Time dependent cosmic ray modulation in the outer heliosphere: Model results along Voyager 1 and 2 trajectories

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PARKER TRANSPORT EQUATION

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

$$\frac{\partial f}{\partial t} = -\mathbf{V} \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln\ P} + J_{source}$$

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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 ELEMENTS OF DIFFUSION TENSOR

The diffusion tensor **K** as introduced in Parker's Transport equation is given by,

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

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

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

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:

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

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where, $\delta B^2_{slab,x} = 0.5\delta B^2_{slab} = 0.1\delta B^2$,

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$$\therefore f_2(t) = C_4 \left(\frac{1}{\delta B}\right)^2$$, where C_4 a constant in units of $(\mathrm{nT})^2$

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From Shalchi et al., 2004 follows:

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

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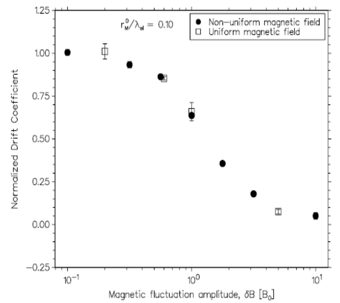
$$\lambda_{\perp}\ \alpha\ \left(\frac{\delta B}{B} \right)^{\frac{4}{3}} \left(\frac{1}{\delta B} \right)^{\frac{2}{3}}$$

$$\therefore f_3(t) = C_5 \left(\frac{\delta B}{B} \right)^{\frac{4}{3}} \left(\frac{1}{\delta B} \right)^{\frac{2}{3}}, \text{where } C_5 \text{ a constant in units of } (\mathrm{nT})^{\frac{2}{3}}$$

Time dependence in drift coefficient



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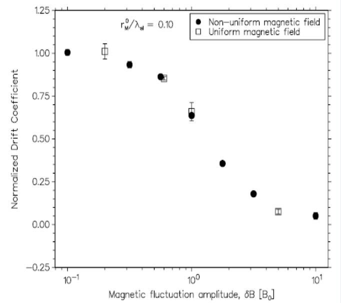

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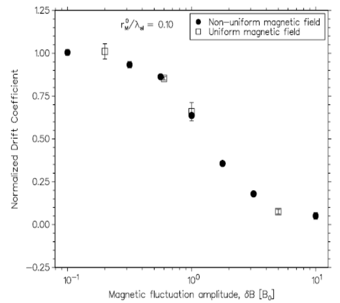

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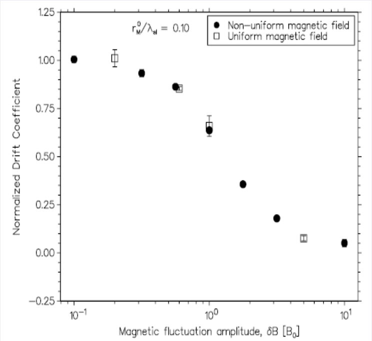
We use a similar dependence, in compound approach but instead of K_A depending on δB it depends on α the tilt angle.

$$f_1(t) = (75.0 - \alpha(t))\, 0.013$$

Ndiitwani et al., 2005

Time dependence in drift coefficient



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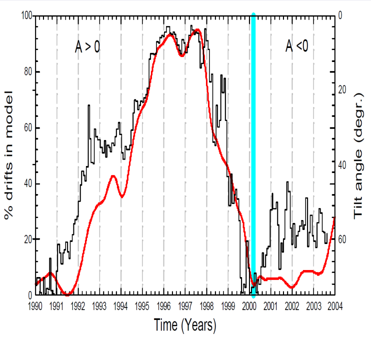
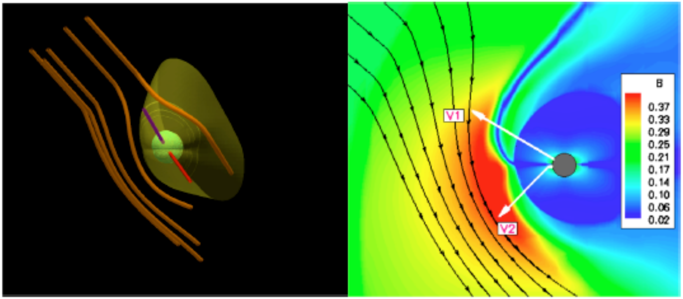


