Secondary cosmic ray nucleus spectra strongly favor reacceleration of particle transport in the Milky Way

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(Dated: October 9, 2018)

The precise observations of Galactic cosmic ray fluxes of the secondary family, such as Li, Be, B, are expected to have significant implications on our understanding of the cosmic ray origin and propagation. Here we employ the recent very precise measurements of those species by the Alpha Magnetic Spectrometer on the International Space Station, together with their parent species (C and O), as well as the data collected by the Voyager-1 spacecraft outside the heliosphere and the Advanced Composition Explorer, we investigate the propagation of cosmic rays in the Milky Way. We find that these new data strongly favor the existence of reacceleration of cosmic rays during the propagation rather than the convective transport. We further find that for the reacceleration model, the slope of rigidity dependence of the diffusion coefficient is close to the Kolmogorov-type of turbulence, and the spectral hardenings of both the primary and secondary particles can be well described by the injection hardening rather than the propagation hardening.

PACS numbers: 96.50.S-

I. INTRODUCTION

It has been well established that charged cosmic rays (CRs) propagate diffusively in the Milky Way, and interact with the interstellar medium, fields, and plasma waves. Such interactions would leave imprints on their spectra and produce secondary particles and radiation \cite{1}. Precise measurements of CR energy spectra, particularly the secondary class such as Li, Be, B or Sc, Ti, V, Cr, Mn are crucial to probing the propagation and interactions of CRs. Using improved data acquired in recent years by, e.g., PAMELA and AMS-02, we do have significantly improved constraints on the CR propagation parameters \cite{2–11}. Nevertheless, the big patterns of the CR propagation are still under debate, and those constraints on the model parameters are model-dependent.

Other than the diffusion in turbulent magnetic fields and the inelastic collisions with the interstellar gas, CR particles are widely postulated to experience convective propagation \cite{12} which is believed to be driven by Galactic stellar winds and/or stochastic reacceleration by randomly moving magnetohydrodynamic (MHD) waves \cite{13}. Previously the measurements are not precise enough to discriminate these two classes of model configurations, although several recent studies showed hints that the reacceleration model was somehow favored compared with the convection one \cite{7,10}. However, there were uncertainties due to the entanglement with assumptions of the source injection and solar modulation.

Here we investigate this problem critically with the most recently published data on Li, Be, B and their parent nuclei C and O by AMS-02 \cite{14,15}. To better constrain the model, the low-energy measurements of these nuclei by Voyager-1 out of the heliosphere \cite{16}, and the medium-energy measurements by the ACE-CRIS instrument at top of the atmosphere are also used. Compared with previous studies, several significant improvements have been employed to minimize the dependence of various kinds of model assumptions. To disentangle with the solar modulation model, the AMS-02 and ACE-CRIS data are corrected to the local interstellar (LIS) results using a non-parametric method based on the wide-band data \cite{17} (see also Ref. \cite{18} for similar results with a different method). Furthermore, the injection spectra of CRs are also described with a non-parametric, spline interpolation method.

II. METHODOLOGY

The propagation of CRs is described by a set of coupled diffusion equations, including the energy losses and fragmentations due to interactions in the medium, the reacceleration and/or the convection effects. For details about the propagation equations one can refer to Ref. \cite{1}. With proper simplifications the propagation equations can be solved analytically (e.g., \cite{19}). However, for general purposes and realistic astrophysical ingredients, a numerical way is usually necessary \cite{20–23}. We use the numerical code GALPROP to calculate the propagation of CRs \cite{24,21}. A cylindrically symmetric geometry of the Galaxy is assumed, with a maximum radius \( r_{\text{max}} = 20 \, \text{kpc} \) and a height of \( z_{\text{h}} \) with \( z_{\text{h}} \) free to be fitted. It has been shown that a three-dimensional configuration of the propagation geometry does have some impacts on the results of propagation \cite{24,26}. We expect that such effects will affect...
simultaneously on both models we are going to compare with, and thus neglect such a complexity.

The diffusion coefficient is parameterized as \( D(\rho) = \beta^\rho D_0(\rho/\rho_0)\delta \), where \( \rho \) is the rigidity of CR particles, \( D_0 \) is (approximately) the diffusion coefficient at \( \rho_0 = 4 \) GV, \( \delta \) is the rigidity-dependence slope, \( \beta \) is the velocity in unit of light speed, and the \( \beta^\rho \) term is employed to empirically describe possible resonant scatterings of CRs off the MHD waves \([27, 28]\). The reacceleration effect is described by a diffusion in the momentum space, and the Alfvèn velocity \( (v_A) \) of the MHD waves is employed to characterize the strength of reacceleration \([13]\). The convection is assumed to be perpendicular to the Galactic plane, and the convection velocity is parameterized as a linear function of the vertical height to the Galactic plane, \( V_c = z \cdot dV_c/dz \).

