Understanding the spectral hardenings and radial distribution of Galactic cosmic rays and Fermi diffuse γ rays with spatially-dependent propagation

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Recent direct measurements of Galactic cosmic ray spectra by balloon/space-borne detectors reveal spectral hardenings of all major nucleus species at rigidities of a few hundred GV. The all-sky diffuse γ-ray emissions measured by the Fermi Large Area Telescope also show spatial variations of the intensities and spectral indices of cosmic rays. These new observations challenge the traditional simple acceleration and/or propagation scenario of Galactic cosmic rays. In this work, we propose a spatially dependent diffusion scenario to explain all these phenomena. The diffusion coefficient is assumed to be anticorrelated with the source distribution, which is a natural expectation from the charged particle transportation in a turbulent magnetic field. The spatially dependent diffusion model also gives a lower level of anisotropies of cosmic rays, which are consistent with observations by underground muons and air shower experiments. The spectral variations of cosmic rays across the Galaxy can be properly reproduced by this model.

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I. INTRODUCTION

It has been widely believed that cosmic rays (CRs) below the "knee" (~PeV) are originated from Galactic accelerators such as remnants of supernova explosion [1]. Charged CRs propagate diffusively in the Milky Way, interact with the interstellar medium (ISM), and produce secondary particles. Such a "standard" paradigm of the production, propagation, and interaction of Galactic CRs works successfully to explain most of the observations of CRs as well as diffuse γ rays [2].

Some recent observations challenge this "standard" picture. Remarkable spectral hardenings of CR nuclei at several hundred GV have been found by balloon and space detectors [3–7]. Several kinds of models incorporating modifications of simple assumptions of the injection, acceleration, and propagation of CRs have been proposed to explain it (e.g., [8–22]). In addition, the diffuse γ-ray emission detected by the Fermi Large Area Telescope (Fermi-LAT) reveals a flatter CR density gradient toward the outer Galaxy region [23]. The gradient problem might imply either a thicker propagation halo of CRs or that there are more sources in the outer Galaxy than that inferred from observations of supernova remnants (SNRs) or pulsars [23]. Most recently, the analysis of the Fermi-LAT diffuse γ ray further suggests spatial variations of both intensities and spectra of CRs [24,25], which cannot be simply reproduced from the conventional CR propagation model.[1]

It was shown that a spatially dependent propagation (SDP) scenario can account for both the CR intensity gradient and the small anisotropies of CR arrival directions [26] (see also the original work of Ref. [27]). In Ref. [28], Recchia *et al.* proposed a model of nonlinear CR propagation with particle scattering and advection off self-generated turbulence to account for the spatial variations of the CR densities and spectra. In this model, the transportation (diffusion and advection) of CRs varies in the Galaxy amounting to a type of SDP model. However, only the one-dimensional diffusion (z direction) of particles is assumed [28]. Furthermore, to account for the spatial variations of the CR intensities and spectra, an exponential decay of the background magnetic field is required. Just recently, Cerri *et al.* proposed an anisotropic diffusion model to interpret the radial dependence of spectra of CRs and suggested that the harder slope in the inner Galaxy was due to the parallel diffusive escape along the poloidal component of the large-scale, regular, magnetic field [29].

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[1]In this work, the conventional propagation model means the model with uniform, single power-law form of the diffusion coefficient, and single power-law source injection spectrum above ~10 GV.

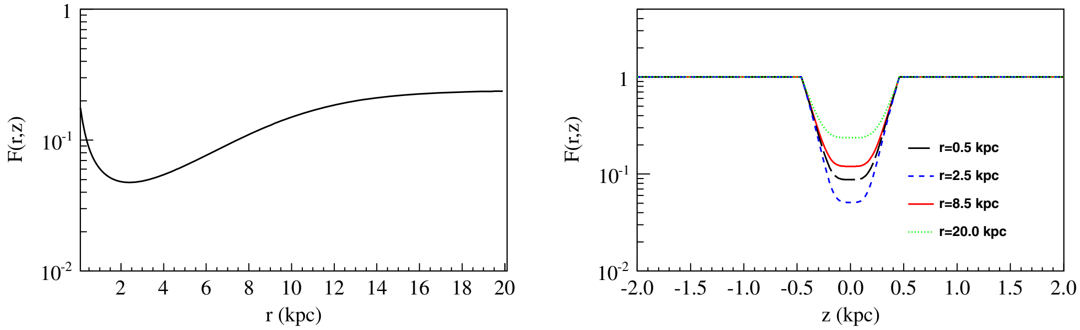

FIG. 1. The distributions of $F(r,z)$ with the radial distance r (left panel; for $z=0$) and vertical height z (right panel).