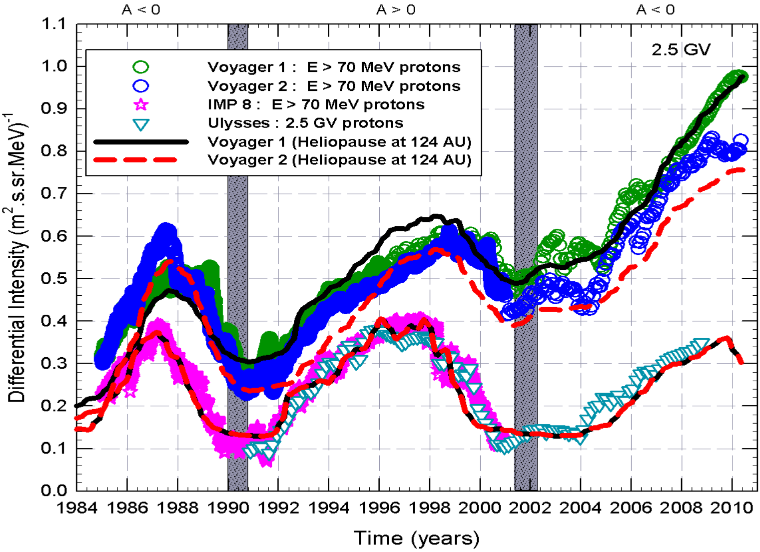
Ndiitwani et al., 2005

Observing signatures of Heliospheric asymmetry?

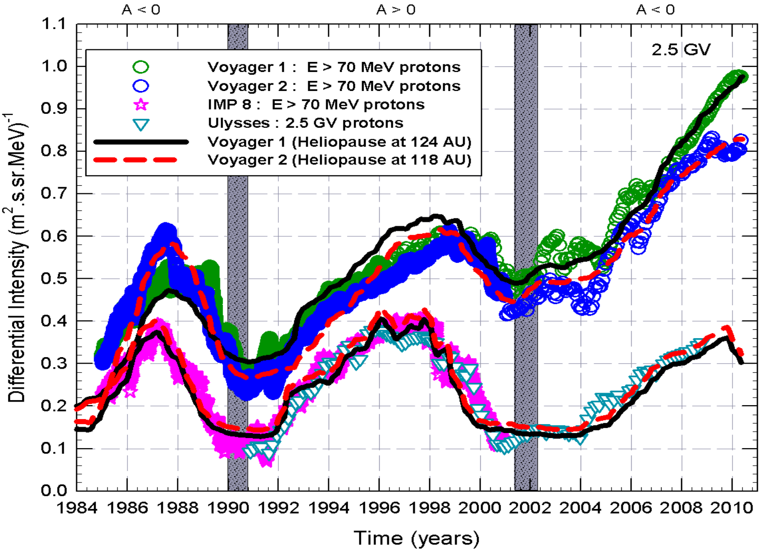


Opher, 2008

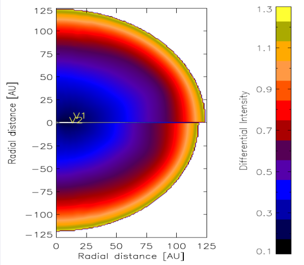
Heliospheric boundary at 124 AU



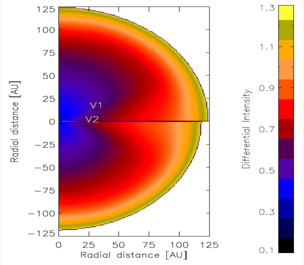
Optimal Model Result



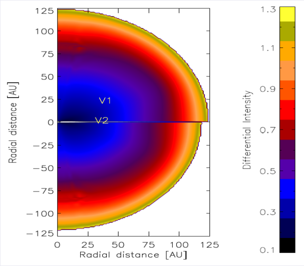
1983, Solar max



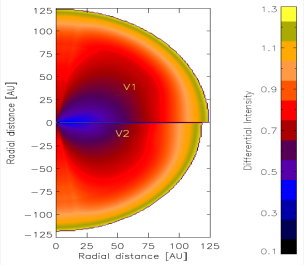
1987, Solar min (A < 0)