To minimize the impact of the parameterization of the injection spectrum of primary CRs, we adopt a non-parametrized method by means of spline interpolation among a few chosen rigidity knots \([17, 29]\). The (logarithmical) flux normalizations at such knots are fitted together with other free parameters. In this work we take 7 knots logarithmically evenly distributed between 0.1 GV and 3 TV. The abundance ratio between primary nuclei C and O is described by a constant factor \( \xi_0 \). In addition, there might be uncertainties of fragmentation cross sections to produce secondary nuclei, which couple with the propagation parameters. In this work we fix the cross section of the Boron production, and multiply two constants \( \xi_{Li} \) and \( \xi_{Be} \) to the predicted fluxes of Li and Be. Finally, the spatial distribution of CRs is assumed to follow the observed distribution of supernova remnants \([2]\).

In total there are 15 free parameters in the model: 5 for the modeling of propagation \( (D_0, \delta, \eta, z_h, v_A) \) or \( dV_c/dz \), 7 for the injection spectrum, 3 for normalizations of Li, Be, and O. We use the Markov Chain Monte Carlo method to deal with this high-dimensional problem and fit the parameters \([30, 31]\).

### III. Results

The fitting results of the main model parameters are given in Table I. It is clear that the reacceleration model fits the data significantly better than the convection model. For the convection model, the minimum \( \chi^2 \) value is about 477.5 for a number of degree-of-freedom of 383, which gives a \( p \)-value of \( 7 \times 10^{-4} \). As for the comparison between the reacceleration and convection models, the Akaike information criterion (AIC) gives a difference of the AIC values of 145.0, which suggests that the convection model is about \( \exp(-145.0/2) = 3.3 \times 10^{-32} \) times as probable as the reacceleration one.

Fig. 1 shows the comparison between the best-fit model calculated fluxes and the data from Voyager-1 \([16]\), ACE-CRIS, and AMS-02 \([17]\), for Li, Be, C, and O nuclei, respectively. We find that the convection model gives on average larger residuals than the reacceleration model. Furthermore, the value of \( \delta \) is larger in the convection model than that in the reacceleration model. It is known that the reacceleration effect would make the bump feature of the secondary-to-primary ratio more prominent, and thus \( \delta \) can be smaller \([20]\). Therefore the predicted secondary fluxes by the convection model are generally softer than that by the reacceleration one.

The spectral hardenings above a few hundred GeV/n are found in both the primary and secondary fluxes \([14, 15, 32–36]\). A direct fitting to the secondary-to-primary ratios results in a change of the slopes for rigidity intervals of 60.3–192 and 192–3300 GV \([15]\), suggesting that a propagation mechanism is responsible to the spectral hardenings \([37, 39]\). Similar conclusion was also found in Ref. \([40]\) for a fitting to the B/C data taking into account the propagation model.

In above we assume a single power-law form of the diffusion coefficient at high rigidities. Clear spectral hardenings can be seen in the fitting results for both primary and secondary nuclei (see Fig. 1), which are expected to be due to the hardening of the injection spectrum. Fig. 2 shows the best-fit injection spectra for the convection and reacceleration models discussed in this work. These non-parametric injection spectra turn out to be similar with broken power-laws usually assumed. The spectra experience a softening at \~{}GV rigidities and a hardening above several hundred GV. The physical origin of such spectral shapes would be very important in understanding the acceleration and/or confinement of CRs at source. Note that the \( \gamma \)-ray emission from supernova remnants also suggests broken power-law forms of particles around GeV energies \([41]\). Possible physical mechanisms include the strong ion-neutral collisions near the shock fronts \([42]\) or the escape of particles from/into finite-size regions \([43, 44]\). The high-energy hardening may be due to the superposition of various sources \([45]\), or the non-linear acceleration \([46]\).

