Numerical Study Galactic Cosmic Ray Modulation Near the Heliopause

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Outline

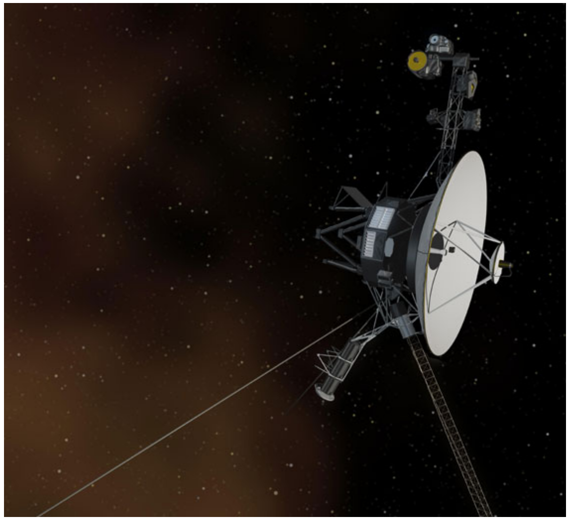
- **Cosmic Ray Modulation Backgroud**

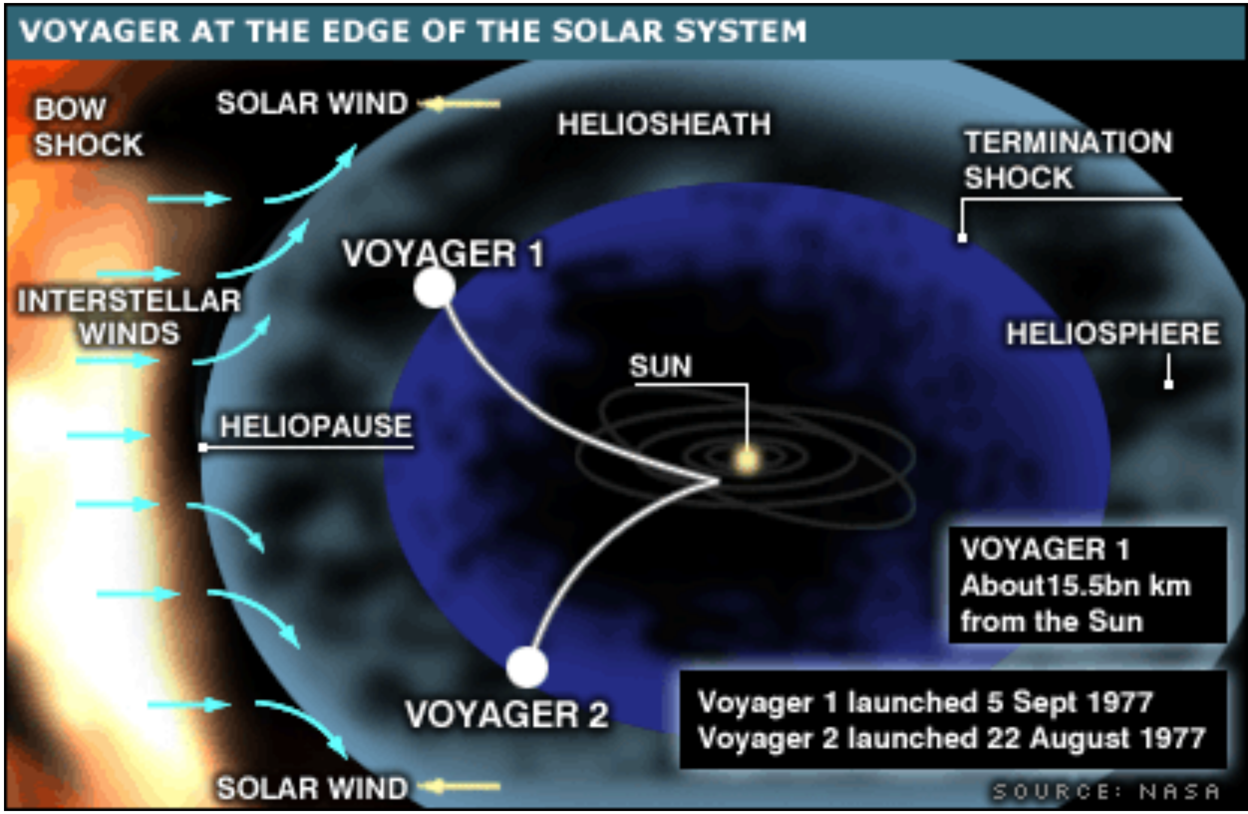
- **Cosmic Ray Modulation Model Based on the Global MHD heliosphere Data**

