Is the B/C slope in AMS-02 data actually telling us something about the diffusion coefficient slope?

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Scientific motivations and goals

There is a common misconception about the fact that high-energy B/C data directly provides the slope of the diffusion coefficient, implying that additional effects at play (convection, reacceleration, and destruction) can be neglected.

Using the code USINE for CR propagation and taking into account all relevant processes, we study:

- the slope of the B/C in different propagation scenarios, and compare to the B/C data from AMS-02.
- the flux slope for different CR species.
A two break diffusion coefficient is used to reproduce the B/C, following first hint of diffusive origin reported in PRL 119, 241101 (2017)

1D model and semi-analytic approach with the USINE code [arxiv:1807.02968]
**Benchmarks for galactic propagation**


The best fit parameters:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BIG</th>
<th>SLIM</th>
<th>QUAINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/dof</td>
<td>61.7/61 = 1.01</td>
<td>61.8/63 = 0.98</td>
<td>62.1/62 = 1.00</td>
</tr>
<tr>
<td>Intermediate-rigidity parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{10}$ [kpc$^2$ Myr$^{-1}$]</td>
<td>$0.30^{+0.03}_{-0.04}$</td>
<td>$0.28^{+0.02}_{-0.02}$</td>
<td>$0.33^{+0.03}_{-0.06}$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$0.48^{+0.04}_{-0.03}$</td>
<td>$0.51^{+0.02}_{-0.02}$</td>
<td>$0.45^{+0.05}_{-0.02}$</td>
</tr>
<tr>
<td>Low-rigidity parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_c$ [km s$^{-1}$]</td>
<td>$0^{+7.4}$</td>
<td>N/A</td>
<td>$0.0^{+8}$</td>
</tr>
<tr>
<td>$V_A$ [km s$^{-1}$]</td>
<td>$67^{+24}_{-67}$</td>
<td>N/A</td>
<td>$101^{+14}_{-15}$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1 (fixed)</td>
<td>1 (fixed)</td>
<td>$-0.09^{+0.35}_{-0.57}$</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>$-0.69^{+0.61}_{-1.26}$</td>
<td>$-0.87^{+0.33}_{-0.31}$</td>
<td>N/A</td>
</tr>
<tr>
<td>$R_1$ [GV]</td>
<td>$3.4^{+1.1}_{-0.9}$</td>
<td>$4.4^{+0.2}_{-0.2}$</td>
<td>N/A</td>
</tr>
<tr>
<td>High-rigidity break parameters (nuisance parameters)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta_h$</td>
<td>0.18</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>$R_h$ [GV]</td>
<td>247</td>
<td>237</td>
<td>270</td>
</tr>
<tr>
<td>$s_h$</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Slide from Y. Genolini
Analysis strategy

- Compute B/C flux ratio as a function of rigidity ($R=pc/Ze$).
- Compute the observed spectral index: $\gamma_{Obs} = \frac{d [\log \phi]}{d [\log R]}$
- Compute the difference wrt theoretical expectations
  $\Delta_{slope} = |\gamma_{Th}| - |\gamma_{Obs}|$
- Extend the work to other CR species, from H to Fe
Purely diffusive scenario

Convection, reacceleration and destruction are neglected.

\[
- \nabla_x \left\{ K(E) \nabla_x \psi_\alpha - \nu_{\text{ism}} \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ \text{tot}(E) \psi_\alpha - \beta K \frac{\partial \psi_\alpha}{\partial E} \right\} \\
+ \sigma_{\beta \rightarrow \alpha} n_{\text{ism}} n_\beta = q_\alpha + \sum_\beta \left\{ \sigma_{\beta \rightarrow \alpha} \nu_\beta n_{\text{ism}} + \nu_{\beta \rightarrow \alpha} \right\} \psi_\beta
\]

<table>
<thead>
<tr>
<th>Free parameters / Models</th>
<th>BIG</th>
<th>BIG Pure diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{10}[\text{kpc}^2] )</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>( \delta )</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>( \eta )</td>
<td>1 or</td>
<td>1</td>
</tr>
<tr>
<td>( \delta_i )</td>
<td>-0.69</td>
<td>-0.69</td>
</tr>
<tr>
<td>( s_i )</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>( R_i \text{[GV]} )</td>
<td>247</td>
<td>247</td>
</tr>
<tr>
<td>( V_A \text{[km/s]} )</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>( V_c \text{[km/s]} )</td>
<td>67</td>
<td>N/A</td>
</tr>
<tr>
<td>( \Delta_h )</td>
<td>0.18</td>
<td>0.18</td>
</tr>
</tbody>
</table>
B/C on a pure diffusion scenario

Goal: simulate the B/C for a given set of propagation parameters, and study its slope with respect to the diffusion coefficient slope

\[
\frac{\Phi_{sec}}{\Phi_{prim}} \propto R^{-\delta}
\]

\[
\frac{\Phi_{sec}}{\Phi_{prim}} \propto R^{-(\delta - \Delta_h)}
\]

\[
\Delta_{slope} = |\gamma_{Th}| - |\gamma_{Obs}|
\]
B/C on a pure diffusion scenario

