Cosmic ray spectral hardening due to dispersion in the source injection spectra

Qiang Yuan (□□), Bing Zhang (□□), and Xiao-Jun Bi (□□□)

Phys. Rev. D **84**, 043002 — Published 9 August 2011

DOI: 10.1103/PhysRevD.84.043002

Cosmic ray spectral hardening due to dispersion in the source injection spectra

Qiang Yuan[1,2](袁强), Bing Zhang[2](张冰) and Xiao-Jun Bi[1](毕效军)
[1]*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P. R. China*
[2]*Department of Physics and Astronomy, University of Nevada Las Vegas, Las Vegas, NV 89154, USA*

Recent cosmic ray (CR) experiments discovered that the CR spectra experience a remarkable hardening for rigidity above several hundred GV. We propose that this is caused by the superposition of the CR energy spectra of many sources that have a dispersion in the injection spectral indices. Adopting similar parameters as those of supernova remnants derived from the Fermi γ-ray observations, we can reproduce the observational CR spectra of different species well. This may be interpreted as evidence to support the supernova remnant origin of CRs below the knee. We further propose that the same mechanism may explain the "ankle" of the ultra high energy CR spectrum.

PACS numbers: 98.70.Sa,96.50.sb,98.38.Mz

Introduction—Nearly 100 years after the discovery of cosmic rays by V. Hess in 1912, several basic questions on CRs, such as the source(s) and the propagation effects, are still not well understood. Precise measurements of the CR spectra and observations of high energy γ-rays and neutrinos, are of great importance to approach the answers to these fundamental questions.

There are several major progresses in the CR measurements in recent years. The balloon-borne experiment Cosmic Ray Energetics And Mass (CREAM) measured the energy spectra of the major species from proton to iron in the energy range from tens of GeV/nucleon to tens of TeV/nucleon with relatively high precision [1, 2]. A remarkable hardening at ~ 200 GeV/nucleon of the spectra of all species was discovered [2]. Most recently the satellite experiment Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) reported the precise measurement about the proton and Helium spectra with rigidity from GV to 1.2 TV [3]. PAMELA data show clearly that the proton and Helium spectra deviate from the single power-law function above ~ 30 GV with a hardening at rigidity ~ 200 GV, which is basically consistent with the results of CREAM and the previous Advanced Thin Ionization Calorimeter (ATIC-2) [4]. The hardening of the CR spectra challenges the traditional CR acceleration and propagation paradigm. Models possibly to explain such a spectral hardening include the multi-component sources [5], or the nonlinear particle acceleration scenarios where the feedback of CRs on the shock is essential (e.g., [6–8]).

Model—In this work we propose that the hardening of the observed CR spectra is due to dispersion of the injection spectra of the CR sources such as supernova remnants (SNRs). A superposition of the spectra of many sources with a distribution of the injection spectra would lead to an asymptotic hardening of the final spectra of CRs [9]. For example for power-law injection spectrum $E^{-\gamma}$, if there is a uniform distribution of the γ index $p(\gamma) = \frac{1}{\gamma_2-\gamma_1}$, the total spectrum will be $\int_{\gamma_1}^{\gamma_2} E^{-\gamma}p(\gamma)\mathrm{d}\gamma \propto (E^{-\gamma_1} - E^{-\gamma_2})/\ln E$, which will asymptotically approach the hardest injection spectrum. Such an effect was adopted to explain the "GeV excess" of Galactic diffuse γ-rays observed by EGRET [10, 11].

Observations of X-ray, GeV and TeV γ-rays indicate that the SNRs can accelerate particles (electrons and/or nuclei) up to very high energies. Those particles are thought to be the most probable sources of the Galactic CRs. Studies of radio emission spectra of SNRs suggest that the spectral indices of accelerated particles have a significant dispersion instead of a uniform value [12].