Although there were quite a few studies on using the SDP models to understand the newly available CR data [13,30–34], those previous works lack a coherent explanation of all the above-mentioned observations simultaneously. In this work, we employ an SDP model of CR propagation to self-consistently account for those observations. The diffusion coefficient is assumed to be anticorrelated with the CR source distribution, which is a natural assumption since the (turbulent) magnetic field strength is expected to be correlated with the matter distribution. We will show that such a simple extension of the conventional CR propagation model can give reasonable fits to most of the available data of CRs and γ rays.

II. MODEL DESCRIPTION

The propagation of charged particles in the Milky Way is usually restricted in a cylinder, with a half-height of z_h, centered at the Galactic center. CRs may further experience convective transportation, reacceleration due to interactions with random magneto-hydrodynamic waves, energy loss due to ionization and Coulomb scattering, and/or fragmentation due to collisions with the ISM. Secondary nuclei are produced via the fragmentations of primary nuclei during their propagation. Here we adopt the diffusion reacceleration model, which is found to well describe the secondary-to-primary ratios and low-energy fluxes of CR nuclei [35–37], to characterize the propagation process of CRs.

The source distribution of CRs is assumed to follow the observed spatial distribution of SNRs,

$$f(r,z) = \left(\frac{r}{r_\odot}\right)^\alpha \exp\left[-\frac{\beta(r-r_\odot)}{r_\odot}\right] \exp\left(-\frac{|z|}{z_s}\right), \quad (1)$$

where $r_\odot = 8.5$ kpc, $z_s = 0.2$ kpc, $\alpha = 1.09$, and $\beta = 3.87$ [38]. We have normalized $f(r,z)$ to 1 at the solar location. The source spectrum of CRs is assumed to be a broken power law in rigidity.

The spatial diffusion coefficient is described with a two halo approach: the inner (disk) and outer halo [13]. The diffusion coefficient D_{xx} is parametrized as

$$D_{xx}(r,z,p) = F(r,z) D_0 \beta \left(\frac{p}{p_0}\right)^{F(r,z)\delta_0}, \quad (2)$$

where $F(r,z)D_0$ represents the normalization factor of the diffusion coefficient at the reference rigidity p_0, and $F(r,z)\delta_0$ reflects the property of the irregular turbulence. The function $F(r,z)$ takes the form as

$$F(r,z) = \frac{N_m}{1+f(r,z)} + \left(1 - \frac{N_m}{1+f(r,z)}\right) \cdot \min\left[\left(\frac{z}{\xi z_h}\right)^n, 1\right], \quad (3)$$

where ξz_h denotes the half thickness of the inner halo, $(1-\xi)z_h$ is the half thickness of the outer halo, N_m is a normalization factor, and n characterizes the sharpness between the inner and outer halos. For $z \ll \xi z_h$ (the inner halo), the diffusion coefficient is obviously anticorrelated with the source distribution $f(r,z)$. For the outer halo where the source term vanishes, the diffusion coefficient recovers the traditional form of $D_0\beta(p/p_0)^{\delta_0}$. To clearly see the behaviors of $F(r,z)$, we show their distributions as functions of r (for $z=0$) and z (for a few values of r) in Fig. 1.

The reacceleration can be characterized by a diffusion in momentum space. The momentum diffusion coefficient D_{pp} relates to D_{xx} via the effective Alfvenic velocity v_A of the ISM [39], as $D_{pp}D_{xx} = \frac{4p^2 v_A^2}{3\delta(4-\delta^2)(4-\delta)}$, where $\delta = F(r,z)\delta_0$.

A numerical method is necessary to solve the diffusion equations, especially in case that the diffusion varies everywhere in the Milky Way. In this work, we use the

TABLE I. Propagation parameters.

D_0 (cm^2 s^{-1})	5.6×10^{28}
δ_0	0.56
v_A (km s^{-1})	6.0
z_h (kpc)	5.0
N_m	0.24
ξ	0.092
n	5

DRAGON code [40,41] to calculate the propagation of CRs. The basic model parameters are given in Table I.

III. RESULTS

A. Primary CRs

We first look at the effect on the spectra of primary CRs. Figure 2 shows the proton spectrum expected from the SDP model and the comparison with the measurements [5,6,42]. It can be seen that the model gives a clear hardening of the spectrum for $E \gtrsim 300$ GeV, which is consistent with the data. In the SDP model, the propagated CR flux can be understood as a sum of two components: a harder one due to the propagation in the disk and a softer one due to the propagation in the halo (see, e.g., the discussion in Ref. [33] for a simplified two-halo diffusion scenario).

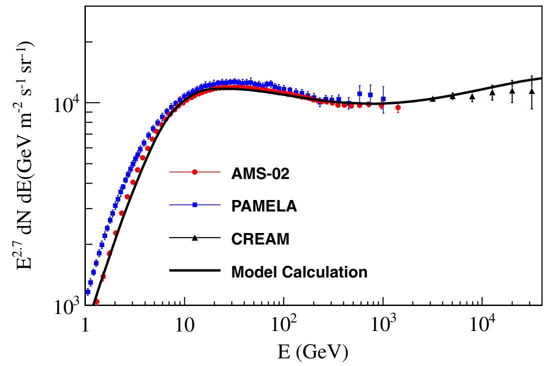

FIG. 2. Model predictions of the proton spectrum, compared with the measurements by PAMELA [5], AMS-02 [6], and CREAM [42].

