ORIGIN OF THE COSMIC-RAY SPECTRAL HARDENING

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ABSTRACT

Recent data from ATIC, CREAM, and PAMELA indicate that the cosmic-ray energy spectra of protons and nuclei exhibit a remarkable hardening at energies above 100 GeV nucleon\(^{-1}\). We propose that the hardening is an interstellar propagation effect that originates from a spatial change of the cosmic-ray transport properties in different regions of the Galaxy. The key hypothesis is that the diffusion coefficient is not separable into energy and space variables as usually assumed. Under this scenario, we can reproduce the observational data well. Our model has several implications for cosmic-ray acceleration/propagation physics and can be tested by ongoing experiments such as the Alpha Magnetic Spectrometer or Fermi-LAT.

Key words: acceleration of particles – cosmic rays – diffusion – turbulence

Online-only material: color figures

1. INTRODUCTION

Understanding the spectral features in cosmic rays (CRs) is of fundamental importance for any theory of their origin and propagation. The spectrum of CR nuclei above \(\sim 10\) GeV nucleon\(^{-1}\) is thought to be the result of acceleration mechanisms in supernova remnants (SNRs), which is steepened by propagation in the interstellar medium (ISM) due to leakage from the Galaxy (Strong et al. 2007). The acceleration of primary CRs is described by the diffusive shock acceleration (DSA) theory that predicts power-law spectra \(Q \propto E^{-\nu}\) with slope \(\nu \approx 2\)–2.2. The CR transport in the turbulent magnetic fields is modeled as a diffusion process, with coefficient \(K \propto E^\delta\), into a magnetic halo of typical height \(2L \sim 10\) kpc. Interactions of CRs with the ISM give rise to secondary nuclei such as Li–Be–B. This description predicts power-law spectra such as \(E^{-\nu-\delta}\) for primary nuclei (e.g., H, He) and \(E^{-\delta}\) for secondary-to-primary ratios (e.g., B/C). The parameters \(\nu\) and \(\delta\) are not firmly predicted a priori and can be inferred from the data. Observations constrain \(\nu + \delta \approx 2.7\) (depending on the element) and \(\delta \sim 0.3\)–0.7, whereby \(\nu \sim 2\)–2.4. Yet this picture dramatically overpredicts the CR anisotropy at \(\gtrsim \)TeV energies, which would suggest an almost energy-independent diffusivity. Although the CR flux may also be affected by stochasticity effects on SNR events (Blasi & Amato 2012b), the high degree of isotropy observed in CRs poses a serious challenge to the conventional approach to the CR propagation. Even more dramatically, the CR spectra at \(E > 100\) GeV nucleon\(^{-1}\) exhibit a remarkable hardening with increasing energies. This feature has been established by recent experiments ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010), and PAMELA (Adriani et al. 2011), though the data are a little discrepant from each other. The proposed explanations interpret the hardening as a source effect connected with acceleration mechanisms (Biermann et al. 2010), nearby SNRs (Thoudam & Hörandel 2012), or arising by different populations of CR sources (Zatsepin & Sokolskaya 2006; Yuan et al. 2011). The subsequent impact of the hardening on the secondary CR production was estimated by Lavalle (2011) for \(e^\pm\), Donato & Serpico (2011) for \(\gamma\) rays, and Vladimirov et al. (2011) for light nuclei. The latter also considered a possible diffusive origin of the effect, described by means of an effective break in the slope of \(K(E)\), around \(\sim 200\) GeV nucleon\(^{-1}\), from \(\delta \approx 0.3\) to \(\delta \approx 0.15\).