The Fermi satellite observed several SNRs in the GeV band with high precision [13–19]. The γ-ray energy spectra and the coincidence with molecular clouds of several SNRs suggest that the γ-rays are most likely of a hadronic origin, although the leptonic origin is not ruled out. A broken power-law injection of protons with the break energy several to tens of GeV seems to describe the γ-ray data well [20, 21]. The fit to γ-rays also indicates that there is a large dispersion of the accelerated CR spectra in SNRs. Assuming the hadronic origin of the γ-ray emission of SNRs, the modeling of the GeV-TeV γ-ray emission from eight sources detected by Fermi and Cherenkov telescopes gives the source particle spectra $\gamma_1 \approx 2.15 \pm 0.33$ and $\gamma_2 \approx 2.54 \pm 0.44$, for energies below and above the break respectively [21].

Here we calculate the superposition effect of CR spectra, assuming that CRs are originated from SNR-like sources. The injection spectrum of each source is assumed to be a broken power-law function of rigidity with the break from several to tens of GV. The spectral indices are assumed to be Gaussian distributed around some average values. The normalization of each source is derived assuming a constant total energy of CRs above 1 GeV for all sources. Since the particle spectra inferred from the

γ-rays might be different from those leaking into the interstellar space [22], the injection parameters are adopted through the fit to the CR data instead of the ones inferred from γ-ray observations.

We employ the GALPROP code [23] to calculate the propagation of CRs, in the diffusive reacceleration frame. The main propagation parameters are $D_0 = 5.8 \times 10^{28}$ cm^2 s^{-1}, $\delta = 0.33$, $v_A = 32$ km s^{-1} and $z_h = 4$ kpc. For each major chemical species we use the superposed spectra of many sources as input and calculate its propagation. The B/C ratio is found well consistent with data and insensitive to the source spectrum.

For rigidity below ~ 30 GV, solar modulation needs to be considered. The force-field approximation is adopted to model the effect [24]. The modulation potential Φ depends on the solar activity, which varies from ~ 200 MV at solar minimum to ~ 1400 MV at solar maximum. For the period when PAMELA operates, the modulation potential was estimated to be $450-550$ MV [3]. According to the fit to the low energy observational data (see Fig. 1), we adopt $\Phi = 550$ MV for proton and Helium (to fit the PAMELA data), and $\Phi = 750$ MV for Carbon, Oxygen and Iron nuclei (to fit the HEAO3 data). A higher modulation potential for HEAO3 was also found in [25].

There is a "knee" of the all-particle spectra at PeV energies, which indicates the existence of break or cutoff on the CR spectra [26]. Such a break or cutoff might be due to the acceleration limit of sources, the propagation/leakage effect from the Galaxy, or interactions with background particles [27]. Here we adopt two kinds of cutoff/break to model the knee structure of the total spectra: a sub-exponential cutoff case with the energy spectrum above the injection break $R^{-\gamma_2}\exp(-R/R_c)$, and a broken power-law case with energy spectrum above the injection break $R^{-\gamma_2}(1+R/R_c)^{-1}$. In both cases we assume that the cutoff/break energy is Z-dependent, i.e., the rigidity R_c is constant[1].

The calculated energy spectra of proton, Helium, Carbon, Oxygen, Iron and the total spectrum, together with the observational data are shown in Fig. 1. The parameters of the model are compiled in Table I. The results show good agreement with the data of each major species and the all particle one. Here a sub-exponential cutoff instead of the standard exponential cutoff is required, in order to reconcile the all-particle spectra with the proton and Helium data around the knee region. Such a sub-exponential cutoff may be originated from stochastic acceleration of particles in the turbulent downstream of weakly magnetized, collisionless shocks [28]. For the cutoff case, the expected all-particle spectrum is lower than the data at energies above tens of PeV. Such a result is consistent with the requirement of a "B component" of Galactic CRs [29]. For the break case, the high energy data of the all-particle spectra can be well reproduced without the "B component", as was also shown in the "poly-gonato" model [26].

TABLE I: Source parameters: injection spectra γ_1, γ_2 and break rigidity R_b, high energy cutoff rigidity R_c and solar modulation potential Φ.

