CR helium is different from that of CR protons. We propose a new idea, that higher energy CRs are generated in a more helium-rich region, to explain the hardening without introducing different sources for CR helium. We argue that CRs are produced in a chemically enriched region, such as a superbubble, and the outward-decreasing abundance naturally leads to the hard spectrum of CR helium if CRs escape from the supernova remnant shock in an energy-dependent way. Our idea uses the fact that CRs escaping from SNRs generally have a different spectrum than those of the acceleration site. The runaway CR spectrum depends not only on the acceleration spectrum at shocks but also on the evolution of the maximum energy and the number of accelerated CRs. We also suggest that the spectral hardening of CRs is caused by the decreasing Mach number in the high-temperature medium. Both the inhomogeneous abundance and the high temperature can be realized in the hot superbubbles with multiple supernovae.

Keywords: cosmic ray—supernova remnant—superbubble

1 Introduction

The origin of cosmic rays (CRs) is a longstanding problem in astrophysics. Recently, CREAM has directly observed the CR compositions with high statistics in the wide energy range up to about 10^{14} eV. Interestingly, CREAM shows that the spectrum of CR helium is harder than that of CR protons and all CR spectra become hard at 10^{11} $\mathrm{eV/n}$ [3]. These results obtained also by ATIC-2 [25] and PAMELA [2].

Supernova remnants (SNRs) are thought as the origin of the Galactic CRs. The most popular SNR acceleration mechanism is the diffusive shock acceleration (DSA) [6, 7]. In fact, *Fermi* and *AGILE* show that middle-age SNRs interacting with molecular clouds emit gamma-rays [1, 29] and the gamma-ray observations support that SNRs produce the bulk of Galactic CRs [22].

According to DSA theory, the spectrum of accelerated particles at a shock does not depend on CR elements. Thus, naively, recent CR observations seem to show that the acceleration site of CR helium is different from that of CR proton. In this paper, considering the inhomogeneous abundance region, we provide a new explanation about the different spectrum of CR proton and helium, even if CR proton and helium are accelerated simultaneously. Our idea uses the fact that CRs escaping from SNRs generally have a different spectrum than that of the acceleration site [19]. The escape of CRs and emission by escaping CRs recently have been under intense investigation [8, 9, 10, 19, 21, 22, 23, 24, 26]. The runaway CR spectrum depends on not only the acceleration spectrum at shocks but also the evolution of the maximum energy and the number of accelerated CRs [19]. We also suggest that the spectral hardening of CRs is caused by the decreasing Mach number in the high temperature medium. Both the inhomogeneous abundance and the high temperature can be realized in the superbubbles with multiple supernovae.

2 Runaway CR spectrum

In this section, we briefly review the runaway CR spectrum (see [19, 21]). We here use a variable χ (for example the shock radius or the SNR age) to describe the evolution of an SNR. Let $F_{\rm SNR}(\chi, p)$ and $p_{\rm max}(\chi)$ be the CR momentum spectrum [$(\mathrm{eV}/c)^{-1}$] and the maximum four momentum of CR inside the SNR at a certain epoch labeled by χ, respectively. CRs escape in order, from the maximum energy CR because the diffusion length of high-energy CRs is larger than that of low-energy CRs. Then, the number of runaway CRs between χ and $\chi + \mathrm{d}\chi$ is

$$F_{\rm SNR}(\chi, p_{\rm max}) \frac{\mathrm{d}p_{\rm max}}{\mathrm{d}\chi} \mathrm{d}\chi \ , \qquad (1)$$

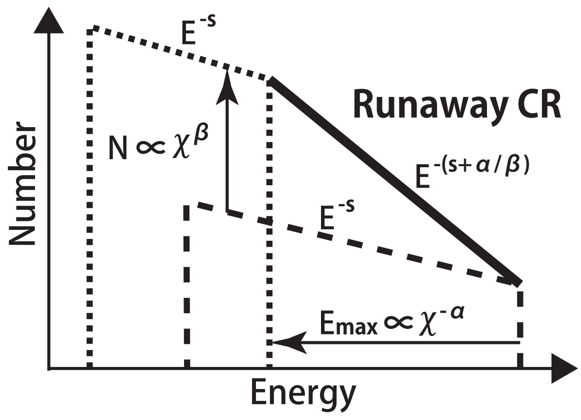

Figure 1: Schematic picture of the runaway CR spectrum. The solid, dashed and dotted lines show the runaway CR spectrum, CR spectrum inside an SNR at an early epoch and CR spectrum inside the SNR at a later epoch, respectively. The solid line of the runaway CR spectrum represents the equation (3). A variable χ (e.g., the shock radius) describes the SNR evolution.