B. Secondary CRs

Figure 3 displays the B/C ratio and the $\bar{p}$ spectrum predicted by the SDP model. Note that the B/C ratio is in slight tension with the $\bar{p}/p$ ratio. The AMS-02 data show that, the $\bar{p}/p$ ratio is almost a constant for rigidities higher than ∼60 GV, while the B/C ratio decreases with rigidities following $R^{-1/3}$ [43]. The most recent results on the secondary Li, Be, and B by the AMS-02 Collaboration showed that the secondary/primary ratios becomes harder by $\sim R^{0.13}$ above 200 GV [44]. This new result becomes more consistent with the $\bar{p}/p$ ratio, and seems to support the propagation origin of the spectral hardenings [45]. Within the uncertainties of the measurements, our model is consistent with the data. At high energies, both ratios are expected to harden gradually. This is again due to the

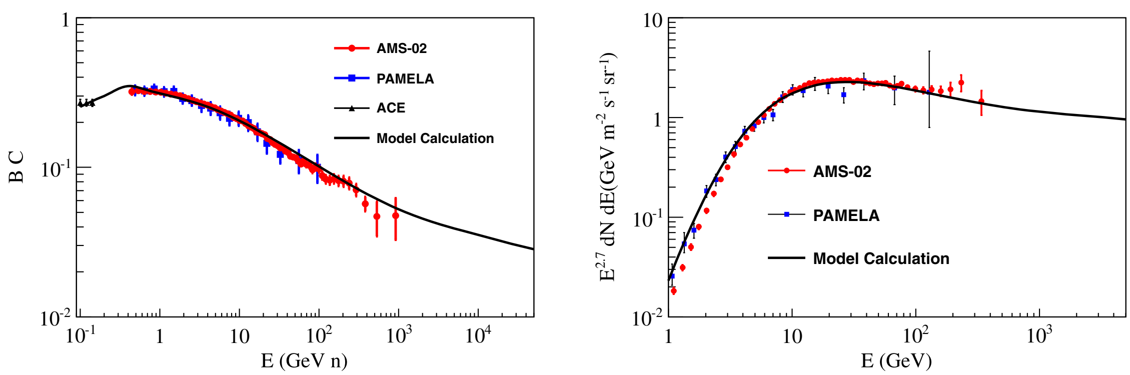

FIG. 3. Model predictions of the B/C ratio (left) and $\bar{p}$ spectrum (right), compared with the observational data by ACE [37], PAMELA [53,54] and AMS-02 [43,55].

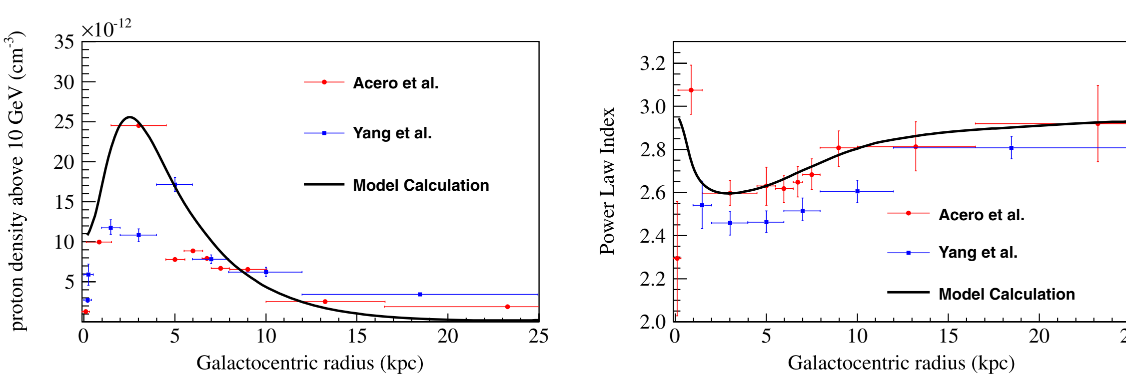

FIG. 4. Model predictions of the radial distributions of the CR proton densities (left) and spectral indices (right), compared with that inferred from Fermi-LAT γ-ray data [24,25].