		γ_1	γ_2	R_b (GV)	R_c (PV)	Φ (GV)
cutoff	p	1.95 ± 0.20	2.52 ± 0.28	$[5, 30]$	0.5	0.55
	He	1.95 ± 0.20	2.50 ± 0.33	$[5, 30]$	0.5	0.55
	C,O,Fe	1.95 ± 0.20	2.58 ± 0.35	$[5, 30]$	0.5	0.75
break	p	1.95 ± 0.20	2.52 ± 0.25	$[5, 30]$	0.5	0.55
	He	1.95 ± 0.20	2.50 ± 0.30	$[5, 30]$	0.5	0.55
	C,O,Fe	1.95 ± 0.20	2.58 ± 0.32	$[5, 30]$	0.5	0.75

Discussion—In such a simple scenario of dispersion of injection spectra of CR sources, the observed hardening of CR spectra by ATIC, CREAM and PAMELA can be reproduced. If the CRs are indeed originated from a population of sources instead of a single major source (e.g., [40, 41]), such an asymptotic hardening effect due to dispersion of source properties is inevitable. The injection parameters are similar to those inferred from the γ-ray observations of SNRsi, which might be evidence that SNRs are the sources of Galactic CRs below $\sim$PV.

The injection spectra of different elements are slightly different, which might be related to the difference in production of different species [42]. We find that the difference between various elements in the injection spectra is not as large as that in the observed ones, possibly because the interaction strengths of various elements are different from each other during propagation. It should be noted that the PAMELA data actually showed a sharp break at ~ 200GV and a gradual softening below the break rigidity [3]. Such detailed features cannot be simply recovered in the present model, where the gradual hardening is expected. The same tension also exists for the multi-component source model and the non-linear acceleration model. We expect that future better measurements of wide band spectra by e.g., the Alpha Magnetic Spectrometer (AMS02, [43]) and the Large High Altitude Air Shower Observatory (LHAASO, [44]) would help to test this model.

[1] It is reasonable to assume a constant R_c for all sources for the propagation/leakage models and the interaction models. However, the break may suffer from a dispersion in the acceleration limit models. We have tested that the result with a dispersion of R_c can actually be well approximated by the model with a proper constant R_c.

