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# Interpretation of new measurements of B/C and diffuse gamma rays using freshly accelerated cosmic rays interacting with surrounding medium

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Big progresses have been achieved in the measurements of cosmic rays and gamma rays in recent years. The diffuse $\gamma$-ray emission above 100 TeV was measured by the Tibet-AS$\gamma$ experiment. Hardenings of the boron-to-carbon and boron-to-oxygen ratios at about 100 GeV/n have been revealed by the DAMPE experiment. These observations indicate modifications to the traditional cosmic-ray propagation and/or interaction model. In this contribution, we propose that the secondary particles produced by the hadronic interactions of freshly accelerated cosmic rays with the interstellar gas near the sources, can naturally account for the diffuse emission and the secondary-to-primary ratios. This model can be further tested by recent measurements with LHAASO.

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## 1. Introduction

With the advancements in new generation experiments, measurements of cosmic rays (CRs) are entering an era of high precision, revealing a multitude of new phenomena. These observations can be used to study the Galactic CRs' origin, propagation, and distribution in the Galaxy. In the standard model of acceleration and propagation, the CR flux is expected to fall off with energy as a single power-law[24, 25]. However, recent observations have challenged this traditional understanding. Many experiments have discovered a phenomenon that the spectra of primary CR particles harden at more than ∼ 200 GV [3, 4, 28] and both proton and helium spectra have been observed to soften at higher energies(>∼ 10 TeV) [9, 14, 28]. Two years ago, the diffuse gamma-ray emission in the Galactic plane above 100 TeV was measured by Tibet-AS$\gamma$ experiment[8]. The Tibet-AS$\gamma$ fluxes are higher than the prediction of the conventional CR propagation model, and additional components or modifications to the conventional propagation framework may be needed.

Most recently, the DAMPE experiment has detected explicit hardenings of the boron-to-carbon and boron-to-oxygen ratios at 100 GeV/n [15]. The findings of spectral hardening of nuclei bring about various alternatives of the traditional CR theory. Most of them fall into, but are not limited to, three categories: acceleration process [20, 23], transport effect [19, 22], and nearby source(s) [30, 32]. The diffuse gamma-ray emission from galactic plane exceeds that predicted from the interactions of cosmic rays in the interstellar medium (ISM). This result could be the consequence of spatial variations in the distribution of cosmic rays or in the dust-to-gas ratio [16] or the significant contributions from unresolved sources. As for transport effect and close-by sources, an excess of boron-to-carbon ratio is also expected in these models.

In 2017, the HAWC collaboration has detected the extended TeV gamma-ray emission of two middle-aged pulsars, Geminga and PSR B0656+14 [1], and the LHAASO Collaboration has recently measured the energy spectrum of gamma-rays surrounding pulsar J0621+3755 [7]. They found that the diffusion coefficient near the source is much smaller than that elsewhere in the ISM. This means that before diffusion in the interstellar space, the cosmic rays experience a slower diffusion process near the source region [17, 27], which has not been considered in the conventional propagation model.

In this work, we consider the scenario where secondary CRs generate from the hadronic interactions between freshly accelerated cosmic rays and the medium when CRs experience a slower diffusion near the sources. We find that the ratio anomalies, i.e., boron-to-carbon and boron-to-oxygen ratios can be naturally accounted for. The excess of diffuse gamma-ray emission can also be explained. This could be tested by the LHAASO experiments.

## 2. Model description

### 2.1 Spatially-dependent propagation

Supernova remnants (SNRs) are the most widely acknowledged origin of primary Galactic CRs. It is commonly hypothesized that cosmic rays are accelerated through the shock waves generated during supernova explosions. The CR particles were accelerated by the sources and injected into the Milky Way. They completed the propagation procedure in the galactic magnetic field and interacted in the interstellar medium (ISM) to produce secondary particles and radiation. The propagation equation for CRs can be written as

$$\begin{aligned}\frac{\partial \psi}{\partial t} &= Q(\vec{r}, p) + \nabla \cdot (D_{xx} \nabla \psi - \vec{V}_c \psi) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2}\right] \\ &\quad - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla \cdot \vec{V}_c)\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}\,, \end{aligned} \tag{1}$$

where $\psi = \mathrm{d}n/\mathrm{d}p$ is the CR density per total particle momentum $p$ at position $\vec{r}$, $Q(\vec{r}, p)$ is the source distribution, $D_{xx}$ is the diffusion coefficient, $D_{pp}$ is the diffusive reacceleration and $\tau_f$ and $\tau_r$ are the characteristic time scales for fragmentation and radioactive decay respectively.