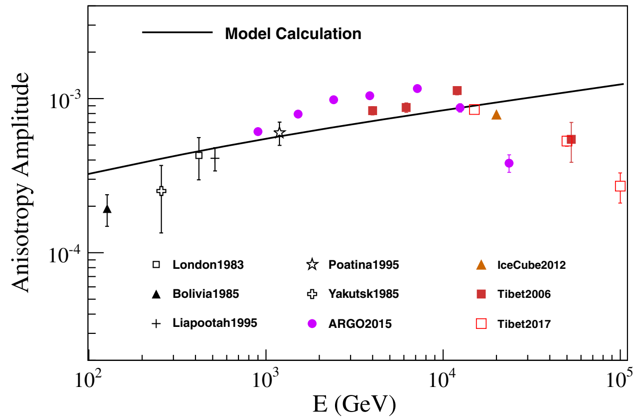

FIG. 5. The anisotropy of CRs expected from the SPD model, compared with the data from underground muon observations: London (1983) [62], Bolivia (1985) [63], Socorro (1985) [63], Yakutsk (1985) [63], Liapootah (1995) [64], Poatina (1995) [65], and air shower array experiments: Tibet (2006, 2017) [57,60], IceCube (2012) [58], and ARGO-YBJ (2015) [59].

two-halo propagation nature of particles (secondary particles would experience one more time diffusion than primary ones). Similar features were also predicted in Ref. [46], in which a two-component model was proposed to account for behaviors of secondary particles. The SDP model can naturally explain the flat behavior of the $\bar{p}/p$ ratio above ~60 GeV, without resorting to either astrophysical sources [19,47,48] or particle dark matter annihilation [49–52].

C. Spatial distribution

The spatial distributions of the CR proton densities and spectral indices are shown in Fig. 4, which are broadly consistent with the results inferred from Fermi-LAT all-sky γ-ray data [24,25]. Note that these two analyses differ by a factor of ~2 in the inner Galaxy, probably due to different gas templates adopted. The quantitative results depend on the source parameters, and are thus uncertain to some extent. Nevertheless, our model correctly reproduce the evolution trends of those quantities, especially for the spectral variation. The CR density reaches a maximum at ~3 kpc, due to the assumed source distribution of SNRs [38]. In the very inner region (Galactic center), the model prediction is higher than the data. This perhaps requires a non-negligible advection of CRs in the inner Galaxy, which may result in the formation of Fermi bubbles [56]. It is also possible that the assumed form of the diffusion coefficient of Eq. (3) is not precise enough to reveal the diffusion process in the inner Galaxy. The spectral indicies vary oppositely as the densities. This can be understood from the assumed diffusion coefficient. The diffusion coefficient is inversely proportional to the source distribution. At a few kpc where the source density is the highest, the diffusion is the slowest and the rigidity dependence of the diffusion coefficient is smallest, therefore the equilibrium CR spectrum is the closest to the source spectrum. The spectra become softer for both the inner and outer Galaxy regions, where the diffusion is faster.