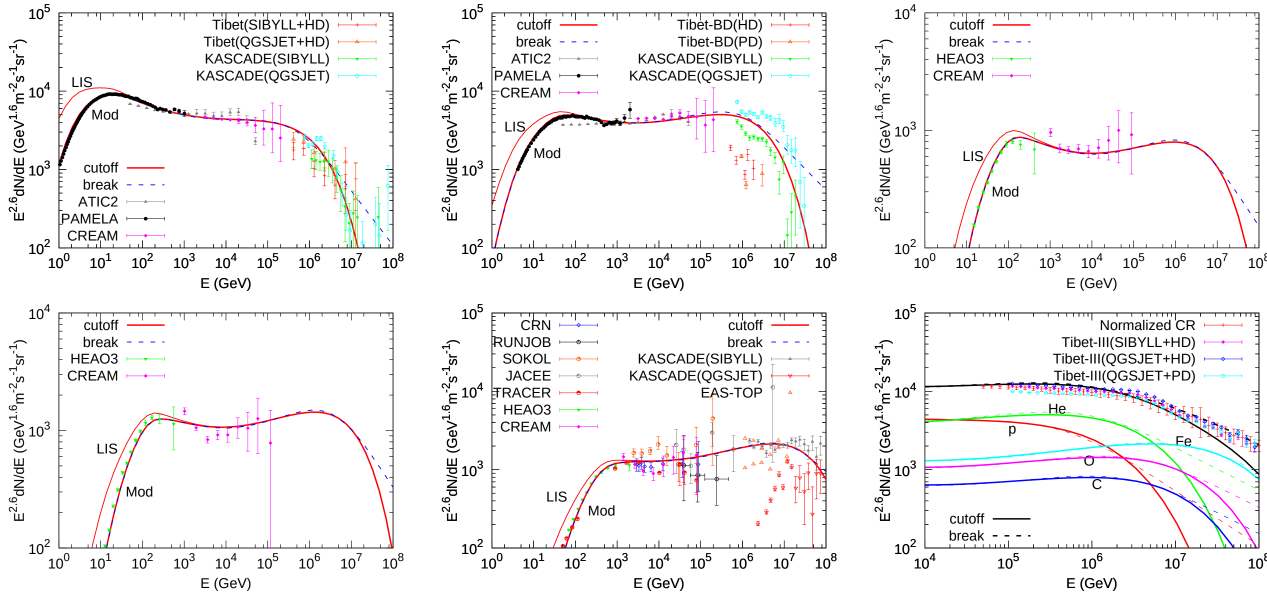

FIG. 1: Energy spectra of proton (top-left), Helium (top-middle), Carbon (top-right), Oxygen (bottom-left), Iron (bottom-middle) and the all-particle one (bottom-right). The local interstellar spectra are labelled with "LIS" and the observed spectra after solar modulation are labelled with "Mod". The solid line in each panel represents a sub-exponential cutoff behavior of the high energy spectra around the knee region, while the dashed line is for broken power-law type. References of the data are—proton: ATIC-2 [4], PAMELA [3], CREAM [2], Tibet [30], KASCADE [31]; Helium: ATIC-2 [4], PAMELA [3], CREAM [2], Tibet-BD [32], KASCADE [31]; Carbon: HEAO3 [33], CREAM [1]; Oxygen: HEAO3 [33], CREAM [1]; Iron: CRN [34], RUNJOB [35], SOKOL [36], JACEE [37], TRACER [38], HEAO3 [33], CREAM [1]; all-particle: Tibet-III [39]. The normalized all-particle data are derived by combining all data with a rescale based on the extrapolation of the direct measurements [26].

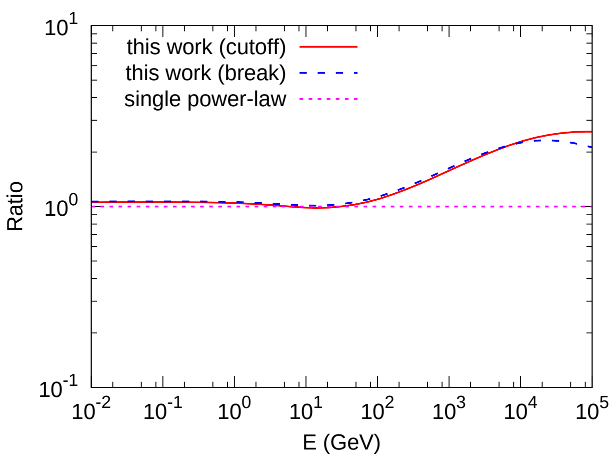

FIG. 2: Ratio of the hadronic component of the diffuse γ-rays between the dispersion scenario expectation and the single power-law model.

There are some implications of the CR spectral hardening, for example, the imprint on the secondary particles such as positrons [45], diffuse γ-rays, and antiprotons [46]. Based on our model CR spectra, we calculate the predicted hadronic-origin diffuse γ-ray fluxes. The total diffuse γ-ray emission consists of hadronic, leptonic and the extra-galactic components, which is very complicated. In the Galactic plane the diffuse γ-ray flux is dominated by the hadronic component as shown in the conventional CR propagation models [47]. The γ-ray yield is calculated using the parameterization of pp interactions given in [48]. For the effect of heavy nuclei we employ a nuclear enhancement factor $\epsilon_M = 1.84$ [49]. The absolute fluxes depend on the propagation model and spatial distribution of CRs. Here we only discuss the relative results. The ratios of the hadronic γ-ray fluxes between our model expectation and that of the traditional single power-law CR spectrum are shown in Fig. 2. It is shown that the γ-ray flux also experiences a hardening above ~ 50 GeV. A similar conclusion was also derived in [46]. For positrons and antiprotons we expect similar behaviors, although the propagation effect may change a little bit the quantitative results. The current Fermi γ-ray data and PAMELA antiproton data can not probe such a hardening of the secondary particles yet.