The diffusion halo is commonly modeled as a flattened cylinder, with the galactic disk situated within it. Cosmic ray sources and the interstellar medium (ISM) are primarily concentrated within the galactic disk. The Sun is positioned on the galactic disk, approximately 8.5 kpc away from the galactic center. The radial boundary of the diffusion halo is typically assumed to align with the galaxy's radius, while the half-thickness remains an uncertain parameter to be determined through fitting cosmic ray data. Within the halo, cosmic rays undergo diffusion, and once they reach the halo's boundary, they can freely escape the diffusive space.

In this work, we used the spatially-dependent propagation (SDP) model. This model divides the diffusive halo into two regions: the inner halo (IH) within the Galactic disk and its surrounding areas, where the diffusion process is relatively slow; and the outer halo (OH) outside the IH, where turbulence is primarily driven by CRs themselves, so the diffusion process tends to be fast, approaching the conventional diffusion model. The half-thickness of the whole diffusive halo is $L$, with the fractions of IH and OH being $\xi$ and $1 - \xi$, respectively. The diffusion coefficient $D$ in the whole region is parameterized as:

$$D(r, z, \mathcal{R}) = D_0 F(r, z) \beta^{\eta} \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{\delta_0 F(r,z)}\,, \tag{2}$$

with

$$F(r, z) = \begin{cases} g(r, z) + [1 - g(r, z)] \left(\dfrac{z}{\xi L}\right)^n, & |z| \leqslant \xi L \\ 1\,, & |z| > \xi L \end{cases}\,. \tag{3}$$

Here, $g(r, z)$ is $N_m/[1 + f(r, z)]$, in which $f(r, z)$ is the source distribution. For more details about the model, one can refer to [18, 21, 26, 31, 32].

## 2.2 Local SNR

The fine structure of spectral hardening and break-off at 200GV and 14 TeV, respectively, appears to originate from a local source. In this study, the progenitor of Geminga, a SNRs, was introduced. The injection process of the SNR is approximated as burst-like. The source injection rate as a function of time and rigidity is assumed to be

$$Q(\mathcal{R}, t) = Q_0(t) \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{-\gamma} \exp\left[-\frac{\mathcal{R}}{\mathcal{R}_c}\right]\,, \tag{4}$$

$$Q_0(t) = q_0 \delta(t - t_0) \ , \tag{5}$$

where $\mathcal{R}_\mathrm{c}$ is the cutoff rigidity and $t_0$ is the time of the supernova explosion. The propagated spectrum from Geminga SNR is thus a convolution of the Green's function and the time-dependent injection rate $Q_0(t)$ [10]

$$\varphi(\vec{r}, \mathcal{R}, t) = \int_{t_i}^{t} G(\vec{r} - \vec{r}\,', t - t', \mathcal{R}) Q_0(t') dt'. \tag{6}$$

### 2.3 Secondary CRs

Secondary particles, such as boron and photons, are brought forth throughout the transport by spallation and radioactive decay. Their source terms read

$$Q_j = \sum_i (n_\mathrm{H} \sigma_{i+\mathrm{H} \to j} + n_\mathrm{He} \sigma_{i+\mathrm{He} \to j}) v \psi_i \ , \tag{7}$$

where $n_\mathrm{H}$ and $n_\mathrm{He}$ is the number density of the interstellar hydrogen and helium, $\sigma_{i+\mathrm{H/He} \to j}$ is the total cross section of the corresponding hadronic interactions, and $\psi_i$ is the differential density of particle species i.

Furthermore, the freshly accelerated CRs at source regions could interact with the gas around the sources before they enter the interstellar space. The injection spectra of boron and photons near the sources are written as

$$Q_j = \sum_i (n_\mathrm{H} \sigma_{i+\mathrm{H} \to j} + n_\mathrm{He} \sigma_{i+\mathrm{He} \to j}) v Q_i(R) \tau. \tag{8}$$

where $\tau$ is the effective confinement time of the particles around the sources.