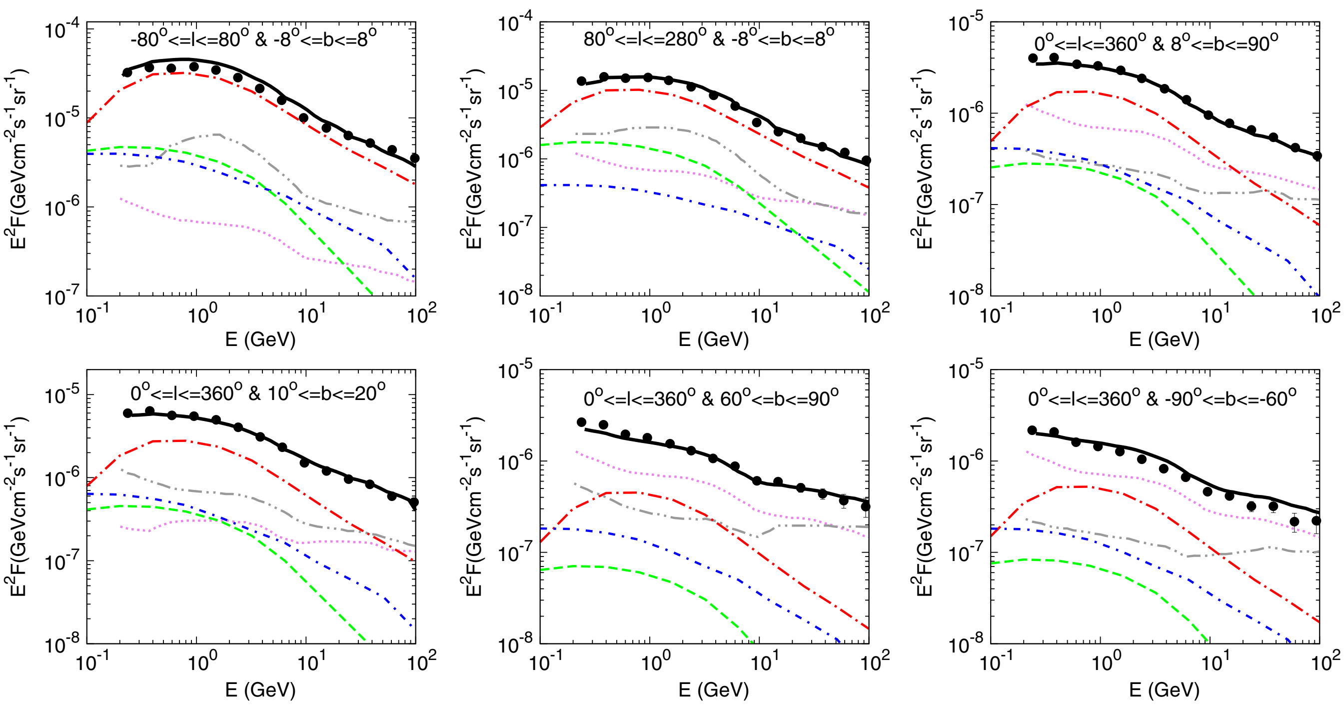

FIG. 6. Model predictions of diffuse γ-ray spectra compared with observations by Fermi-LAT [66]. The model calculations include the π^0-decay (red; long dashed-dotted), inverse Compton scattering (blue; dashed-dotted), bremsstrahlung (green; dashed) components of the Galactic diffuse emission, the isotropic background (magenta; dotted), and detected sources (gray; dashed-dotted-dotted). The black solid lines give the total results from the model.

D. Anisotropies

The CR anisotropies predicted in the SDP model is lower by nearly an order of magnitude than that of the conventional diffusion model [13,32,34], which is consistent with observations below ~10 TeV energies [57–59], as shown in Fig. 5. We note that, however, the phase evolution of the CR anisotropies with energies [60] cannot be simply accounted for by any large scale diffusion model without considering e.g., the local source and/or magnetic field effect [61].

E. Diffuse γ-ray emission

The Fermi-LAT observations of diffuse γ-ray emission are consistent with the expectation of the conventional CR propagation model at high and intermediate latitudes, but show excesses in the Galactic plane for energies above a few GeV [66]. We show in Fig. 6 the comparison of the γ-ray spectra in six sky regions between the SDP model predictions and the data. We find that the Galactic plane excesses can be well accounted for by the SDP model, due primarily to the spectral hardening of CRs. The model slightly overproduce γ rays in the inner Galaxy [panel (a)], because of an over-high CR density (Fig. 4). As we have discussed in subsection IIIC, an advection of CRs may be present in the Galactic center.

IV. DISCUSSION

Many models have been proposed to explain the new observations of CRs, especially the spectral hardenings. These models can be classified into several classes. Here we briefly discuss different types of models and their (potential) performances on different observables.

The modification of the injection spectra of nuclei at source due to either the intrinsic dispersion of the source properties [9] or the nonlinear acceleration mechanism [15] can make concave particle spectra at production. In this kind of model, the propagation is assumed to be the conventional one, and the spectral hardening of CRs is global in the Milky Way. We may expect that the (high-energy) B/C ratio from this model is simply follow the inverse of the energy dependence of the diffusion coefficient, and can thus well fit the data (see for example, Ref. [37]). The new data of secondary Li, Be, and B by AMS-02 favor slightly a break of the secondary/primary ratio at high energies [44]. Whether this kind of model can be convincingly excluded may need further studies. The (high-energy) $\bar{p}/p$ ratio should, in principle, decrease with energies. Given the relatively large uncertainties of the measurements, the model prediction of $\bar{p}/p$ is marginally consistent with the data. Obviously, this model can not explain the spatial variation of the CR spectral indices. The gradient and anisotropy of CRs cannot be accounted for either. As for the diffuse γ rays, Ref. [66] employed the conventional CR propagation model without considering hardenings of the injection spectra, and they found excesses at the Galactic plane. To what extent such mismatches can be solved if the spectral hardenings are included needs further study.

A second class of models incorporates a pheonomenalogical modification of the rigidity dependence of the diffusion coefficient, e.g., from $R^{0.30}$ below 300 GV to $R^{0.15}$ above [10]. In a framework where there is a transition of particle interactions with self-generated turbulence to one with externally generated turbulence, Ref. [12] gives such a break in the diffusion coefficient. However, quantitatively, they predicted a rigidity dependence change from $R^{0.7}$ to $R^{0.33}$. The required break of the diffusion coefficient is currently largely empirical. In this scenario, the B/C and $\bar{p}/p$ ratios would also have breaks at corresponding rigidities. Since this modification is global in the Milky Way, the spatial variation of the CR spectral indices cannot be reproduced. The anisotropy of CRs in this model decrease moderately and can be marginally consistent with the data [10]. However, the gradient problem as revealed by Fermi-LAT γ rays should also exist, since it is related to low-energy CRs which are the same for this model and the conventional one. It has been shown that, at intermediate latitudes, the diffuse γ-ray spectrum for this model is consistent with the Fermi-LAT data [10]. However, the consistency with the Galactic plane excesses needs further studies.