We also note that the dip-cutoff structure is very similar to the ankle-GZK structure of ultra high energy CRs (UHECRs). Considering the fact that UHECRs should also suffer from such a hardening effect if they are from a population of sources, we would expect the same mechanism to be responsible for the ankle-GZK structure of

UHECRs. Following [50], we assume the injection spectrum of UHECRs is a broken power-law function with an exponential cutoff. The logarithm of break energy $\log(E_b/\mathrm{eV})$ is assumed to be uniformly distributed in [17, 18] and the cutoff energy is $E_c \sim 5 \times 10^{19}$ eV. The spectral index is 2.0 ± 0.2 below E_b and 3.6 ± 0.6 above E_b. Assuming a pure proton component [51], we present the expected superposed UHECR spectrum in Fig. 3. We would expect a similar result for any other single chemical species. Note that the Pierre Auger Observatory data showed a gradual increase in mass composition [53]. Since the relative abundance of each chemical species is not yet well constrained experimentally, we cannot perform a detailed modeling. In any case, we propose that the superposition effect from a population of UHECR sources with a dispersion in the injection spectrum provides a new ingredient to model the UHECR spectrum. Since the interactions between UHECRs and the background photons are unavoidable if UHECRs are produced at cosmological distances [50], we may in turn expect that UHECRs are produced locally or even in the Galaxy [54] if the mechanism proposed in this work is responsible for the shape of the UHECR spectrum. More generally, it is possible that both the superposition and the interaction effects are in operation to give the ankle-GZK structure of UHECRs.

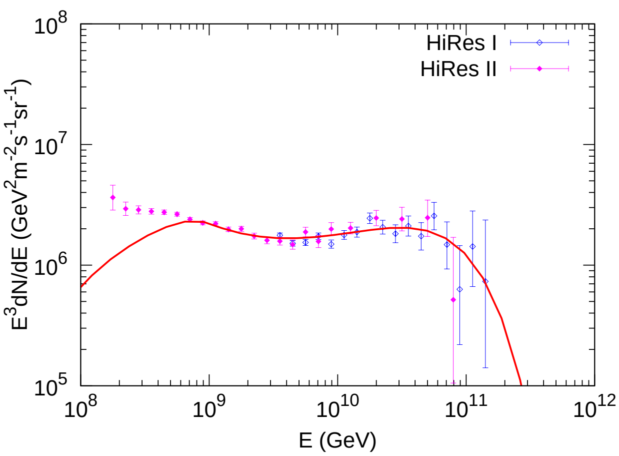

FIG. 3: Calculated energy spectra of UHECRs for pure protons, compared with the HiRes data [52].

Acknowledgments

This work is supported by NSF under grant AST-0908362, NASA under grants NNX10AP53G and NNX10AD48G, and Natural Sciences Foundation of China under grant 11075169, and the 973 project under grant 2010CB833000.

[1] H. S. Ahn *et al.*, Astrophys. J. **707**, 593 (2009).
[2] H. S. Ahn *et al.*, Astrophys. J. **714**, L89 (2010).
[3] O. Adriani *et al.*, Science **332**, 69 (2011).
[4] A. D. Panov *et al.*, Bulletin of the Russian Academy of Science **71**, 494 (2007).
[5] V. I. Zatsepin and N. V. Sokolskaya, Astron. Astrophys. **458**, 1 (2006).
[6] E. G. Berezhko and D. C. Ellison, Astrophys. J. **526**, 385 (1999).
[7] M. A. Malkov and L. O'C Drury, Rep. Prog. Phys. **64**, 429 (2001).
[8] V. S. Ptuskin, V. Zirakashvili and E. S. Seo, Astrophys. J. **718**, 31 (2010).
[9] K. Brecher and G. R. Burbidge, Astrophys. J. **174**, 253

