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

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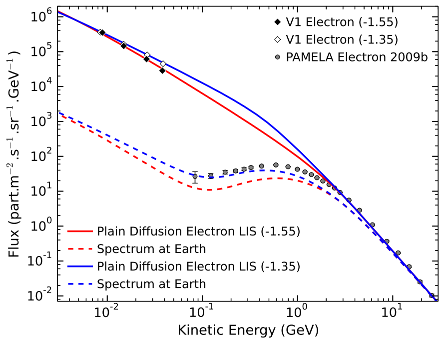
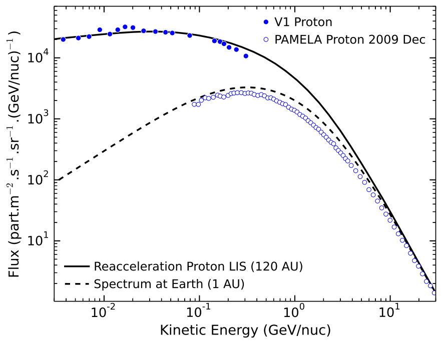
Introduction

- 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 the 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.
  (Bisschoff & Potgieter, ApJ, 794:166, 2014)
- Proton, Helium, Carbon LIS's caculated by including reacceleration in model.
  (Bisschoff & Potgieter, Ap&SS, 361:48, 2016)
- 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:

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

- 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: $V_c(z),\ V_c(0) = 0,\ dV_c/dz > 0$

  (Convection of CRs perpendicularly away from galactic plane)

GALPROP Model Parameters Used

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.

Model Parameters	Resulting Model
K_0 (10^{28} cm^2 s^{-1})	5.1
P_0 (GV)	4.0
δ_1	0.3
δ_2	0.4
$P_{\alpha 0}$ (GV)	9.0
α_1	-1.86
α_2	-2.36
$P_{\alpha e0}$ (GV)	4.0
α_{e1}	-1.9
α_{e2}	-2.7
V_A (km.s^{-1})	30.0
dV_c/dz (km.s^{-1}.kpc^{-1})	5.0

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 helioshere, 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

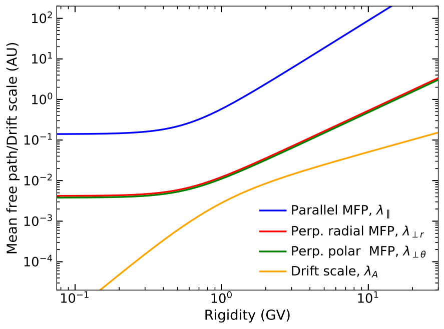
$$\frac{\partial f}{\partial t} = -\mathbf{V}_{sw} \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}_{sw})\frac{\partial f}{\partial \ln p}$$

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

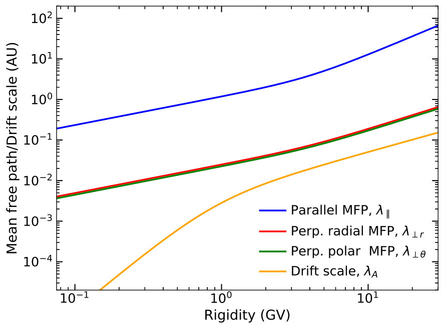
- $K_{\parallel} = (K_{\parallel})_0 \beta \left(\frac{B_0}{B}\right) \left(\frac{P}{P_0}\right)^a \left(\frac{\left(\frac{P}{P_0}\right)^c + \left(\frac{P_k}{P_0}\right)^c}{1+\left(\frac{P_k}{P_0}\right)^c}\right)^{\frac{b-a}{c}}$
- $K_{\perp r} = 0.02 K_{\parallel}$
- $K_{\perp\theta} = 0.01 K_{\parallel} f_{\perp\theta}$
- $K_A = (K_A)_0 \, \frac{\beta P}{3B} \left(\frac{\left(\frac{P}{P_{A0}}\right)^2}{1+\left(\frac{P}{P_{A0}}\right)^2}\right)$

Example Parameters, MFPs and Drift Scales

Parameters (2009b period)	Electrons and Positrons	Protons and Light Nuclei
$\lambda_{\parallel 0}$ (AU)	0.593	1.185
K_{A0}	0.90	0.90
P_{A0} (GV)	0.90	0.90
c_1	0.00	0.70
$c_{2\parallel}$	2.25	1.52
$c_{2\perp}$	1.688	1.14
c_3	2.70	2.50
P_k (GV)	0.57	4.00
$d_{\perp\theta}$	6.00	6.00