## 3. Results

In Fig. 1, we show the comparison between the best-fit model results and the observational data of proton and helium. The solid line is the flux in the local interstellar environment and the dashed line is that after solar modulation. The hardening of the proton and helium spectra around several hundred GeV can be attributed to the summation of the background contribution and the local SNR contribution, and the softening around 14 TeV and 34 TeV is mainly due to the spectral cutoff of the local SNR injection.

In Fig. 2, we show the B/C and B/O ratios for the models. The secondary particles produced by the propagation process in the Milky Way (blue line) and in the vicinity of the sources (red line). The sum of these two components (black line) naturally explains the hardenings of the B/C and B/O ratios. The dashed lines are the spectra in the local ISM, and the solid lines are the modulated spectra near the Earth.

The DGE is produced through three major processes: decay of $\pi^0$ produced in pp-collisions, ICS and bremsstrahlung of CREs. Comparisons between the results of the models and the experimental data are shown in Fig. 3. At high energies, the $\pi^0$ decay component dominates the DGE. Therefore we only consider the $\pi^0$ decay component in comparing the model calculation with the measurements

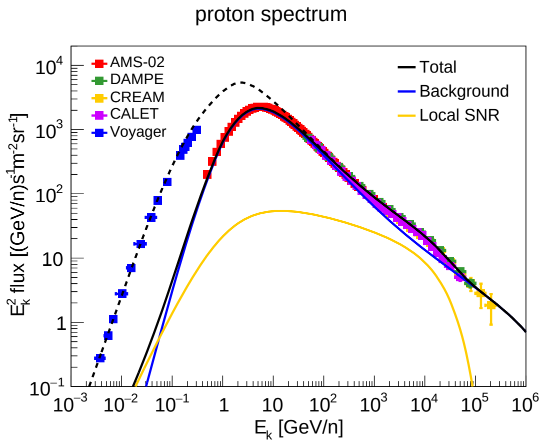

**Figure 1:** Credit:[31]. The proton and helium spectra expected from the model, compared with the measurements. The blue solid lines are the fluxes from background SNRs, and the yellow solid lines are the contribution from the local SNR. The black lines are the total fluxes. The data points are taken from the Voyager(blue) [13], AMS-02 (red) [3, 5], DAMPE (green) [9, 14], CALET (violet) [2] and CREAM-II (yellow) [28] experiments.

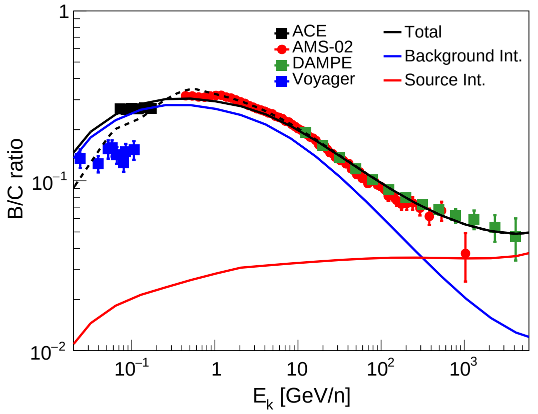

**Figure 2:** Credit:[31]. B/C and B/O ratios. The data points are taken from the Voyager(blue) [13], ACE (black) [29], AMS-02 (red) [3, 6] and DAMPE (green) [9] experiments.

by ARGO-YBJ and Tibet-AS$\gamma$ (the top panel, for two sky regions, 25° <l< 100°, |b|< 5° and 50° <l< 200°, |b| < 5°, respectively). The DGE fluxes from the background sources are lower by a factor of several than the data, as also shown therein. The inclusion of the secondary production from freshly accelerated CRs interacting with the surrounding gas, which has a harder spectrum than the CRs diffusing out, can reproduce the data well.

