TIME-DEPENDENT COSMIC RAY MODULATION IN THE OUTER HELIOSPHERE

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Model is based on time-dependent 2D solution of Parker Transport Equation given by,

\[
\frac{\partial f}{\partial t} = -\mathbf{V} \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P} + J_{\text{source}}
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- second term is the spatial diffusion parallel and perpendicular to the average HMF and particle drifts.
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- second term is the spatial diffusion parallel and perpendicular to the average HMF and particle drifts.
- third term is the energy changes.
- and the last term is the possible sources of cosmic rays inside the heliosphere, which is zero for this study.
The diffusion tensor $K$ as introduced in Parker’s Transport equation is given by,

$$K = \begin{bmatrix} K_{||} & 0 & 0 \\ 0 & K_{\perp \theta} & K_A \\ 0 & -K_A & K_{\perp r} \end{bmatrix}$$
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- the anti-symmetric element $K_A$ describes particle drifts which include gradient, curvature and heliospheric current sheet drift in the large scale HMF.
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COMPOUND APPROACH

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- The diffusion and drift coefficients are scaled time-dependently via a function $f_2(t)$, where

$$f_2(t) = \left( \frac{B_0}{B(t)} \right)^{\frac{\alpha(t)}{\alpha_0}}$$

This function is now dependent on the measured HMF magnitude and tilt angle.
From Teufel and Schlickeiser, 2003 follows:

$$\lambda_|| = \frac{3s}{\sqrt{\pi}(s - 1)} \frac{R^2}{b} \frac{k_{\text{min}}}{\delta B_{\text{slab},x}} \left( \frac{B_0}{\delta B_{\text{slab},x}} \right)^2 K$$
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where, \( \delta B_{\text{slab},x}^2 = 0.5\delta B_{\text{slab}}^2 = 0.1\delta B^2 \),

\[ R = k \min R_L , \quad R_L = \frac{P}{B_0} \quad \text{and} \quad s = 5/3 \]
From Teufel and Schlickeiser, 2003 follows:

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\lambda_\parallel = \frac{3s}{\sqrt{\pi} (s - 1)} \frac{R^2}{b} \frac{R^2}{k_{min}} \left( \frac{B_0}{\delta B_{slab,x}} \right)^2 K
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At 2.5 GV we approximate \( K \) to be a constant resulting in a time dependence for \( \lambda_\parallel \) as,

\[
\lambda_\parallel \propto \left( \frac{1}{\delta B} \right)^2
\]
From Shalchi et al., 2004 follows:

\[ \lambda_\perp \approx \left[ \frac{2v - 1}{4v} F_2(v) \, l_{slab} \, a^2 \, \frac{\delta B^2}{B_0^2} \, \frac{2\sqrt{3}}{25} \right]^{\frac{2}{3}} \lambda_{||}^{\frac{1}{3}} \]
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At 2.5 GV we approximate the time dependence for \( \lambda_\perp \) as,

\[ \lambda_\perp \propto \left( \frac{\delta B}{B_0} \right)^{\frac{4}{3}} \left( \frac{1}{\delta B} \right)^{\frac{2}{3}} \]
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We use a similar dependence, in compound approach but instead of $K_A$ depending on $\delta B$ it depends on $\alpha$ the tilt angle.

$$f_3(t) = (75.0 - \alpha(t)) \times 0.013$$

Ndiitwani et al., 2005
Time dependence in drift coefficient

Minnie et al., 2007

Ndiitwani et al., 2005
Along Voyager 1 trajectory
Observing signatures of Heliospheric asymmetry?

Opher, 2008
Heliospheric boundary at 124 AU

Cosmic ray intensities from 1984 to 2009

- Voyager 1 > 70 MeV Protons
- Voyager 2 > 70 MeV Protons
- IMP 8 > 70 MeV Protons
- Ulysses 2.5 GV Protons

Voyager 1
Voyager 2

Differential Intensity (m^2.s.sr.MeV)^{-1}

Time (years):

2.5 GV
Heliospheric boundary at 118 AU

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Voyager 1
Voyager 2

Differential Intensity (m².s.sr.MeV⁻¹)

Time (years)

2.5 GV
Optimal Model Result

Cosmic ray intensities from 1984 to 2009

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- Ulysses 2.5 GV Protons
- Voyager 1 (124 AU)
- Voyager 2 (118 AU)

Differential Intensity (m²·s⁻¹·sr⁻¹·MeV⁻¹)


A < 0
A > 0
2.5 GV
2002, Solar max

2009, Solar min (A < 0)
Predicting intensities up to heliopause along Voyager 1 and 2 trajectory
A possible Heliospheric boundary position along Voyager 1 and Voyager 2 trajectory
Conclusion

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Next phase is to predict a possible range for the local interstellar spectra. We predict a steady increase in Voyager 1 cosmic ray intensity observations up to heliopause. But for Voyager 2 there is still a large modulation volume left, leading to solar cycle related changes in intensities up to heliopause.
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Voyager 2 > 70 MeV Protons

- **Solar cycle**
- **Solar cycle shifted by +3 years**
- **Solar cycle shifted by -3 years**

Differential Intensity $(m^2 \cdot s^{-1} \cdot sr \cdot MeV^{-1})$

Time (Years)

Thank You!