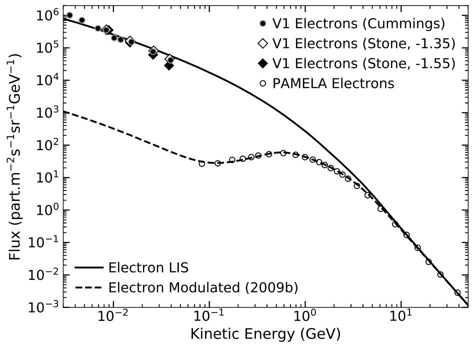


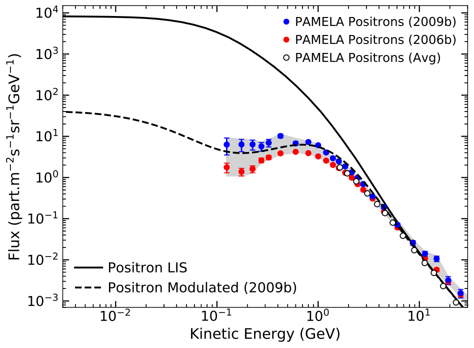
For electrons and positrons.



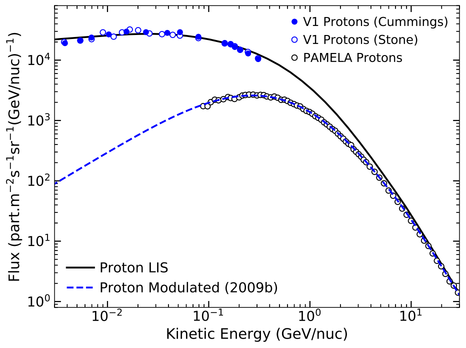
For protons and nuclei.