(1972).
[10] M. Pohl and J. A. Esposito, Astrophys. J. **507**, 327 (1998).
[11] I. Büsching, M. Pohl and R. Schlickeiser, Astron. Astrophys. **377**, 1056 (2001).
[12] D. A. Green, American Institute of Physics Conference Series, **558**, 59 (2001).
[13] A. A. Abdo *et al.*, Astrophys. J. **706**, L1 (2009).
[14] A. A. Abdo *et al.*, Science **327**, 1103 (2010).
[15] A. A. Abdo *et al.*, Astrophys. J. **712**, 459 (2010).
[16] A. A. Abdo *et al.*, Astrophys. J. **710**, L92 (2010).
[17] A. A. Abdo *et al.*, Astrophys. J. **718**, 348 (2010).
[18] A. A. Abdo *et al.*, Astrophys. J. **722**, 1303 (2010).
[19] A. A. Abdo *et al.*, Astrophys. J. **734**, 28 (2011).
[20] Y. Ohira, K. Murase and R. Yamazaki, Mon. Not. Roy. Astron. Soc. **410**, 1577 (2011).
[21] Q. Yuan, P.-F. Yin and X.-J. Bi, Astropart. Phys. **35**, 33 (2011).
[22] D. Caprioli, E. Amato and P. Blasi, Astropart. Phys. **33**, 160 (2010).
[23] A. W. Strong and I. V. Moskalenko, Astrophys. J. **509**, 212 (1998).
[24] L. J. Gleeson and W. I. Axford, Astrophys. J. **154**, 1011 (1968).
[25] R. Trotta *et al.*, Astrophys. J. **729**, 106 (2011).
[26] J. R. Hörandel, Astropart. Phys. **19**, 193 (2003).
[27] J. R. Hörandel, Astropart. Phys. **21**, 241 (2004).
[28] S. Liu *et al.*, Astrophys. J. **683**, L163 (2008).
[29] A. M. Hillas, J. Phys. G Nucl. Phys. **31**, 95 (2005).
[30] M. Amenomori *et al.*, J. Phys. Conf. Series **47**, 51 (2006).
[31] T. Antoni *et al.*, Astropart. Phys. **24**, 1 (2005).
[32] M. Amenomori *et al.*, Phys. Rev. D **62**, 112002 (2000).
[33] J. J. Engelmann *et al.*, Astron. Astropys. **233**, 96 (1990).
[34] D. Mueller *et al.*, Astrophys. J. **374**, 356 (1991).
[35] V. A. Derbina *et al.*, Astrophys. J. **628**, L41 (2005).
[36] I. P. Ivanenko *et al.*, Int. Cosmic Ray Conf. **2**, 17 (1993).
[37] K. Asakimori *et al.*, Int. Cosmic Ray Conf. **2**, 707 (1995).
[38] M. Ave *et al.*, Astrophys. J. **678**, 262 (2008).
[39] M. Amenomori *et al.*, Astrophys. J. **678**, 1165 (2008).
[40] A. D. Erlykin and A. W. Wolfendale, J. Phys. G Nucl. Phys. **23**, 979 (1997).
[41] Y. Q. Guo *et al.*, ArXiv e-prints:1101.5192
[42] Y. Ohira and K. Ioka, Astrophys. J. **729**, L130 (2011).
[43] http://ams.cern.ch/
[44] Z. Cao, Chin. Phys. C **34**, 249 (2010).
[45] J. Lavalle, Mon. Not. Roy. Astron. Soc. **414**, 985 (2011).
[46] F. Donato and P. D. Serpico, Phys. Rev. D **83**, 023014 (2011).
[47] A. W. Strong, I. V. Moskalenko and O. Reimer, Astrophys. J. **613**, 962 (2004).
[48] T. Kamae *et al.*, Astrophys. J. **647**, 692 (2006).
[49] M. Mori, Astropart. Phys. **31**, 341 (2009).
[50] V. Berezinsky, A. Gazizov and S. Grigorieva, Phys. Rev. D **74**, 043005 (2006).
[51] R. U. Abbasi *et al.*, Astrophys. J. **622**, 910 (2005).
[52] R. U. Abbasi *et al.*, Phys. Rev. Lett. **100**, 101101 (2008).
[53] J. Abraham *et al.*, Phys. Rev. Lett. **104**, 091101 (2010).
[54] A. Calvez, A. Kusenko and S. Nagataki, Phys. Rev. Lett. **105**, 091101 (2010).