Bayesian analysis of Cosmic Ray Propagation Parameters: antiproton-to-proton ratio is consistent with spatial-dependent Model prediction.

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• Spatial Dependent Propagation Model

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Transport Equation

\[ Q = Q_{pri} + Q_{sec}. \]

\[ Q_{pri} \propto R^{-\nu} : \text{primary source term;} \]

\[ Q_{sec} = \sum_j \Gamma_j^{sp} \psi_j : \text{secondary production term from spallation of } j \text{ nuclei with rate } \Gamma_j^{sp} \]

\[ \psi = \psi(E,r,z) : \text{particle number density} \]

\[ \frac{\partial \psi}{\partial t} = Q + \nabla \cdot (D \nabla \psi) - \psi \Gamma + \frac{\partial}{\partial E} (\dot{E} \psi) \]

\[ \dot{E} = -\frac{dE}{dt} : \text{ionization and Coulomb losses} \]

\[ D(R) \propto R^\delta : \text{rigidity } (R = \frac{p}{Z}) \text{ dependent diffusion coefficient} \]

For homogeneous diffusion model, primary particles at high energies: \[ \psi(R) \propto R^{-\nu-\delta} , \text{ single power law.} \]
High energy breaks in the H and He spectra

M. Aguilar et al.,

M. Aguilar et al.,

Current explanations:
1) multi-component populations
2) the CR injection, Q(R), non-linear effects in diffusive-shock-acceleration mechanisms
3) Nonlinear propagation or inhomogeneous diffusion coefficient D(R)
Introduction to Spatial dependent propagation model

Recent studies based on gamma-ray observations:
1) Galactic wind (S. Recchia et al., arXiv:1604.07682)

NGC 891

Near Infrared

Radio
Spatial dependent propagation model (Two-Halo-Model)

Diffusion Coefficient as a function of space:

\[ D_{xx}(r, z, p) = \begin{cases} 
D_0 \beta^n \left( \frac{R}{R_0} \right) \delta & |z| < \xi z_h \\
\chi D_0 \beta^n \left( \frac{R}{R_0} \right) \delta F(r, z) & |z| > \xi z_h 
\end{cases} \]

\[ F(r, z) = \left\{ \frac{1}{1 + \exp(f(r))} + \Delta/\delta \right\} \left( \frac{z}{\xi z_h} \right)^n \]

N.Tommassetti, arXiv: 1509.05775
Yi-Qing Guo, Zhen Tian, Chao Jin, arXiv: 1509.08227v1

**DRAGON** package is used to solve the propagation equation.
• Spatial Dependent Propagation Model

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Bayesian analysis

- 8-parameter set: $\theta$
- Observed data set: $D$
- The posterior distribution

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)}$$

- depends on the likelihood function $L(\theta) = P(D|\theta)$ and on the prior probability distribution $P(\theta)$.
Markov Chain Monte-Carlo

- The transition probability to move from $\theta_n$ to $\theta_{n+1}$ in the parameter space:
  \[ T(\theta_n, \theta_{n+1}) \]

- An arbitrary proposal density distribution:
  \[ q(\theta_n, \theta_{n+1}) \]

- The probability to accept this new point:
  \[ \alpha(\theta_n, \theta_{n+1}) = \min \left\{ 1, \frac{P(\theta_{n+1})q(\theta_{n+1}, \theta_n)}{P(\theta_n)q(\theta_n, \theta_{n+1})} \right\} \]

- We get
  \[ T(\theta_n, \theta_{n+1}) = \alpha(\theta_n, \theta_{n+1})q(\theta_n, \theta_{n+1}) \]

- It converges to a balance
  \[ P(\theta_{n+1})T(\theta_{n+1}, \theta_n) = P(\theta_n)T(\theta_n, \theta_{n+1}) \]
Data sample to constrain parameters:
1) H, He and C spectra
2) B/C
3) ${^{10}\text{Be}}/{^{9}\text{Be}}$

\[
\delta = 0.149
\]
\[
\delta + \Delta = 0.149 + 0.523
\]
• Spatial Dependent Propagation Model

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Antiproton production in CRs from collisions

• In space, four channels mainly contribute directly to antiproton production.