Reference [46] proposed a two component model (labeled as "Two components A" in Table II) to explain the secondary CR data and the diffuse γ rays. In this model, a harder secondary component is assumed and added to the conventional component. It has been shown that the $\bar{p}/p$ ratio and diffuse γ rays can be explained. This model also gives a hardening of the B/C ratio at high energies, which is consistent with the new data of AMS-02 [44]. However, all the results related to the primary CRs, including the spectral hardenings, spatial variations, and gradient and anisotropies, are not reproduced.

Reference [18] proposed a model with two types of SNRs (labeled as "Two components B") which have different behaviors of the secondary production. Secondary particles are not only produced during the propagation but also around the old SNR population (and get accelerated meanwhile). The other young SNR population produce harder primary CRs, but are less efficient in generating secondary particles. This model can account for the primary spectral hardenings and the featureless B/C ratio [18]. The $\bar{p}/p$ ratio is not expected to be well reproduced. The spatial variations of the CR spectra are not accounted for either, as long as there are no significant differences of the spatial distributions of these two SNR populations. Since the source distribution and propagation are similar with the conventional model, we expect that the gradient and anisotropy problems remain. The diffuse γ-ray emission of this model should be similar to the injection/propagation model.

Some works employed nearby source(s) to account for either the primary CR spectral hardenings or the secondary

TABLE II. Summary of different models confronting the observables.

	Primary hardenings	B/C	$\bar{p}/p$	Spatial distribution	CR anisotropies	Diffuse γ rays	Reference
Injection	√	○	○	×	×	?	[9,15]
Propagation	√	√	○	×	○	?	[10]
Two components A	×	√	√	×	×	√	[46]
Two components B	√	○	○	×	×	?	[18]
Local source	√	√	√	×	√	×	[19]
Superbubble	√	○	○	×	×	?	[8]
SDP	√	√	○	√	√	○	This work

Note: "√" means good agreement, "×" means disagreement, "○" means marginal agreement, and "?" means not clear and more detailed analysis is needed.

excesses [11,14,16,19,67]. In Ref. [19], it has been shown that adding a nearby source which has effective interactions with molecular clouds, the primary CR spectra, B/C and $\bar{p}/p$ ratios, positron and electron fluxes, as well as the anisotropies can be reasonably accounted for. The contribution of the nearby source to CRs is mostly local, and hence the CR spatial variations and diffuse γ rays cannot be well explained.

Superbubbles have been suggested to be main sources of CRs and are responsible for the spectral hardenings and He/p ratio [8,68]. This idea is supported by the fact that most of the Galactic supernovae explode in superbubbles [69]. The resulting CR spectral and spatial distributions of this scenario is similar to that of the "injection" model discussed above. Therefore, the spatial variations and anisotropies may not be well reproduced.

We summarize the comparison of different models with different observables in Table II. Since the spatial variations of CR spectra and the diffuse γ rays require changes of the global properties of CR injection and/or propagation, all models except the SDP model can reasonably give such results. Furthermore, most of models face the difficulty to be consistent with the CR gradient and anisotropies. In the local source model, the anisotropies can be small only when finely tuned model parameters are adopted (source location is the anti-Galactic center direction) to cancel the anisotropies from the diffusion of Galactic CRs. The SDP model can easily decrease the gradient and anisotropies to be consistent with the data.

V. SUMMARY

In this work, we suggest an SDP model of Galactic CRs to account for the new observational features of CRs and diffuse γ rays. The SDP model introduces an anticorrelation between the diffusion properties and the source distribution of CRs. The physical origin of this anticorrelation is natural: the turbulent magnetic field which regulates the diffusion of particles is correlated with the matter distribution. This simple extension of the conventional uniform diffusion model explains the primary spectral hardenings, secondary-to-primary ratios, spatial variations of CR intensities, and spectra inferred from Fermi-LAT diffuse γ rays, CR anisotropies, and the Galactic plane excesses of diffuse γ rays. Compared with other proposals of modifications of the conventional CR origin and/or propagation model, the SDP model can explain most of the observations, with little tuning of the model parameters.

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[1] V. L. Ginzburg and S. I. Syrovatskii, *The Origin of Cosmic Rays* (Macmillan, New York, 1964).

[2] A. W. Strong, I. V. Moskalenko, and V. S. Ptuskin, Annu. Rev. Nucl. Part. Sci. **57**, 285 (2007).

[3] A. D. Panov, J. H. Adams, Jr., H. S. Ahn, K. E. Batkov, G. L. Bashindzhagyan, J. W. Watts, J. P. Wefel, J. Wu, O. Ganel, T. G. Guzik *et al.*, Bull. Russ. Acad. Sci. Phys. **71**, 494 (2007).

[4] H. S. Ahn, P. Allison, M. G. Bagliesi, J. J. Beatty, G. Bigongiari, J. T. Childers, N. B. Conklin, S. Coutu, M. A. DuVernois, O. Ganel *et al.*, Astrophys. J. Lett. **714**, L89 (2010).

[5] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Borisov *et al.*, Science **332**, 69 (2011).