Contrary to these works, we propose that the hardening originates from a spatial change of the CR diffusion properties in the different regions of the Galaxy. In fact, propagation studies assume that CRs experience the same type of diffusion in the whole propagation region, with only a few exceptions for particular environments (e.g., in SNR shells or inside the heliosphere) that are treated separately. A more realistic position-dependent diffusivity (correlated with the SNR density) is considered in some works (e.g., Shibata et al. 2004; Gebauer & de Boer 2009; Di Bernardo et al. 2010), but they still adopt a unique energy dependence for \(K\) in the whole halo, which leads to essentially unchanged results for the shapes of CR spectra at Earth. Such descriptions may represent an oversimplification of the problem. In theoretical considerations, the diffusion is caused by the CR scattering on hydromagnetic waves, which, in turn, depends on the nature and scale distribution of the magnetic-field irregularities. While SNR explosions may generate large irregularities in the region near the Galactic plane, the situation in the outer halo is much different because there are no SNRs. The main source of turbulent motion in the halo is presumably represented by CRs themselves. From these considerations, Erlykin & Wolfendale (2002) found that the turbulence spectrum in the halo (in the far outer Galaxy) should be flatter than that in the plane (in the inner Galaxy). This implies strong latitudinal changes (gradual radial changes) for the parameter \(\delta\) and suggests spectral variations of CRs throughout the Galaxy. Noticeably, new data reported by the Fermi Large Area Telescope (LAT) on the diffuse \(\gamma\)-ray emission at \(10\)–100 GeV of energy seem to support these suggestions. The \(\gamma\)-ray spectra observed near the Galactic plane (latitude \(|b| < 8^\circ\)) are found to be harder than those at higher latitudes, and similar differences are also found between the inner Galaxy (longitude \(l < 80^\circ\) or \(l > 280^\circ\)) and the outer Galaxy (Ackermann et al. 2012).

In this Letter, we focus our attention on the latitudinal changes of the CR diffusion properties (which are expected to be more extreme) and we show that they inevitably lead to a pronounced hardening for the energy spectra of CR nuclei at Earth. Using analytical calculations, we
examine the implications of this scenario for the main CR observables—primary spectra, secondary-to-primary ratios, and latitudinal anisotropy—and discuss its connections with the open problems in the CR acceleration/propagation physics.

2. CALCULATIONS

We use a simple model of CR diffusion and nuclear interactions. The effects of energy changes and convection are disregarded. The Galaxy is modeled to be a disk, with half-thickness $h$, containing the interstellar gas (number density $n$) and the CR sources. The disk is surrounded by a diffusive halo of half-thickness $L$ and zero matter density. For simplicity we give a one-dimensional description (infinite disk radius) in the thin disk limit ($h \ll L$) and we restrict to stable species. For each CR nucleus, the transport equation reads

$$\frac{dN}{dt} = \frac{d}{dz} \left( K(z) \frac{dN}{dz} \right) - 2h\delta(z)\Gamma^{\text{inel}} N + 2h\delta(z)Q,$$

(1)

where $N(z)$ is its number density as function of the $z$-coordinate, $K(z)$ is the position-dependent diffusion coefficient, and $\Gamma^{\text{inel}} = \beta c n \sigma^{\text{inel}}$ is the destruction rate in the ISM at velocity $\beta c$ and cross section $\sigma^{\text{inel}}$. The source term $Q$ can be split into a primary term $Q_{\text{pri}}$, from SNRs, and a secondary production term $Q_{\text{sec}} = \sum_j \Gamma_j N_j$ from spallation of heavier ($j$) nuclei with rate $\Gamma_j$. The quantities $N, K, Q,$ and $\Gamma^{\text{inel}}$ depend on energy $E$. Since no energy changes are considered, such a dependence is only implicit and can be ignored for the moment. To solve Equation (1) we assume steady-state conditions ($dN/dt = 0$). We define $\alpha(z) := K'/K$, $\alpha_2 := -2h\Gamma^{\text{inel}}/K_0$, and $\alpha_3 := 2hQ/K_0$, where we have denoted $K' = \partial K/\partial z$ and $K_0 = K(z=0)$. In the halo ($z \ll 0$) the equation reads $\alpha_2N + \alpha_3N' = 0$, which is readily solved as $N_{\pm}(z) = p_\pm + u_\pm \lambda(z)$, where the subscripts $\mp$ indicate the solutions in the $z \lesssim 0$ half-planes. The function $\lambda(z)$ is defined as

$$\lambda(z) = \int_0^z e^{-|z'|^2 \alpha(z')} dz'.$$

(2)