which corresponds to the number of runaway CRs between $p = p_{\rm max}(\chi)$ and $p = p_{\rm max}(\chi) + {\rm d}p$, $F_{\rm esc}(p){\rm d}p$. Hence, $F_{\rm esc}(p)$ is

$$F_{\rm esc}(p) = F_{\rm SNR}(p_{\rm max}^{-1}(p), p) \ , \quad (2)$$

where $p_{\rm max}^{-1}(p)$ is the inverse function of $p_{\rm max}(\chi)$. Assuming $F_{\rm SNR}(\chi, p) \propto \chi^{\beta} p^{-s}$ and $p_{\rm max}(\chi) \propto \chi^{-\alpha}$, we obtain the runaway CR spectrum as

$$F_{\rm esc}(p) \propto p^{-\left(s+\frac{\beta}{\alpha}\right)} \ , \quad (3)$$

where α and β are parameters to describe the evolution of maximum energy and the number of accelerated CRs, respectively. (We use $\alpha \sim 6.5$ and $\beta \sim 1.5$ later.) Therefore, the runaway CR spectrum $F_{\rm esc}$ is different from that in the SNR $F_{\rm SNR} \propto p^{-s}$. Figure 1 shows the schematic picture of the runaway CR spectrum. In this paper, we use the shock radius, $R_{\rm sh}$, as χ.

The evolution of the maximum energy of CRs at the SNR has not been understood. This strongly depends on the evolution of the magnetic field around the shock. Although magnetic field amplifications have been investigated by simulations [11, 17, 16, 27], the evolution of the magnetic field has not been completely understood yet. Here we assume that CRs with the knee energy escape at $R = R_{\rm Sedov}$, where $R_{\rm Sedov}$ is the shock radius at the beginning of the Sedov phase. Furthermore, we use the phenomenological approach with the power-law dependence [10, 20],

$$p_{\rm max}(R_{\rm sh}) = p_{\rm knee} Z \left(\frac{R_{\rm sh}}{R_{\rm Sedov}}\right)^{-\alpha} \ , \quad (4)$$

where $p_{\rm knee} = 10^{15.5}$ eV$/c$ is the four momentum of the knee energy.

The evolution of the number of CRs inside the SNR has not been also understood. This depends on the injection mechanism [19] and the density profile around the SNR. We here adopt the thermal leakage model [15] as an injection model. For the total density profile, $\rho_{\rm tot}(R_{\rm sh}) \approx m_{\rm p}\left(n_{\rm p}(R_{\rm sh}) + 4n_{\rm He}(R_{\rm sh})\right)$ where $n_{\rm p}$ and $n_{\rm He}$ are the number density of proton and helium and $m_{\rm p}$ is the proton mass, the shock velocity of the Sedov phase is

$$u_{\rm sh}(R_{\rm sh}) \propto \rho_{\rm tot}(R_{\rm sh})^{-\frac{1}{2}} R_{\rm sh}^{-\frac{3}{2}} \ . \quad (5)$$

In the thermal leakage model, the injection momentum of element i is proportional to the shock velocity, $p_{{\rm inj},i} \propto u_{\rm sh}$, and the number density of CR with momentum $p_{{\rm inj},i}$ is proportional to the density, $p_{{\rm inj},i}^3 f_i(p_{{\rm inj},i}) \propto n_i(R_{\rm sh})$, where f_i is the distribution function of CR element i. Hence, the number of CR element i with a reference momentum $p = m_{\rm p}c$, $F_{{\rm SNR},i}(R_{\rm sh}, m_{\rm p}c)$ is

$$\begin{aligned} F_{{\rm SNR},i}(R_{\rm sh}, m_{\rm p}c) &\propto R_{\rm sh}^3 f_i(m_{\rm p}c) \\ &\propto R_{\rm sh}^3 p_{{\rm inj},i}^{s+2} f_i(p_{{\rm inj},i}) \\ &\propto R_{\rm sh}^3 n_i(R_{\rm sh}) p_{{\rm inj},i}^{s-1} \\ &\propto n_i(R_{\rm sh}) \rho_{\rm tot}(R_{\rm sh})^{\frac{1-s}{2}} R_{\rm sh}^{\frac{3(3-s)}{2}} \end{aligned} \quad (6)$$

where $f_i(p)p^2 \propto p^{-s}$. Because $n_i(R_{\rm sh})\rho_{\rm tot}(R_{\rm sh})^{\frac{1-s}{2}}$ is not always a single power-law form, the evolution of the number of accelerated CRs can not be always described by a constant β in this case.