Expected behavior:

\[ \frac{\Phi_{\text{sec}}}{\Phi_{\text{prim}}} \propto R^{-\delta} \]

\[ \frac{\Phi_{\text{sec}}}{\Phi_{\text{prim}}} \propto R^{-(\delta - \Delta_h)} \]

Expected behavior:

\[ \Delta_{\text{slope}} = 0 \]

\[ \Delta_{\text{slope}} = \Delta_h \]
**B/C on a pure diffusion scenario**

Our result is in agreement with the expected behaviour above 50 GV. Below 50 GV, even for the purely diffusive regime, departure from expectations is due to secondary production.
Full transport scenario

Destruction, convection and reacceleration are taken into account.

\[
- \vec{\nabla}_x \left\{ K(E) \vec{\nabla}_x \psi_\alpha - \vec{V}_c \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{tot}(E) \psi_\alpha - \beta^2 K_{pp} \frac{\partial \psi_\alpha}{\partial E} \right\} \\
+ \sigma_\alpha v_\alpha n_{ism} \psi_\alpha + \Gamma_\alpha \psi_\alpha = q_\alpha + \sum_\beta \left\{ \sigma_{\beta \rightarrow \alpha} v_\beta n_{ism} + \Gamma_{\beta \rightarrow \alpha} \right\} \psi_\beta
\]
**B/C on a Full transport model**

![Plot showing expected behavior](https://lpsc.in2p3.fr/usine)

\[ \Delta_{\text{slope}} = |\gamma_{\text{Th}}| - |\gamma_{\text{Obs}}| \]

**Expected behavior:**

- \( \Delta_{\text{slope}} = 0 \)
- \( \Delta_{\text{slope}} = \Delta_h \)

**Models:**
- BIG
- SLIM
- QUAIINT
- AMS-02 (2018)
B/C on a full transport model

The B/C slope rigidity dependence is shaped in particular by inelastic interactions up to TeV energies.

(https://lpsc.in2p3.fr/usine)

- BIG
- SLIM
- QUAIN'T
- AMS-02 (2018)
**B/C on a full transport model**

The B/C slope rigidity dependence is shaped in particular by inelastic interactions up to TeV energies.

AMS data above 50 GV:

\[ B/C \propto R^{-1/3} \]

\[ \Delta_{slope} = |\gamma_{th}| - |\gamma_{obs}| = \delta - |\gamma_{obs}| = 0.48 - 0.33 = 0.15 \]
Take home message

- The slope of the B/C should be disregarded as a direct indicator of the diffusion coefficient, because additional physical processes, in particular inelastic interactions, play a major role up the TV region.

Is this universal or species dependent?

- Dominant effect is destruction, and X-section depends on A: consequences on data slopes?
Flux slope dependence on Z: diffusion-only scenario

(https://lpsc.in2p3.fr/usine)

BIG: Diffusion and secondary production at 50 GV

$\gamma_{obs}$ vs Atomic Number, $Z$

$\gamma^P_{Th}$, $\gamma^S_{Th}$
Flux slope dependence on $Z$: diffusion-only scenario

BIG: Diffusion and secondary production at 50 GV

$\Phi_P \propto \frac{q}{K} \propto R^{-\alpha-\delta}$
Flux slope dependence on Z: diffusion-only scenario

(https://lpsc.in2p3.fr/usine)

BIG: Diffusion and secondary production at 50 GV

\[ \Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta} \]
Flux slope dependence on Z: diffusion-only scenario

BIG: Diffusion and secondary production at 50 GV

\[ \Phi_n^{\text{step}} \propto \frac{\Phi_P}{K} \propto R^{-\alpha-(n+1)\delta} \]

\[ \Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta} \]
Flux slope dependence on Z: diffusion-only scenario

Even in diffusion-only scenario, departure from naive expectation due to multi-step production

$$\Phi_s \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta}$$

$$\Phi_{n\text{-step}} \propto \frac{\Phi_P}{K} \propto R^{-\alpha-(n+1)\delta}$$
Secondary CR production

Relative contributions per production process for elemental fluxes (at 50 and 2 TV).

The species with the highest primary content are H, O, Si, and Fe (black), while Li, Be, B, F, and Cl to V have the highest secondary component from both single (red) and multi-step production (blue and green).
Full propagation model

\[ \Phi_P \propto \frac{q}{K} \propto R^{-\alpha - \delta} \]

\[ \Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha - 2\delta} \]
Full propagation model

Result: Neither primary nor secondary data slope provide direct indication of “source + diffusion” coefficient.

Increasing slope with Z for primary and secondary elements.

$\Phi_P \propto \frac{q}{K} \propto R^{-\alpha-\delta}$

$\Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta}$
Summary

- The B/C slope should not be interpreted as the diffusion coefficient spectral index, since additional physical processes, especially inelastic collisions play an important role.

- Up to TV rigidities, the measured flux spectral index as a function $Z$ differs significantly from the values expected in diffusion-only scenario.

- We expect a slope difference between light and heavy nuclei at $\sim 50$ GV, this difference decreasing with rigidity. AMS-02, CALET, DAMPE should see this effect in their data.