The boundary conditions, $N(\pm L) = 0$, provide the relation $u_\pm = -p/\Lambda_{\pm}$, where $\Lambda_{\pm} := \lambda(\pm L)$. From the continuity condition in the disk, $N'(0) \equiv N_s(0)$, one obtains $p_+ = p_0$. Assuming that $K(z)$ is an even function, one can see that $\lambda(z)$ must be odd. Thus, we define $\lambda(z) \equiv \lambda(|z|)$ and $\Lambda \equiv \lambda(L)$, so that $u_{\pm} = \mp p/\Lambda$. To determine $p$, we integrate the transport equation in a thin region across the disk:

$$N'_s(e) - N'_s(-e) + \int_{-e}^{e} \alpha_1 N' dz + \alpha_2 N(0) + \alpha_3 = 0.$$  

(3)

The limit $e \to 0$ gives $p = \alpha_3/(2\Lambda^{-1} - \alpha_2)$. After replacing $\alpha_1, \alpha_2,$ and $\alpha_3$ with the original quantities, the solution reads

$$N(z) = \frac{Q}{k_0 \Lambda + \Gamma^{\text{inel}}} \left[ 1 - \frac{\lambda(z)}{\Lambda} \right].$$

(4)

The function $\lambda(z)$ can be expressed as

$$\lambda(z) = \int_0^{|z|} e^{-\int_{z'}^{|z|} K'/K dz'} dz' = K_0 \int_0^{|z|} \frac{dz}{K(z)}.$$  

(5)

From this toy model, one can recover the homogeneous diffusion model (HM) by setting $K' \equiv 0$, which gives $\lambda = |z|$ and $\Lambda = L$.

Simple models of inhomogeneous diffusion can be described by a diffusion coefficient of the type $K(z, E) \equiv f(z)K(E)$. For example, Di Bernardo et al. (2010) adopt $f(z) = e^{\gamma z}$, in this case one finds $\lambda = z(1 - e^{-|z|/\Lambda})$, where the limit $z_1 \gg L$ recovers the HM, and the limit $z_1 \ll L$ gives $\Lambda \approx z_1$. The latter case provides a more natural description of the latitudinal CR density profile, as it is insensitive to the halo boundaries $\pm L$. However, the model predictions in terms of CR spectra at Earth remain equivalent to those of the HM after a proper choice of $\Lambda$. This is a general property of Equation (5): as long as $K(z, E)$ is separable in $z$ and $E$, the function $\lambda$ is independent on energy and the spectra at $z = 0$ are equivalent to a mere rescaling of the model parameters. We remark that the energy–space variable separation is implicitly assumed in all CR propagation models.

Physically, it describes a unique diffusion regime in the whole halo, given by $K_0(E)$, while $f(z)$ allows for spatial variations in its normalization. The quantity $\Lambda$ can be regarded as an effective halo height experienced by CRs at equilibrium.

We now put into practice our hypothesis on the latitudinal variations of the CR diffusion properties, which implies that $K(z, E)$ is not separable as $f(z)K_0(E)$ everywhere. We follow the arguments given in Erlykin & Wolfendale (2002), but our aim is not to inspect the astrophysical plausibility of their suggestions. Rather, we consider a phenomenological scenario in order to illustrate the effect and its consequences for the main CR observables. We adopt a simple two-halo model (THM) consisting in two diffusive zones. The inner halo, representing the region influenced by SNRs, is taken to surround the disk for a typical size $\xi L$ of a few hundred pc ($\xi \sim 0.1$). The outer halo, representing a wider region where the turbulence is driven by CRs, is defined by $\xi L < |z| < L$. The diffusion coefficient is taken of the type

$$K(z, \rho) = \begin{cases} k_0 \beta \rho^\delta & \text{for } |z| < \xi L \text{ (inner halo)} \cr k_0 \beta \rho^{\delta+\Lambda} & \text{for } |z| > \xi L \text{ (outer halo)}. \end{cases}$$