3 Basic idea

3.1 Different spectrum of CR proton and helium

According to the test particle DSA theory, the index s of relativistic CR energy spectrum depends only on the velocity jump at the shock,

$$s = \frac{u_1 + 2u_2}{u_1 - u_2} = 2\frac{M^2 + 1}{M^2 - 1} \ , \quad (7)$$

where we use the Rankine-Hugoniot relation at the second equation and M is the Mach number. Then, the index of the runaway CR spectrum, $s_{\rm esc}$, is

$$s_{\rm esc} = s + \frac{\beta}{\alpha} \ , \quad (8)$$

in equation (3). Therefore, if β/α (in particular β, the index for the accelerated CR number evolution) is different, the runaway CR spectrum is different between the CR compositions. This is our main idea to explain the helium hardening observed by CREAM, ATIC-2, and PAMELA. From equation (6), β depends on the ambient number density n_i. Therefore, different density profiles make different runaway CR spectra (See Section 4 for more details). Figure 2 shows the schematic picture of our idea.

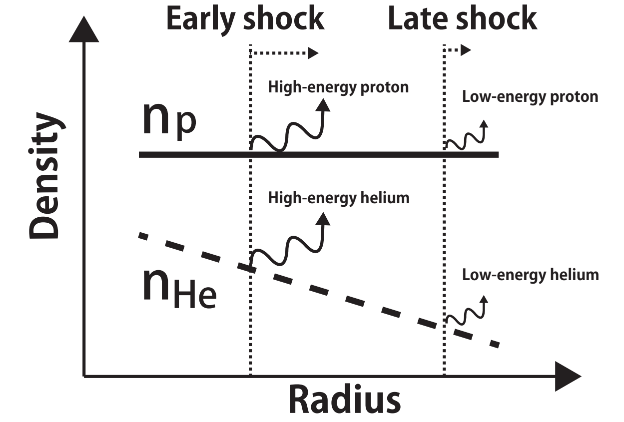

Figure 2: Schematic picture of the formation of the different spectrum. The solid and dashed line show the proton density and the helium density, respectively. The dotted lines show the shock front. In early phase, high-energy CR proton and CR helium escape, and in late phase, low-energy CR proton and CR helium escape. The ratio of CR helium to CR proton increases with the CR energy.

3.2 Spectral hardening of all CRs at the same energy per nucleon

In this subsection, we discuss the spectral hardening of the observed CRs. The Galactic CR spectrum observed at the Earth, $F_{\rm obs}$, is obtained by the simple leaky box model

$$F_{\rm obs} \propto F_{\rm esc}(p)/D(p) \propto F_{\rm esc}(p)p^{-\gamma} \ , \qquad (9)$$

where $D(p) \propto p^{\gamma}$ is the diffusion coefficient [28]. Hence, the index of the observed spectrum is

$$s_{\rm obs} = s + \frac{\beta}{\alpha} + \gamma \ . \qquad (10)$$

The deviation from a single power law means that at least one of s, α, β, and γ has an energy dependence or that the origin of low energy CRs below 10^{11} eV is different from that of high energy CRs above 10^{11} eV.

In this paper, we discuss only the energy dependence of s. From equation (7), s depends on the shock radius because the Mach number M decreases with the shock radius. Then we can expect the spectral harding of all CR compositions at the same rigidity cp/Ze, that is, at approximately the same energy per nucleon. From equation (5), the Mach number is

$$M \approx 10^3 \left(\frac{\rho_{\rm tot}(R_{\rm sh})}{\rho_{\rm tot}(R_{\rm Sedov})}\right)^{-\frac{1}{2}} \left(\frac{T}{10^4\ {\rm K}}\right)^{-\frac{1}{2}} \left(\frac{R_{\rm sh}}{R_{\rm Sedov}}\right)^{-\frac{3}{2}} , \qquad (11)$$

where T is the surrounding temperature and we assume that the ejecta mass and the energy of supernova explosion are $1\ {\rm M}_{\odot}$ and 10^{51} erg, respectively. From equations (4), (7) and (11), we can obtain s as a function of p (see § 4).