We then check that whether the data require an additional break of the diffusion coefficient or not. Two more parameters, the break rigidity \( \rho_B \) and the high energy slope \( \eta_B \), have been added in the model\(^1\). We find that for the reacceleration model, the addition of the break of the diffusion coefficient

| Parameter | Unit | Convection | Reacceleration |
|-----------|------|-------------|---------------|
| \( D_0 \) | \( 10^{29} \text{cm}^2\text{s}^{-1} \) | 3.30 ± 0.07 | 4.53 ± 0.18 |
| \( \delta \) | | 0.481 ± 0.006 | 0.348 ± 0.010 |
| \( z_h \) | (kpc) | 3.97 ± 0.20 | 3.18 ± 0.20 |
| \( v_A \) | (km s\(^{-1}\)) | ... | 34.9 ± 1.6 |
| \( dV_c/dz \) | (km s\(^{-1}\) kpc\(^{-1}\)) | < 1.45 \(| \times 10^{-6} | 3.58 ± 1.01 |
| \( \eta \) | | −1.55 ± 0.08 | 0.15 ± 0.11 |
| \( \xi_{Li} \) | | 1.155 ± 0.007 | 1.144 ± 0.007 |
| \( \xi_{Be} \) | | 1.024 ± 0.007 | 1.016 ± 0.006 |
| \( \chi^2_{\text{reac}}/\text{dof} \) | | 477.5/383 | 332.5/383 |

\(^1\)The error is smaller than the grid size of 0.2 kpc. We conservatively adopt 0.2 kpc as the error. \(^2\)95% upper limit.

\(^1\) Note that the momentum diffusion coefficient depends on the parameter \( \delta \) \([13]\). Here the break rigidity is restricted to be larger than 100 GV, where the reacceleration effect is expected to be small. Therefore only the low rigidity slope \( \delta \) is relevant to the reacceleration.
The reacceleration model and open for the convection model) defined as (data−model)/error.

In this work we scrutinize the CR propagation models with the newest precise measurements of both the primary and secondary CR fluxes by AMS-02 and Voyager-1. Usually the CR propagation entangles with the injection and the solar modulation, making the conclusion ambiguous. Several approaches are adopted to make the study of the propagation problem less model-dependent. First, the AMS-02 and ACE-CRIS data were corrected to the LIS results using a minimum model-dependent way [17]. Then we use a non-parametric method with spline interpolation to describe the injection spectrum. This way can minimize the impact of the assumption of the injection spectrum by any other kinds of functions.

With those approaches, we find that the propagation model with reacceleration of CRs with scattering off randomly moving MHD waves is strongly favored by the observational data. Compared with the model with a convection velocity, the best-fit $\chi^2$ value of the reacceleration model is smaller by about 147.5 with the same numbers of degrees of freedom. This conclusion can only be achieved with significantly improved measurements of the data in a very wide energy range. Also the improvement of the analysis method with a global fitting tool and the elimination of dependence of the solar modulation and source injection models are helpful.

We further find that for the reacceleration model, no high-rigidity ($O(10^5)$ GV) hardening of the diffusion coefficient is necessary to account for the spectral hardenings of both the primary and secondary nuclei. The observed spectral hardenings can be largely due to the hardening of the injection spectrum. For the convection model which suggests a relative large $\delta$, the inclusion of a spectral break of the diffusion coefficient can improve the fit moderately. Compared with the reacceleration model, the convection model still fits the data much poorer even with such a propagation break.

Antiprotons can also be used as a diagnostics of the propagation model. We have done fittings to the proton and antiproton fluxes measured by Voyager-1 [16] and AMS-02 [35,47].
with the convection and reacceleration models based on the mean propagation parameters given in Table I and find that the reacceleration model (with a minimum $\chi^2_{p+\theta} = 187.4$) is favored than the convection one ($\chi^2_{p+\theta} = 346.0$). Note, however, there are complications from the uncertainties of the propagation parameters, the antiproton production cross section, the charge-sign dependence of the solar modulation, and/or possible exotic contribution from e.g., the dark matter.

Although there are quite a number of discussions in literature to extend the propagation of CRs with more complicated configurations, such as the spatial variation of the propagation properties [38, 39] and the anisotropic diffusion with respect to ordered magnetic fields [48], our results show that a simple two-dimensional, isotropic, and uniform propagation scenario can give quite good description to the locally measured CRs. Better understanding of the CR transport may be achieved with more precise measurements of the CR distribution in the Galaxy, by e.g., $\gamma$-rays.

Acknowledgments

We thank V. Ptuskin for helpful discussion. This work is supported by the National Key R&D Program of China (No. 2016YFA0400200), the National Natural Science Foundation of China (Nos. 11433009, 11722328, U1738205, U1738209, 11851305), the Key Research Program of Frontier Sciences of Chinese Academy of Sciences (No. QYZDJ-SSW-SYS024), and the 100 Talents program of Chinese Academy of Sciences.