  • $p + p(\text{ISM}) \rightarrow ap + X$
  • $p + \text{He}(\text{ISM}) \rightarrow ap + X$
  • $\text{He} + p(\text{ISM}) \rightarrow ap + X$
  • $\text{He} + \text{He}(\text{ISM}) \rightarrow ap + X$

• On the ground, there are experiments:
  • 1) $p+p$ data can be used to validate the $p+p$ models.
  • 2) $p+C$ data can be used as a cross check of $p+\text{He}$. 
NA49:
158 GeV/c proton beam

EPOS LHC is the best model.
BRAHMS: 20000 GeV/c proton beam

EPOS LHC and EPOS 1.99 behave well.
ALICE:
405000 GeV/c proton beam

EPOS LHC and QGSJET04 perform well.

\[ p + p \rightarrow \bar{p} \ (\sqrt{s} = 900 \text{ GeV}) \]
• EPOS LHC is chosen as a reference model.

• We give an error estimation of this model according to the chi2 between this model and experimental data.
• Spatial Dependent Propagation Model
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Propagation and injection error dominates the total error at high energies, which can be improved by B/C measured by AMS02, CALET and DAMPE.

Cross section is taken from EPOS LHC model. Cross section error has a significant contribution, which can be improved by ground experiments.

Solar modulation error is estimated by varying solar modulation potential from 200 MeV to 700 MeV.
Prediction of ap/p with EPOS LHC

Ap/p prediction is consistent with measured data.
Error break down of positron flux

Propagation and injection error dominates the total error at high energies, which can be improved by B/C measured by AMS02, CALET and DAMPE.


Solar modulation error is estimated by varying solar modulation potential from 200 MeV to 700 MeV.
Prediction of positron flux

Positron prediction of two-halo-model is harder than that of one-halo-model. Extra component is needed.
• Spatial Dependent Propagation Model

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The result of $L$ does not converge.
Inner halo height: $0.873^{+0.340}_{-0.286}$ [kpc]

1) The inner halo height $= \xi L$ can converge mainly due to Be-10 to Be-9 low energy data. For $R = 4\ GeV$, $L_{10} \sim 0.5\ [kpc] < 0.873[kpc]$

2) We need high energy($>200\ GeV/n$) Be/B data to constrain $L_{outer}$.

3) x-ray and $\gamma$-ray observation may help to constrain the size of the outer halo.
Summaries

- Antiparticles predicted by Spatial-Dependent-Model is presented:
  - 1) antiproton-to-proton ratio prediction is consistent with the measured data.
  - 2) positron flux prediction is lower than data. Extra component is needed.

- We validate EPOS LHC as the best model.

- The error break down of the antiparticles is shown. The total error is dominated by propagation and cross section errors.

- Disk height is around ~1 kpc.
• Backup slides
preliminary
A fast scan

• the following variables fixed:

\[ \eta = -0.4 \]
\[ \phi = 0.5 \text{ GeV} \]
\[ n = 5 \]
\[ R_0 = 0.25 \text{ GeV} \]

\[ D_0 \beta^\eta \left( \frac{R}{R_0} \right)^\delta, \eta \text{ is a factor} \]
(D.Gaggero et al., arXiv:1311.5575)

Solar modulation potential
(A. Ghelfi et al., arXiv:1607.01976)

Smooth function variable
Normalization Energy.
The following variables fitted

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>(L)</td>
<td>Halo height.</td>
</tr>
<tr>
<td>(D_0)</td>
<td>Diffusion coefficient</td>
</tr>
<tr>
<td>(\chi)</td>
<td>Ratio between outer and inner Diffusion coefficients</td>
</tr>
<tr>
<td>(\delta)</td>
<td>Diffusion index of outer</td>
</tr>
<tr>
<td>(\xi)</td>
<td>Halo height/Galaxy disk height.</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Diffusion index difference between inner and outer</td>
</tr>
<tr>
<td>(\Delta \nu)</td>
<td>Injection index difference between proton and other nuclei(He, C and O), decided by proton, Helium and Carbon fluxes.</td>
</tr>
<tr>
<td>(\nu)</td>
<td>Proton injection index</td>
</tr>
</tbody>
</table>
Antiproton production in Cosmic rays from decays

• Anti-\(\bar{n}\) \(\rightarrow\) anti-\(\bar{p}\) + e\(^+\) + \(\nu\)

• Its life time is \(881.5(15)\) s when \(\beta\gamma = 0\) and \(\sim 10^{5}\) s when \(\beta\gamma \sim 100\).

• Compared to propagation time \(10^{5}\) yr, this lifetime is negligible.
Antiproton production cross section uncertainties.