(6)

That is, the effective halo height is a rigidity-dependent quantity that affects the model predictions at $z = 0$. This effect can be better understood if one neglects the term $\Gamma^{\text{inel}}$ and takes a source term $Q_{\text{pri}} \sim \rho^{-v}$. From Equations (4) and (7) one finds

$$N_0 \equiv N(z = 0) \sim \frac{L}{k_0} \left[ \xi \rho^{v-\delta} + (1 - \xi) \rho^{v-\delta-\Lambda} \right],$$

(8)

which describes the CR spectrum as a result of two components. Its differential log-slope as a function of rigidity reads

$$\gamma(\rho) = \frac{d \log N_0}{d \log \rho} \approx v + \delta + \frac{\Delta}{1 + \frac{\Delta}{1 - \xi} \rho^\Lambda},$$

(9)

which indicates a clear transition between two regimes. In practice, the low-energy regime ($\gamma \approx v + \delta + \Lambda$) is never
reached due to spallation (neglected in the above equations) that becomes relevant and even dominant over escape ($\Gamma_{\text{inel}} \gg (K_0/h \Lambda)$). In this case the log-slope is better approximated by $\gamma \sim v + (1/2)(\delta + \Delta)$ (Blasi & Amato 2012a). The hard high-energy regime ($\gamma \approx v + \delta$) is determined by the diffusion properties of the inner halo only, because the outer halo is characterized by a much faster particle leakage. In this limit one has $\Lambda \approx \xi L$. The effect vanishes at all rigidities when passing to the HM limit of $\xi \to 1$ (one halo) or $\Delta \to 0$ (identical halos), where one recovers the usual relation $\gamma = v + \delta$. Furthermore, from Equation (4), it can be seen that the intensity of the harder component diminishes gradually with increasing $|\gamma|$, i.e., the CR spectra at high energies are steeper in the outer halo.

3. RESULTS AND DISCUSSIONS

We compute the THM spectra at Earth by $J(E) = (\beta c/4\pi) N_0(E)$, from Equation (4), at kinetic energies above 10 GeV. The SNR energy spectra are taken as $Q_{\text{SNR}} = Y \beta^{-1} (R/R_0)^{-\gamma} e^{-R/R_{\max}}$, where $R_{\max}$ represents the maximum acceleration rigidity attainable by SNRs. The constants $Y$ are determined from the data at $\sim 100$ GeV nucleon$^{-1}$. The indices $v$ are taken as $Z$-dependent to account for the observed discrepancies among elements. Malkov et al. (2012) and Ohira & Ioka (2011) made strong argument for ascribing such discrepancies to SNRs. The ISM surface density is taken as $h \times n \approx 100$ pc $\times 1$ cm$^{-3}$. The two halos are defined by $L \approx 5$ kpc and $\xi L \approx 0.5$ kpc, but the physical parameters that enter the model are $K_0/L$ and $\xi$, where both quantities are also degenerated with $K_0$. Concerning the diffusion parameters, we consider two case studies: THMa ($\delta \approx 1/3$ and $\Delta \approx 0.55$) which adopts a Kolmogorov-type diffusion in the inner halo, and THMb ($\delta \approx 1/6$ and $\Delta \approx 0.55$) to test the extreme case of a very slow diffusivity. The main parameters are summarized in Table 1. The practical implementation of the model follows Tomassetti & Donato (2012); see also Maurin et al. (2001).