Electron and Positron LIS's

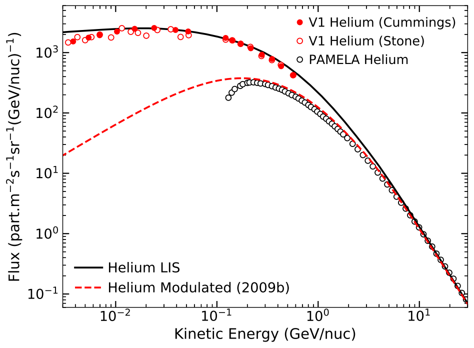




Proton and Helium LIS's

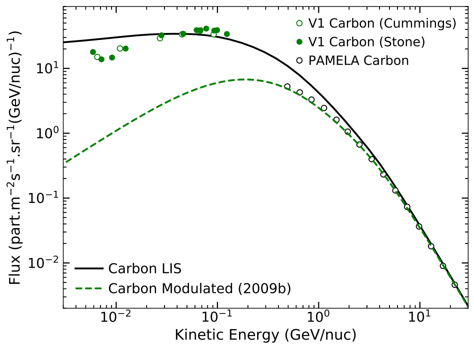


Proton LIS

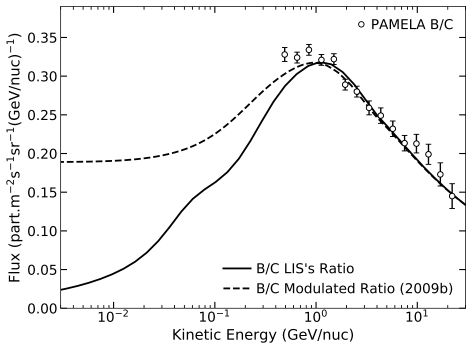


Helium LIS

Carbon LIS and B/C ratio

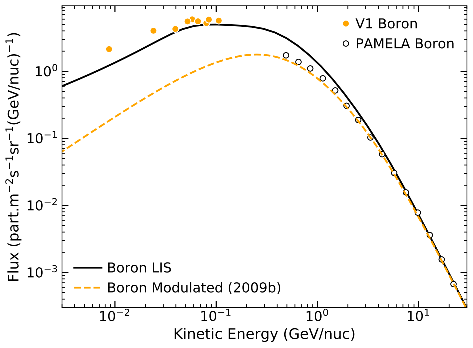


Carbon LIS

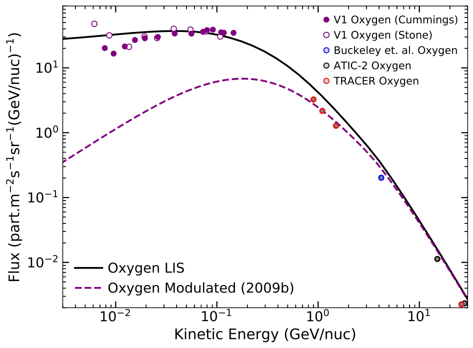


B/C Ratio

Boron and Oxygen LIS's



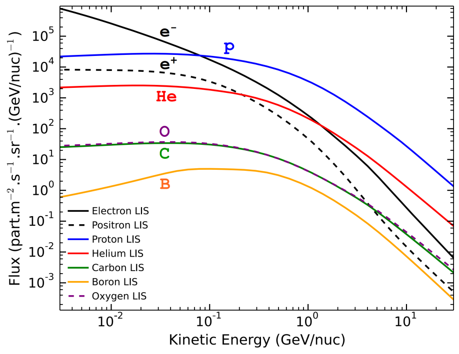
Boron LIS



Oxygen LIS

Resulting LIS's and Conclusions

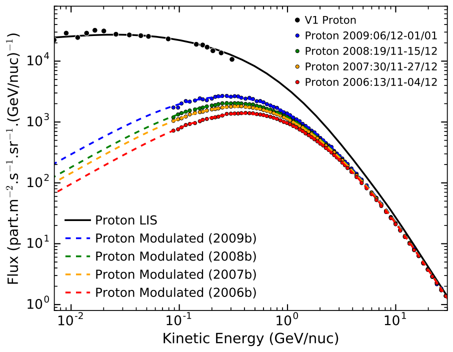
- Calculate and test LIS's for CR electrons, positrons, protons.
- Constrained by V1 at low energies, PAMELA at high energies. And by a modulation model and PAMELA in between.
- Use same models to extend approach to Helium, Carbon, Boron and Oxygen.



Bisschoff, Potgieter & Aslam, ApJ, 878:59, 2019

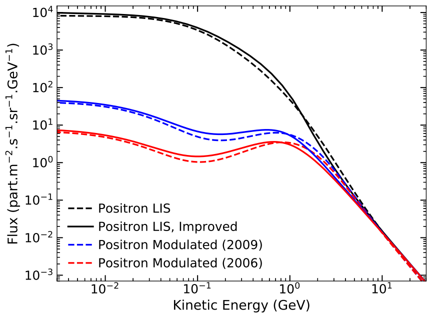
Resulting LIS's and Conclusions

- 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.



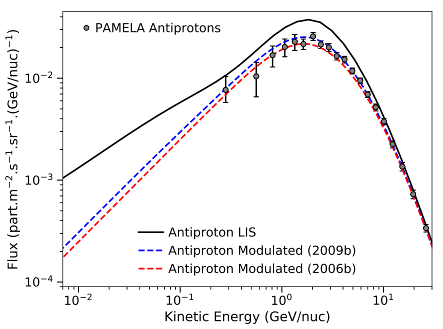
Potential Improvements

- 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.

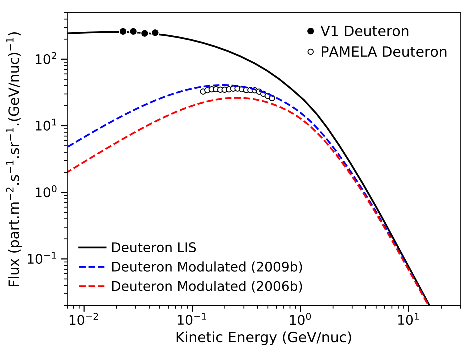


Further Applications

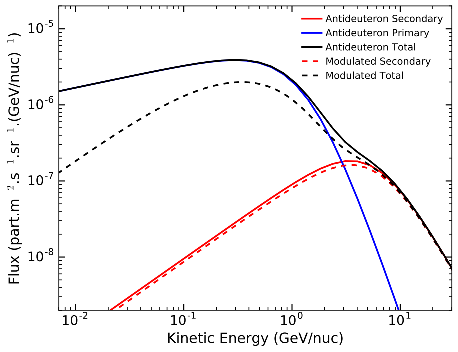
- Isotopes and antimatter CR spectra can also be investigated with this approach.
- Deuteron and antiprotons have few observations and LIS's are not well determined.
- Antideuteron can also be modulated, even if an input LIS can only be estimated.



Further Applications



Deuteron Tests



Antideuteron Tests