A new set of self-consistent very local interstellar spectra for electrons, positrons, protons and light nuclei

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• Voyager 1 observations beyond the heliopause have decreased the uncertainty of the LIS’s at those lower energies.
• Together with vastly improved higher energy observations at 1 AU, only certain energies are left undetermined.
• To bridge the gap between these observations a CR propagation model (GALPROP) can be used to calculate the LIS’s.
• The calculated LIS’s can then be used as input to a sophisticated heliospheric modulation model to test the spectra against 1 AU observations.
• This enables a wider range of observations to be more directly used, as well as allowing LIS’s to be inferred for CRs with less observations, such as for antimatter.
First Published Results

- Used GALPROP to calculate LIS's to match the V1 observations.
- Electron LIS calculated with a plain diffusion model.  
- Proton, Helium, Carbon LIS's calculated by including reacceleration in model.  
- LIS's not tested against observations at 1 AU.
- LIS's limited to V1 observations shown by Stone et al. 2013.
CR Propagation in the GALPROP Code

• GALPROP is a comprehensive galactic propagation code developed by A. Strong & I.V. Moskalenko (http://galprop.stanford.edu). Models propagation of CRs through the Galaxy to calculate galactic spectra.

• Propagates CRs through the cylindric volume of a model galaxy from source distributions in the galactic plane.

• Describes the propagation as a largely diffusive process and solves the propagation equation:

\[
\frac{\partial f}{\partial t} = S(r, p) + \nabla \cdot (K \nabla f - Vf) + \frac{\partial}{\partial p} \left[p^2 K_p \frac{\partial f}{\partial p} + \frac{p}{3} (\nabla \cdot V)f - \dot{p}f\right] - \frac{f}{\tau}
\]

• Diffusion: \( K = \beta K_0 (P/P_{\delta 0})^\delta \)

• Reacceleration: \( K_p = p^2 V_a^2 / (9K) \)
  (Stochastic acceleration away from sources)

• Convection: \( V_c(z), \ V_c(0) = 0, \ \frac{dV_c}{dz} > 0 \)
  (Convection of CRs perpendicularly away from galactic plane)
Varying the parameters within a parameter space as suggested by other propagation parameter studies leads to the following values with which a set of self-consistent LIS’s can be calculated.

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Resulting Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_0 \left(10^{28} \text{ cm}^2 \text{ s}^{-1}\right)$</td>
<td>5.1</td>
</tr>
<tr>
<td>$P_0 \left(\text{GV}\right)$</td>
<td>4.0</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.4</td>
</tr>
<tr>
<td>$P_{\alpha 0} \left(\text{GV}\right)$</td>
<td>9.0</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>-1.86</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>-2.36</td>
</tr>
<tr>
<td>$P_{\alpha e 0} \left(\text{GV}\right)$</td>
<td>4.0</td>
</tr>
<tr>
<td>$\alpha_{e1}$</td>
<td>-1.9</td>
</tr>
<tr>
<td>$\alpha_{e2}$</td>
<td>-2.7</td>
</tr>
<tr>
<td>$V_A \left(\text{km.s}^{-1}\right)$</td>
<td>30.0</td>
</tr>
<tr>
<td>$dV_c/dz \left(\text{km.s}^{-1}.\text{kpc}^{-1}\right)$</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Heliospheric 3D Modulation Model

- To more accurately take into account solar modulation a sophisticated 3D steady state modulation model is used to implement the CR transport equation in the heliosphere.
- This model considers major modulation mechanisms of convection and adiabatic cooling due to the solar wind, and particle diffusion and drifts due to the HMF.
- Included in the model is a wavy current sheet and heliosheath, but not considered is shock acceleration at the termination shock.
- Use CR LIS’s as input to calculate the relevant CR spectra anywhere in heliosphere, for most CR particles or isotopes.
- Has proven successful over a wide range of time periods to accurately model charge-sign dependent modulation.
Transport Equation in the Modulation Code

\[
\frac{\partial f}{\partial t} = -V_{sw} \cdot \nabla f + \nabla \cdot (K \cdot \nabla f) + \frac{1}{3} (\nabla \cdot V_{sw}) \frac{\partial f}{\partial \ln p}
\]

Tensor: \( K = \begin{bmatrix} K_{\parallel} & 0 & 0 \\ 0 & K_{\perp \theta} & K_A \\ 0 & -K_A & K_{\perp r} \end{bmatrix} \)

- \( K_{\parallel} = (K_{\parallel})_0 \beta \left( \frac{B_0}{B} \right) \left( \frac{P}{P_0} \right)^a \left( \frac{\left( \frac{P}{P_0} \right)^c + \left( \frac{P_k}{P_0} \right)^c}{1 + \left( \frac{P_k}{P_0} \right)^c} \right)^\frac{b-a}{c} \)