## 4. Conclusion

In this contribution, we propose that the excesses of secondary CRs originate from the hadronic interactions between the freshly accelerated cosmic rays and the medium, as CRs experience a slower

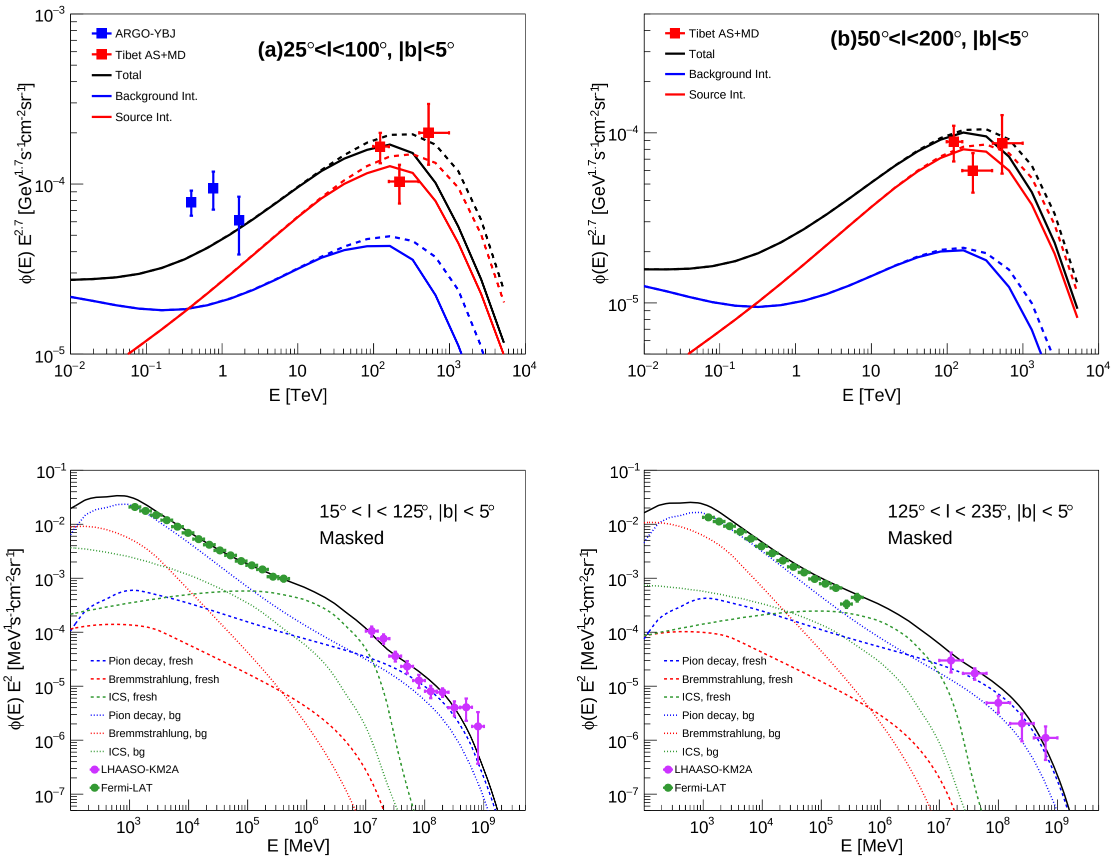

**Figure 3:** Credit:[32]. Diffuse gamma-ray emission of the different regions of the galactic plane. The data points are taken from the ARGO-YBJ (blue) [11], Tibet AS+MD (red) [8], Fermi-LAT (green) [33] and LHAASO-KM2A (violet) [12] experiments.

diffusion near the sources. This process has been neglected in the previous studies of the propagation model. In comparison with the secondaries generated during propagation, the secondary CR flux generated in the source regions is harder and extends to TeV energies. Therefore, the ratio anomalies, i.e., boron-to-carbon and boron-to-oxygen ratios could be naturally accounted for.

The DGE at ultra-high energies is believed to be produced through the interaction of CRs with the ISM, and is thus a good tracer to study the propagation of galactic CRs. The measurements of DGE above 100 TeV energies by Tibet-AS$\gamma$ recently shows a significant excess compared with the prediction of the conventional CRs propagation and interaction model. We find that possible hadronic interactions of CRs with the ambient gas surrounding the acceleration sources can account for the ultra-high energy DGE observed by Tibet-AS$\gamma$. The harder spectra of CRs in the vicinity of the sources can naturally explain the high energy part of the DGE, while keeping the low-energy part unaffected. We find that with proper model parameters, all these CR measurements can be well reproduced.

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