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,

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K = \begin{bmatrix}
K_{\parallel} & 0 & 0 \\
0 & K_{\perp\theta} & K_A \\
0 & -K_A & K_{\perp r}
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- $K_{\perp\theta}$ and $K_{\perp r}$ denote the diffusion coefficients perpendicular to the mean HMF in the polar and radial direction respectively, and
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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

- Introduced by Ferreira (2002) and Ferreira and Potgieter (2004) a model to describe long-term time dependent cosmic ray modulation.
- This model incorporates drifts and time dependent changes in the diffusion coefficients resulting effectively in propagating diffusion barriers to model cosmic ray intensities over 11 and 22 year cycles.
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Results from this model are compared with Ulysses and Voyager observations.

The diffusion and drift coefficients are scaled time-dependently via a function $f(t)$, where $f(t) = \left(\frac{B_0}{B(t)}\right)^{\alpha(t)}\alpha_0$.

This function is now dependent on the measured HMF magnitude and tilt angle.
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This function is now dependent on the measured HMF magnitude and tilt angle.
RECENT THEORY: Parallel Mean Free Path

From Teufel and Schlickeiser, 2003 follows:

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

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

\[ \lambda_\parallel = \frac{3s}{\sqrt{\pi(s-1)}} \frac{R^2}{b k_{\text{min}}} \left( \frac{B_0}{\delta B_{\text{slab},x}} \right)^2 K \]

where, \( \delta B_{\text{slab},x}^2 = 0.5 \delta B_{\text{slab}}^2 = 0.1 \delta B^2 \),

\[ R = k_{\text{min}} R_L \quad , \quad R_L = \frac{P}{B_0} \quad \text{and} \quad s = 5/3 \]

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:

\[ \lambda_\perp \approx \left[ \frac{2v - 1}{4v} F_2(v) \, l_{slab} \, a^2 \, \frac{\delta B^2}{B_0^2} \, \frac{2\sqrt{3}}{25} \right]^{\frac{2}{3}} \lambda_\parallel^{\frac{1}{3}} \]
RECENT THEORY: Perpendicular Mean Free Path

From Shalchi et al., 2004 follows:

\[ \lambda_\perp \approx \left[ \frac{2v - 1}{4v} F_2(v) l_{slab} a^2 \frac{\delta B^2}{B_0^2} \frac{2\sqrt{3}}{25} \right]^{\frac{2}{3}} \lambda_{\parallel}^{\frac{1}{3}} \]

At 2.5 GV we approximate the time dependence for \( \lambda_\perp \) as,

\[ \lambda_\perp \propto \left( \frac{\delta B}{B_0} \right)^{\frac{4}{3}} \left( \frac{1}{\delta B} \right)^{\frac{2}{3}} \]
Minnie et al. (2007), showed that $K_A$ depends on $\delta B$, which can change over a solar cycle.
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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.

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

Ndiitwani et al., 2005
Time dependence in drift coefficient

Minnie et al., 2007

Ndiitwani et al., 2005
Along Voyager 1 trajectory

Cosmic ray intensities from 1984 to 2009

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

- Voyager 1 > 70 MeV Protons
- IMP 8 > 70 MeV Protons
- Ulysses 2.5 GV Protons
- Compound Approach
- Recent Theory

Time (years)

1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010
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

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

Time (years)
Heliospheric boundary at 118 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 and Voyager 2

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

Time (years)
Optimal Model Result

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

Time (years)

1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010

Cosmic ray intensities from 1984 to 2009

A > 0

A < 0

2.5 GV

Voyager 1 (74 MeV)
Voyager 2 (118 AU)
Imp 8 (70 MeV Protons)
Voyager 1 (250 MeV Protons)
Voyager 2 (124 AU)
1983, Solar max

1987, Solar min (A < 0)

1990, Solar max

1997, Solar min (A > 0)
2002, Solar max

2009, Solar min (A < 0)
Predicting intensities up to heliopause along Voyager 1 and 2 trajectory
Tilt Angle

Voyager Trajectory

HMF and Variance
A possible Heliospheric boundary position along Voyager 1 and Voyager 2 trajectory
Conclusion

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Conclusion

- This is an investigation into time-dependent cosmic ray modulation in the outer heliosphere.
- This talk highlighted our findings regarding the sensitivity of intensities to variations in the boundary position and possible asymmetry of the heliosphere.
- 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.
Thank You!