The energy spectra of H, He, CNO, and Fe are shown in Figure 1 in comparison with the data. Results are shown for THMb only (THMa and THMb predictions are indistinguishable for primary CRs). Our calculations (solid lines) are in good agreement with the data within their uncertainties. At low energies ($\lesssim 10$ GeV nucleon$^{-1}$) the solar modulation is apparent and it is described using a force-field modulation potential $\phi \approx 400$ MV (Gleeson & Axford 1968). Note, however, that our model may be inadequate in this energy region due to the low-energy approximations. At higher energies, our model reproduces the observed changes in slope well, in agreement with the trends indicated by the data. It should be noted, however, that the sharp spectral structures suggested by the PAMELA data at $\sim 300$ GeV cannot be recovered. The THM predictions are also compared with HM power-law extrapolations (dashed line) to better illustrate the differences. It can be seen that the spectral upturn is slightly less pronounced for elements with large mass $M$ such as Fe, due to the competing action of the term $\Gamma_{\text{inel}}$

| Table 1: Model Parameters |
|---------------------------|
| Parameters                | THMa        | THMb        |
| $v$ (H; He; CNO; Fe)      | 2.29; 2.17; 2.17; 2.20 | 2.43; 2.31; 2.31; 2.34 |
| $R_0$, $R_{\max}$         | 2 GV; 2.5 $\times$ 10$^6$ GV | 2 GV; 2.5 $\times$ 10$^6$ GV |
| $k_0/L$                   | 0.007 kpc Myr$^{-1}$ | 0.010 kpc Myr$^{-1}$ |
| $\delta$, $\Delta$, $\xi$ | 1/3; 0.55; 0.1 | 1/6; 0.55; 0.1 |

Figure 1. CR spectra for H, He, CNO, and Fe from our calculations and data as function of kinetic energy. The data are from PAMELA (Adriani et al. 2011), ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010; Yoon et al. 2011), JACEE (Asakimori et al. 1998), and KASCADE (Antoni et al. 2005).

(A color version of this figure is available in the online journal.)
below a few 100 GeV nucleon\(^{-1}\) (note that \(\Gamma_{\text{mel}} \propto M^{0.3}\)). Above \(\sim 100\) TeV nucleon\(^{-1}\), the elemental \textit{knees} are matched well using \(R_{\text{max}} = 2.5 \times 10^{6}\) GV, which is somewhat lower than that from HM-based estimates (Blasi & Amato 2012a). For instance, the HM spectra of Figure 1 (dashed lines) employ \(R_{\text{max}} = 7 \times 10^{6}\) GV.

A distinctive feature of our model is provided by the secondary-to-primary ratios. From Equation (4), neglecting \(\Gamma_{\text{mel}}\), it is easy to see that, roughly, secondary-to-primary ratios must harden as \(\propto \Lambda/K_0\). In Figure 2(a) we plot the B/C ratio. Remarkably, THMb describes the data well down to energies of 1 GeV nucleon\(^{-1}\), notwithstanding the low-energy approximations. Its low-energy behavior is very similar to that of HM, which uses \(\delta = 0.6\) in the whole halo. At energies above \(\sim 50\) GeV nucleon\(^{-1}\), THMb predicts a significant flattening for the B/C ratio, which is also suggested by recent data from TRACER. Similar conclusions can be drawn for THMAs. We also expect a similar trend (but less obvious) for the \(\overline{p}/p\) ratio, which should be flatter than that estimated in Donato & Servoli (2011). All these features can be tested by the upcoming Alpha Magnetic Spectrometer (AMS)\(^{1}\) data on elemental spectra (H to Fe) and nuclear ratios (B/C or \(\overline{p}/p\)). We remark that a multichannel study may be necessary to disentangle this effect from other possible processes; see, e.g., Tomassetti & Donato (2012).

The hardening of the B/C ratio is also connected with the anisotropy. This can be illustrated for the latitudinal component of the anisotropy, \(\eta_z\), which is due to the vertical outflow of CRs from the Galactic plane. It can be written as

\[
\eta_z(E) \approx \frac{3K_0(E) \zeta_0}{c\Lambda(E) h},
\]

where \(\zeta_0/h \approx 0.2\) (Jones et al. 2001, and references therein).