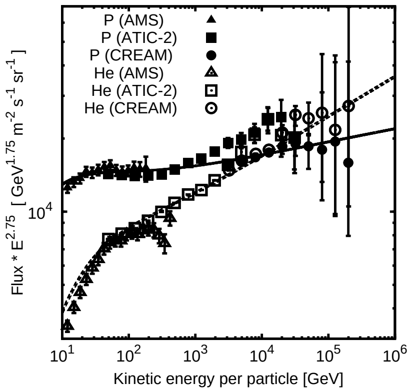

Figure 3: Comparison of our model [21] (solid and dashed line) with AMS (triangle) [4, 5], ATIC-2 (square) [25] and CREAM (circle) [3] observations for Galactic CRs. Filled symbols and the solid line show CR proton. Open symbols and the dashed line show CR helium.

4 Comparison of our model with observations

In this section, specifying model parameters, we calculate the Galactic CR spectrum. For simplicity, we here assume the number densities of proton and helium as follows,

$$\begin{aligned} n_{\rm p}(R_{\rm sh}) &= n_{\rm p,0} \\ n_{\rm He}(R_{\rm sh}) &= \zeta n_{\rm p,0}\left(\frac{R_{\rm sh}}{R_{\rm Sedov}}\right)^{-\delta} \ , \end{aligned} \qquad (12)$$

where $n_{\rm p,0}$ is the number density of proton at $R_{\rm sh} = R_{\rm Sedov}$, and $\zeta n_{\rm p,0}$ is the normalization factor of the helium density. We set $\zeta = 10^{6.5(\delta/\alpha)-1}$ so that the helium abundance is that of the solar abundance, $n_{\rm He}/n_{\rm p} = 0.1$ (i.e., $Y \approx 0.25$), when $cp_{\rm max} = Z$ GeV with equation (4). Note that the power-law dependence is a first step approximation for the mean value. Then, from equations (2), (4), (6), (9), observed spectra of CR proton and helium are

$$\begin{aligned} F_{\rm obs,p} &= F_{\rm p,knee}\left\{\frac{1+\zeta\,(p/p_{\rm knee})^{\frac{\delta}{\alpha}}}{1+\zeta}\right\}^{\frac{1-s(p)}{2}} \\ &\quad \times \left(\frac{p}{p_{\rm knee}}\right)^{-\left[s(p)+\frac{3\{3-s(p)\}}{2\alpha}+\gamma\right]} , \qquad (13) \\ F_{\rm obs,He} &= \epsilon F_{\rm p,knee}\left\{\frac{1+\zeta\,(p/Zp_{\rm knee})^{\frac{\delta}{\alpha}}}{1+\zeta}\right\}^{\frac{1-s(p)}{2}} \\ &\quad \times \left(\frac{p}{Zp_{\rm knee}}\right)^{-\left[s(p)+\frac{3\{3-s(p)\}-2\delta}{2\alpha}+\gamma\right]} , \qquad (14) \end{aligned}$$

where $F_{\rm p,knee}$ and $\epsilon F_{\rm p,knee}$ are normalization factors of CR proton and helium and $Z = 2$ for helium, and $s(p)$ is obtained from equations (4), (7) and (11). In this model, all parameters are α, γ, δ, ϵ, T, $F_{\rm p,knee}$.

Figure 3 shows the comparison of our model with observations. We take into account the solar modulation effects with the modulation potential $\Phi = 450$ MV. Our model is in excellent agreement with the observed spectra, with $\alpha = 6.5$, $\gamma = 0.43$, $\delta = 0.715$, $\epsilon = 0.31$, $T = 10^6$ K. The different spectra of CR proton and helium originate from the different density profiles in equations (12). The high temperature $T \sim 10^6$ K is necessary for the spectral hardening of CR protons and helium at 100 GeV/n.