[6] M. Aguilar, D. Aisa, B. Alpat, A. Alvino, G. Ambrosi, K. Andeen, L. Arruda, N. Attig, P. Azzarello, A. Bachlechner *et al.*, Phys. Rev. Lett. **114**, 171103 (2015).

[7] M. Aguilar, D. Aisa, B. Alpat, A. Alvino, G. Ambrosi, K. Andeen, L. Arruda, N. Attig, P. Azzarello, A. Bachlechner *et al.*, Phys. Rev. Lett. **115**, 211101 (2015).

[8] Y. Ohira and K. Ioka, Astrophys. J. Lett. **729**, L13 (2011).

[9] Q. Yuan, B. Zhang, and X.-J. Bi, Phys. Rev. D **84**, 043002 (2011).

[10] A. E. Vladimirov, G. Jóhannesson, I. V. Moskalenko, and T. A. Porter, Astrophys. J. **752**, 68 (2012).

[11] A. D. Erlykin and A. W. Wolfendale, Astropart. Phys. **35**, 449 (2012).

[12] P. Blasi, E. Amato, and P. D. Serpico, Phys. Rev. Lett. **109**, 061101 (2012).

[13] N. Tomassetti, Astrophys. J. Lett. **752**, L13 (2012).

[14] S. Thoudam and J. R. Hörandel, Mon. Not. R. Astron. Soc. **421**, 1209 (2012).

[15] V. Ptuskin, V. Zirakashvili, and E.-S. Seo, Astrophys. J. **763**, 47 (2013).

[16] G. Bernard, T. Delahaye, Y.-Y. Keum, W. Liu, P. Salati, and R. Taillet, Astron. Astrophys. **555**, A48 (2013).

[17] S. Thoudam and J. R. Hörandel, Astron. Astrophys. **567**, A33 (2014).

[18] N. Tomassetti and F. Donato, Astrophys. J. Lett. **803**, L15 (2015).

[19] W. Liu, X.-J. Bi, S.-J. Lin, B.-B. Wang, and P.-F. Yin, Phys. Rev. D **96**, 023006 (2017).

[20] Y. Zhang, S. Liu, and Q. Yuan, Astrophys. J. Lett. **844**, L3 (2017).

[21] A. M. Taylor and G. Giacinti, Phys. Rev. D **95**, 023001 (2017).

[22] W. de Boer, L. Bosse, I. Gebauer, A. Neumann, and P. L. Biermann, Phys. Rev. D **96**, 043012 (2017).

[23] M. Ackermann, M. Ajello, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, B. Berenji, E. D. Bloom *et al.*, Astrophys. J. **726**, 81 (2011).

[24] R. Yang, F. Aharonian, and C. Evoli, Phys. Rev. D **93**, 123007 (2016).

[25] F. Acero, M. Ackermann, M. Ajello, A. Albert, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi *et al.*, Astrophys. J. Suppl. Ser. **223**, 26 (2016).

[26] C. Evoli, D. Gaggero, D. Grasso, and L. Maccione, Phys. Rev. Lett. **108**, 211102 (2012).

[27] A. D. Erlykin and A. W. Wolfendale, J. Phys. G **28**, 2329 (2002).

[28] S. Recchia, P. Blasi, and G. Morlino, Mon. Not. R. Astron. Soc. **462**, L88 (2016).

[29] S. S. Cerri, D. Gaggero, A. Vittino, C. Evoli, and D. Grasso, J. Cosmol. Astropart. Phys. 10 (2017) 019.

[30] N. Tomassetti, Phys. Rev. D **92**, 081301 (2015).

[31] C. Jin, Y.-Q. Guo, and H.-B. Hu, Chin. Phys. C **40**, 015101 (2016).

[32] Y.-Q. Guo, Z. Tian, and C. Jin, Astrophys. J. **819**, 54 (2016).

[33] J. Feng, N. Tomassetti, and A. Oliva, Phys. Rev. D **94**, 123007 (2016).

[34] Y.-Q. Guo and Q. Yuan, arXiv:1701.07136.

[35] R. Trotta, G. Jóhannesson, I. V. Moskalenko, T. A. Porter, R. R. de Austri, and A. W. Strong, Astrophys. J. **729**, 106 (2011).

[36] G. Jóhannesson, R. R. de Austri, A. C. Vincent, I. V. Moskalenko, E. Orlando, T. A. Porter, A. W. Strong, R. Trotta, F. Feroz, P. Graff *et al.*, Astrophys. J. **824**, 16 (2016).

[37] Q. Yuan, S.-J. Lin, K. Fang, and X.-J. Bi, Phys. Rev. D **95**, 083007 (2017).

[38] G. L. Case and D. Bhattacharya, Astrophys. J. **504**, 761 (1998).

[39] E. S. Seo and V. S. Ptuskin, Astrophys. J. **431**, 705 (1994).

[40] C. Evoli, D. Gaggero, D. Grasso, and L. Maccione, J. Cosmol. Astropart. Phys. 10 (2008) 18.