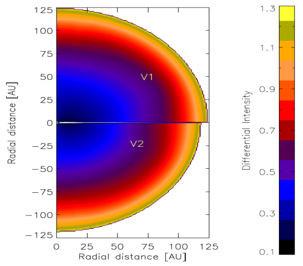
1990, Solar max



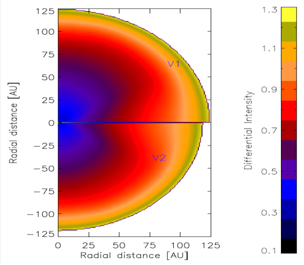
1997, Solar min (A > 0)



2002, Solar max

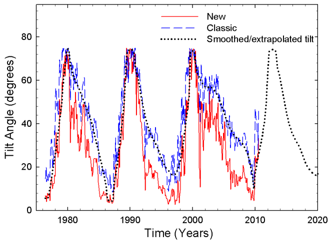


2009, Solar min (A < 0)



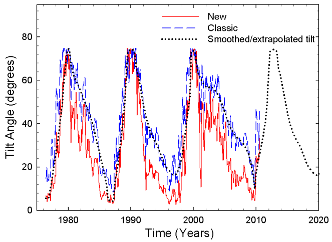
Predicting 133-242 MeV intensities up to heliopause along Voyager 1 and 2 trajectory

Tilt Angle

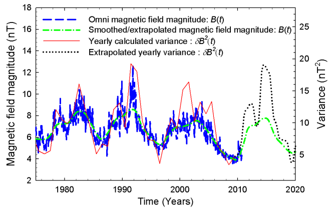


New
Classic
Smoothed/extrapolated tilt
Tilt Angle (degrees)
0
20
40
60
80
1980
1990
2000
2010
2020
Time (Years)

Tilt Angle



HMF and Variance



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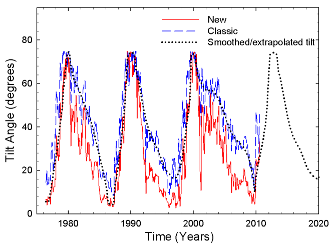