5 Discussion

To make the different spectrum, our model requires that the helium abundance around the explosion center is higher than that of the solar abundance. SNRs in superbubbles are one of candidates. Higdon et al. (1998) show that supernova ejecta can dominate the superbubble mass within a core radius of one third of the superbubble radius [13]. In the stellar wind and the supernova explosion, the stellar hydrogen envelope has lower density and higher velocity than that of helium. Then we expect that the helium fraction in the center of superbubbles is higher than that in the outer region. Furthermore, to make the concave spectrum, our model requires an ambient medium with high temperature, $T = 10^6$ K. This is also consistent with superbubbles. According to the CR composition study, superbubbles have been considered as the origin of Galactic CRs [14].

The spatial variation of the helium ionization degree can also change the injection history [9]. The injection efficiency of the large rigidity is thought to be higher than that of low rigidity since particles with large rigidity can easily penetrate through the shock front from the downstream region. If the ionization degree increases with the SNR radius, the CR helium spectrum becomes harder than the CR proton one, $\beta_{\rm He} < \beta_{\rm p}$. However, the rigidity dependence of the injection efficiency has not been understood completely. Moreover, the injection from neutral particles should also be understood [18, 20].

6 Conclusion

Runway CR spectra depend on not only CR spectra inside the SNR but also the evolution of the maximum energy and the number of accelerated CRs. Therefore, taking account of the inhomogeneous abundance region, runaway CR spectra of different CR elements have different spectra.

Our model is in excellent agreement with observed spectra of CR proton and helium. Harder spectrum of CR helium is due to the enhancement of the helium abundance around the explosion center. On the other hand, the concave spectra of all CR elements are due to the decreasing Mach number in the hot gas with $\sim 10^6$ K. These results suggests that the origin of the Galactic CR is SNRs in superbubbles.

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References

[1] Abdo, A. A., et al., ApJ, 2009, **706**: L1-L6
[2] Adriani, O., et al., Science, 2011, **332**: 69-72
[3] Ahn, H. S., et. al., ApJ, 2010, **714**: L89-L93
[4] Alcaraz, J., et. al., Phys. Lett. B, 2000a, **490**: 27-35
[5] Alcaraz, J., et. al., Phys. Lett. B, 2000b, **494**: 193-202
[6] Bell, A. R., MNRAS, 1978, **182**: 147-156
[7] Blandford, R. D., Ostriker, J. P., ApJ, 1978, **221**: L29-L32
[8] Caprioli, D., et al., Astropart. Phys.,2010, **33**: 160-168
[9] Drury, L. O'C., 2010, arXiv:1009.4799
[10] Gabici, S., et al., MNRAS, 2009, **369**: 1629-1639
[11] Gargaté, L., et al, ApJ, 2010, **711**: L127-L132
[12] Giacalone, J. Jokipii, J. R., ApJ, 2007, **663**: L41-L44
[13] Higdon, J. C., et al, ApJ, 1998, **509**: L33-L36
[14] Lingenfelter, R. E., Higdon, J. C., ApJ, 2007, **660**: 330
[15] Malkov, M. A., Völk, H. J., A&A, 1995, **300**: 605-626
[16] Niemiec, J., et al., ApJ, 2008, **684**: 1174-1189
[17] Ohira, Y., et al., ApJ, 2009, **698**: 445-450
[18] Ohira, Y., et al., ApJ, 2009, **703**: L59-L62
[19] Ohira, Y., et al., A&A, 2010, **513**: A17
[20] Ohira, Y., Takahara, F., ApJ, 2010, **721**: L43-L47
[21] Ohira, Y., Ioka, K., ApJ, 2011, **513**: L13
[22] Ohira, Y., et al., MNRAS, 2011, **410**: 1577-1582
[23] Ohira, Y., et al., 2011, arXiv:1103.4140
[24] Ohira, Y., et al., 2011, arXiv:1106.1810
[25] Panov, A. D., et al., Bull. Russ. Acad. Sci.: Phys., 2009, **73**: 564-567
[26] Ptuskin, V. S., Zirakashvili, V. N., A&A, 2005, **429**: 755-765
[27] Riquelme, M. A., Spitkovsky, A., ApJ, 2009, **694**: 624-642
[28] Strong, A.W., et al., Annu. Rev. Nucl. Part. Sci., 2007, **57**: 285-327
[29] Tavani, M., et al., ApJ, 2010, **710**: L151-L155