[41] C. Evoli, D. Gaggero, A. Vittino, G. Di Bernardo, M. Di Mauro, A. Ligorini, P. Ullio, and D. Grasso, J. Cosmol. Astropart. Phys. 2 (2017) 015.

[42] Y. S. Yoon, T. Anderson, A. Barrau, N. B. Conklin, S. Coutu, L. Derome, J. H. Han, J. A. Jeon, K. C. Kim, M. H. Kim *et al.*, Astrophys. J. **839**, 5 (2017).

[43] M. Aguilar, D. Aisa, A. Alvino, G. Ambrosi, K. Andeen, L. Arruda, N. Attig, P. Azzarello, A. Bachlechner, F. Barao *et al.*, Phys. Rev. Lett. **117**, 231102 (2016).

[44] M. Aguilar *et al.*, Phys. Rev. Lett. **120**, 021101 (2018).

[45] Y. Génolini, P. D. Serpico, M. Boudaud, S. Caroff, V. Poulin, L. Derome, J. Lavalle, D. Maurin, V. Poireau, S. Rosier *et al.*, Phys. Rev. Lett. **119**, 241101 (2017).

[46] Y.-Q. Guo, H.-B. Hu, and Z. Tian, Chin. Phys. C **40**, 115001 (2016).

[47] K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. **2016**, 021E01 (2016).

[48] I. Cholis, D. Hooper, and T. Linden, Phys. Rev. D **95**, 123007 (2017).

[49] X.-J. Huang, C.-C. Wei, Y.-L. Wu, W.-H. Zhang, and Y.-F. Zhou, Phys. Rev. D **95**, 063021 (2017).

[50] T. Li, J. High Energy Phys. 04 (2017) 112.

[51] J. Feng and H.-H. Zhang, arXiv:1701.02263.

[52] S.-J. Lin, X.-J. Bi, J. Feng, P.-F. Yin, and Z.-H. Yu, arXiv: 1612.04001.

[53] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno *et al.*, Astrophys. J. **791**, 93 (2014).

[54] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Borisov *et al.*, Phys. Rev. Lett. **105**, 121101 (2010).

[55] M. Aguilar, L. A. Cavasonza, B. Alpat, G. Ambrosi, L. Arruda, N. Attig, S. Aupetit, P. Azzarello, A. Bachlechner, F. Barao *et al.*, Phys. Rev. Lett. **117**, 091103 (2016).

[56] M. Su, T. R. Slatyer, and D. P. Finkbeiner, Astrophys. J. **724**, 1044 (2010).

[57] M. Amenomori, S. Ayabe, X. J. Bi, D. Chen, S. W. Cui, Danzengluobu, L. K. Ding, X. H. Ding, C. F. Feng, Z. Feng *et al.*, Science **314**, 439 (2006).

[58] R. Abbasi, Y. Abdou, T. Abu-Zayyad, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. M. Allen, D. Altmann, K. Andeen *et al.*, Astrophys. J. **746**, 33 (2012).

[59] B. Bartoli, P. Bernardini, X. J. Bi, Z. Cao, S. Catalanotti, S. Z. Chen, T. L. Chen, S. W. Cui, B. Z. Dai, A. D'Amone *et al.*, Astrophys. J. **809**, 90 (2015).

[60] M. Amenomori, X. J. Bi, D. Chen, T. L. Chen, W. Y. Chen, S. W. Cui, Danzengluobu, L. K. Ding, C. F. Feng, Z. Feng *et al.*, Astrophys. J. **836**, 153 (2017).
[61] M. Ahlers, Phys. Rev. Lett. **117**, 151103 (2016).
[62] T. Thambyahpillai, in *Proceedings of International Cosmic Ray Conference* (1983), Vol. 3, p. 383.
[63] D. B. Swinson and K. Nagashima, Planet. Space Sci. **33**, 1069 (1985).
[64] K. Munakata, S. Yasue, S. Mori, C. Kato, M. Koyama, S. Akahane, Z. Fujii, H. Ueno, J. E. Humble, A. G. Fenton *et al.*, in *Proceedings of International Cosmic Ray Conference* (1995), Vol. 4, p. 639.
[65] K. B. Fenton, A. G. Fenton, and J. E. Humble, in *Proceedings of International Cosmic Ray Conference* (1995), Vol. 4, p. 635.
[66] M. Ackermann, M. Ajello, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, K. Bechtol, R. Bellazzini, B. Berenji *et al.*, Astrophys. J. **750**, 3 (2012).
[67] Y. Fujita, K. Kohri, R. Yamazaki, and K. Ioka, Phys. Rev. D **80**, 063003 (2009).
[68] Y. Ohira, N. Kawanaka, and K. Ioka, Phys. Rev. D **93**, 083001 (2016).
[69] J. C. Higdon and R. E. Lingenfelter, Astrophys. J. **628**, 738 (2005).