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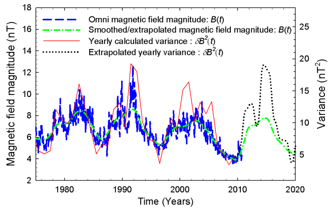
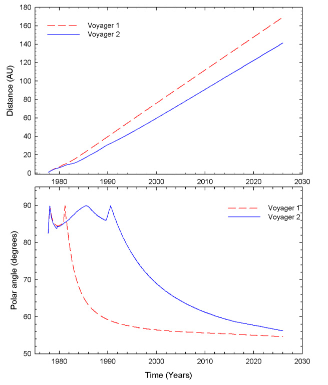
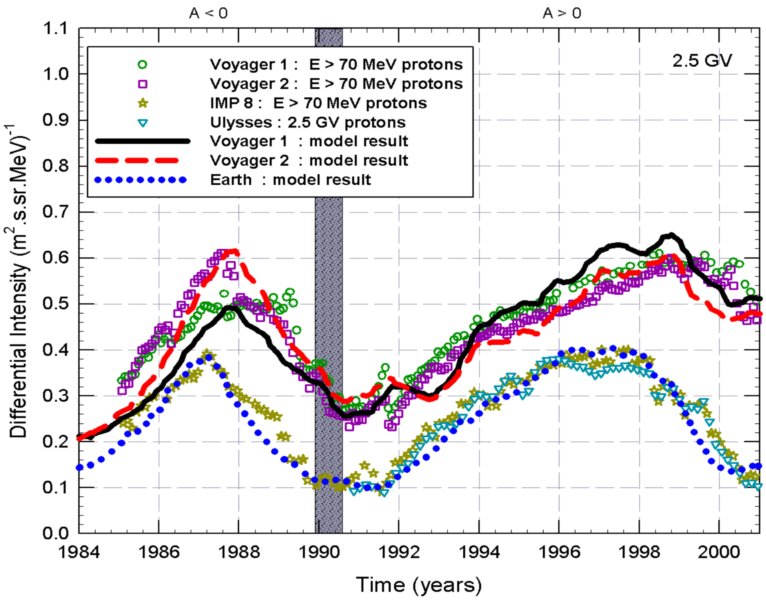
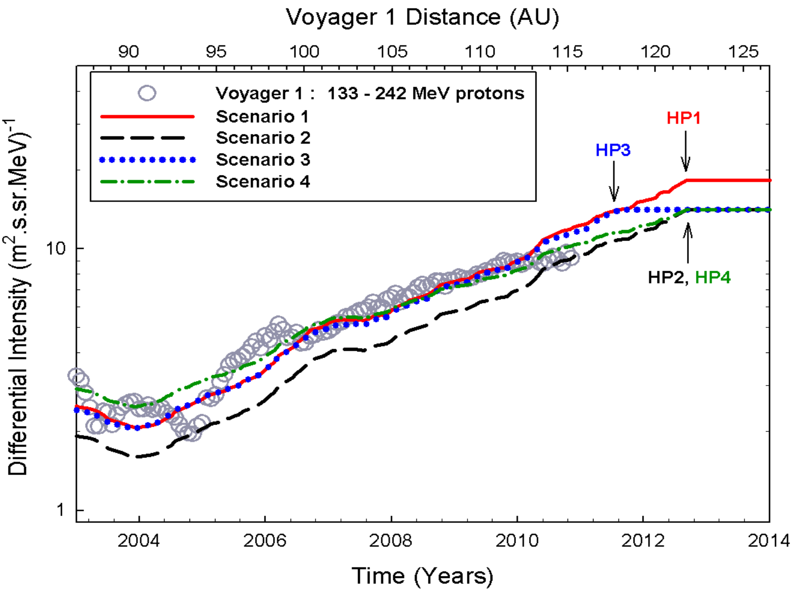


Voyager Trajectory

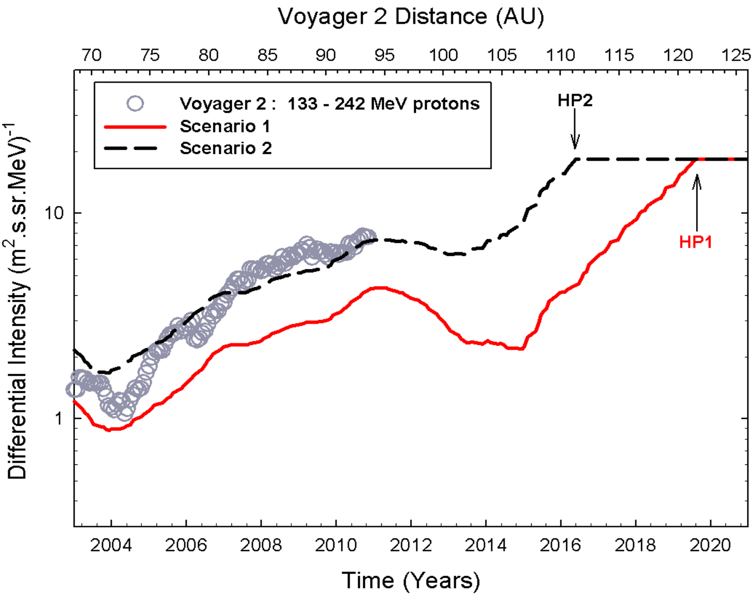



A < 0
A > 0
2.5 GV
Voyager 1 : E > 70 MeV protons
Voyager 2 : E > 70 MeV protons
IMP 8 : E > 70 MeV protons
Ulysses : 2.5 GV protons
Voyager 1 : model result
Voyager 2 : model result
Earth : model result
Differential Intensity (m^2.s.sr.MeV)$^{-1}$
Time (years)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1984
1986
1988
1990
1992
1994
1996
1998
2000

Along Voyager 1 trajectory



Along Voyager 2 trajectory



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Thank You!