Figure 2(b) shows \(\eta_z(E)\) for the considered models compared with direct measurements of the anisotropy amplitude. Due to limitations implicit in Equation (10) as well as possible contributions from stochasticity (Blasi & Amato 2012b), the model comparison with the data is necessarily qualitative. We focus on the comparison among the models, which is more instructive. \(\eta_z\) increases with energy as \(\sim K_0/A\) (which is fixed by the B/C ratio and cannot be arbitrarily changed) so that the HM yields \(\eta_z \propto E^2\), whereas THMAs and THMbs predict a natural flattening of \(\eta_z\). In particular, THMb predicts a much lower anisotropy while keeping a good agreement with the B/C data at \(E < 100\) GeV nucleon\(^{-1}\). Its high-energy behavior \(\eta_z \propto E^{1/6}\) is similar to that of Scenario P in Vladimirov et al. (2011), but our model does not fall into any of their scenarios. It is interesting to note that the anisotropy may also be reduced at all energies if one accounts for a proper radial dependence for \(K\). This is shown in Evoli et al. (2012), who assumed a spatial correlation between diffusivity and SNR density. In our THMb model, the source spectra are fairly soft \((\nu \gtrsim 2.3)\) for the DSA requirements; however, they are not exceedingly soft according to recent calculations where the Alfvén speed of the scattering centers is accounted (Caprioli 2011). On the other hand, THMa gives a dependence \(\eta_z \propto E^{1/3}\) at high energies, but requires \(\nu \approx 2.2\), which agrees better with the basic DSA predictions. We recall that state-of-the-art models employ \(\nu \approx 2.4\) and \(\delta \approx 1/3\) (Strong et al. 2007) and require large amounts of reacceleration to match the B/C data. Besides, other B/C or \(\overline{p}/p\) combined analyses favor \(\delta \approx 1/2\) and smaller amounts of reacceleration (Di Bernardo et al. 2010). Within our scenario, the observed steepness of the low-energy B/C ratio shares the same origin of the high-energy hardening of the primary spectra. It can be therefore explained, under a purely diffusive picture, why all HM-based studies lead to systematically large values for the parameter \(\delta\).

4. CONCLUSIONS

In this Letter, we have proposed a new interpretation for the spectral hardening observed in CRs. As shown, it may be a consequence of a spatial change of the CR diffusion properties in the Galaxy. From this scenario the hardening arises naturally as a local effect and vanishes gradually in the outer halo, where the CR spectra are also predicted to be steeper. This effect must be experienced by all CR nuclei as well as by secondary-to-primary ratios. Recent data (e.g., Fermi-LAT or TRACER) seem to support this scenario, but the predicted spectral upturn is more gradual than that suggested by PAMELA data. With dedicated analysis of the data forthcoming from AMS or Fermi-LAT, our model can be resolutely tested and discriminated against other interpretations.

Our scenario has remarkable implications for the CR physics. With the THMAs setup, we have shown that a Kolmogorov diffusion for the inner halo \((\delta \sim 1/3)\) is consistent with relatively hard source spectra \((\nu \sim 2.2)\). With the THMb setup, we have shown that a very slow diffusion for the inner halo \((\delta \sim 1/6)\) can reconcile the anisotropy with the B/C ratio. Interestingly, it does not require prohibitively steep source spectra as one might expect. Both formulations are based on plain diffusion

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\(^{1}\) http://www.ams02.org
models where the diffusion coefficient is not separable into energy (rigidity) and space terms as usually assumed. Their good agreement with data suggests that the CR propagation at $\lesssim 50$ GeV nucleon$^{-1}$ might be affected only moderately by low-energy effects such as reacceleration. At the highest energies, we found that the elemental knees can be matched using $\sim 2.5 \times 10^6$ GV of maximum SNR rigidity, which is attainable by known acceleration mechanisms.

Further elaborations may be performed using numerical methods, in order to introduce a radial dependence of $K$ or other effects connected with the Galactic structure. Calculations of other observables such as $\bar{p}/p$, $^{10}\text{Be}/^{9}\text{Be}$, or $\gamma$-rays may lead to a deeper understanding of the effect. We hope that our proposal will stimulate further investigations on this subject.

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