- \( K_{\perp r} = 0.02 K_{\parallel} \)

- \( K_{\perp \theta} = 0.01 K_{\parallel} f_{\perp \theta} \)

- \( K_A = (K_A)_0 \frac{\beta P}{3B} \left( \frac{\left( \frac{P}{P_{A0}} \right)^2}{1 + \left( \frac{P}{P_{A0}} \right)^2} \right) \)
Example Parameters, MFPs and Drift Scales

<table>
<thead>
<tr>
<th>Parameters (2009b period)</th>
<th>Electrons and Positrons</th>
<th>Protons and Light Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{</td>
<td></td>
<td>0}$ (AU)</td>
</tr>
<tr>
<td>$K_{A0}$</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>$P_{A0}$ (GV)</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>$c_1$</td>
<td>0.00</td>
<td>0.70</td>
</tr>
<tr>
<td>$c_2</td>
<td></td>
<td>$</td>
</tr>
<tr>
<td>$c_2\perp$</td>
<td>1.688</td>
<td>1.14</td>
</tr>
<tr>
<td>$c_3$</td>
<td>2.70</td>
<td>2.50</td>
</tr>
<tr>
<td>$P_k$ (GV)</td>
<td>0.57</td>
<td>4.00</td>
</tr>
<tr>
<td>$d_{\perp \theta}$</td>
<td>6.00</td>
<td>6.00</td>
</tr>
</tbody>
</table>

For electrons and positrons.

For protons and nuclei.
Electron and Positron LIS’s

- **V1 Electrons (Cummings)**
- **V1 Electrons (Stone, -1.35)**
- **V1 Electrons (Stone, -1.55)**
- **PAMELA Electrons**

- **Electron LIS**
- **Electron Modulated (2009b)**

- **Positron LIS**
- **Positron Modulated (2009b)**

**Flux (part. m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) GeV\(^{-1}\))**

**Kinetic Energy (GeV)**
Proton and Helium LIS’s

![Proton LIS](image1)

![Helium LIS](image2)
Carbon LIS and B/C ratio

Carbon LIS

V1 Carbon (Cummings)
V1 Carbon (Stone)
PAMELA Carbon
Carbon LIS
Carbon Modulated (2009b)

B/C Ratio

PAMELA B/C
B/C LIS's Ratio
B/C Modulated Ratio (2009b)
Boron and Oxygen LIS’s

**Boron LIS**

- **Kinetic Energy (GeV/nuc)**
- **Flux (part. m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (GeV/nuc\(^{-1}\))**

- V1 Boron
- PAMELA Boron
- Boron LIS
- Boron Modulated (2009b)

**Oxygen LIS**

- **Kinetic Energy (GeV/nuc)**
- **Flux (part. m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (GeV/nuc\(^{-1}\))**

- V1 Oxygen (Cummings)
- V1 Oxygen (Stone)
- Buckley et. al. Oxygen
- ATIC-2 Oxygen
- TRACER Oxygen
- Oxygen LIS
- Oxygen Modulated (2009b)
• Calculate and test LIS’s for CR electrons, positrons, protons.
• Constrained by V1 at low energies, PAMELA at high energies. And by a modulation model and PAMELA in between.
• Use same models to extend approach to Helium, Carbon, Boron and Oxygen.

• Already successfully expanded modulation to greater range of time periods for PAMELA electrons, positrons, protons and Helium.

• With these LIS’s and modulation model, more observational data can be explored throughout the solar cycle, such as for AMS-02 observations.
Potential Improvements

- Lower energy LIS’s observed by V1, Cummings et al. 2016, not reproduced by this GALPROP model as closely. But has no effect on the modulated spectra.
- Positron LIS still uncertain, might need more modification to the calculated LIS.
- The LIS’s, dependent on the GALPROP parameters chosen, might still need improving, but general shape and trends will likely remain.
Further Applications

- Isotopes and antimatter CR spectra can also be investigated with this approach.
- Deuteron and antiprotons have few observations and LIS’s are not well determined.
- Antideuteron can also be modulated, even if an input LIS can only be estimated.

![Graph showing data points and curves for PAMELA Antiprotons and Antiproton LISs.](image-url)
Further Applications

Deuteron Tests

- V1 Deuteron
- PAMELA Deuteron
- Deuteron LIS
- Modulated Deuteron (2009b)
- Modulated Deuteron (2006b)

Antideuteron Tests

- Antideuteron Secondary
- Antideuteron Primary
- Antideuteron Total
- Modulated Secondary
- Modulated Total