- Study Galactic Cosmic Ray Modulation near the Heliopause(HP)

- Conclusions

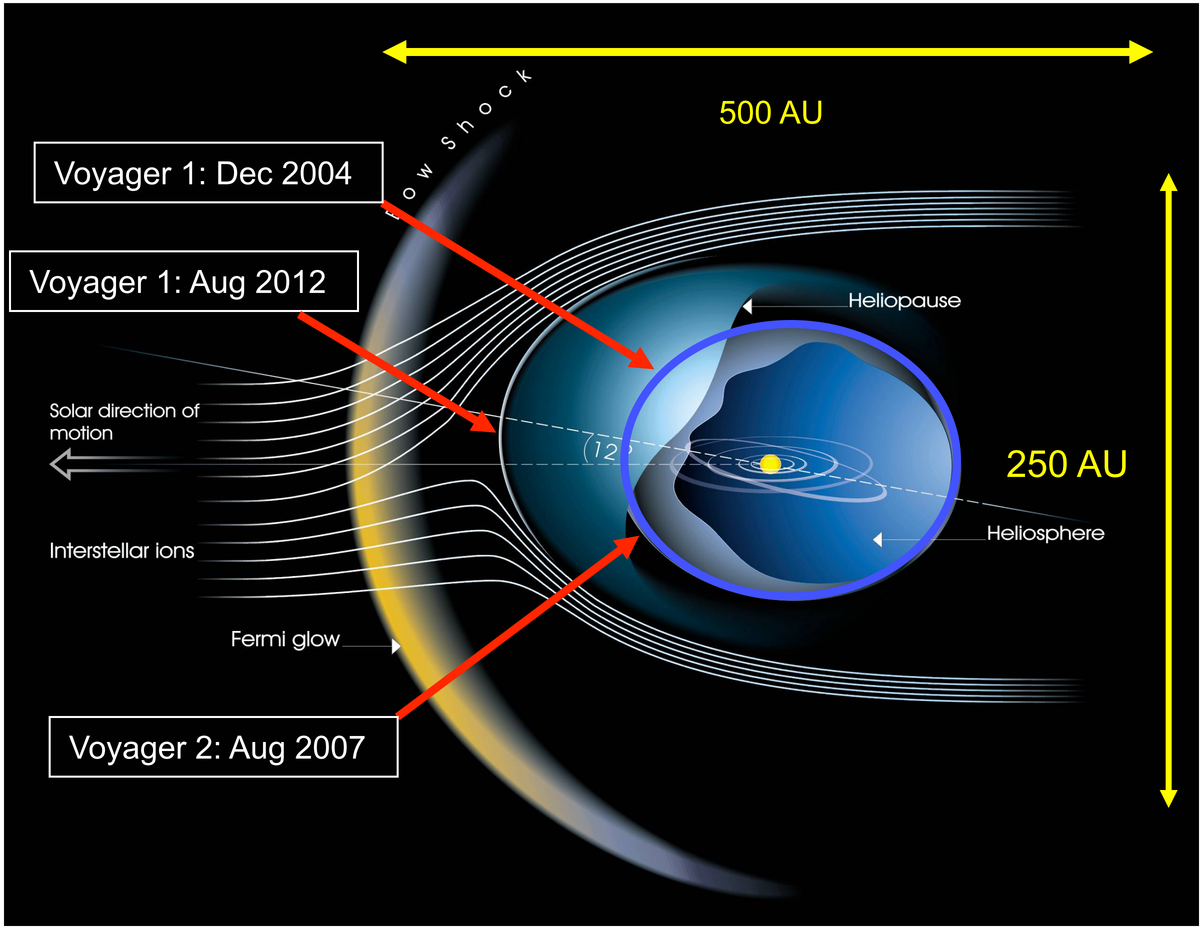
Voyager Missions





- Voyager Mission, Lauched in 1977, farthest manmade spacecraft.

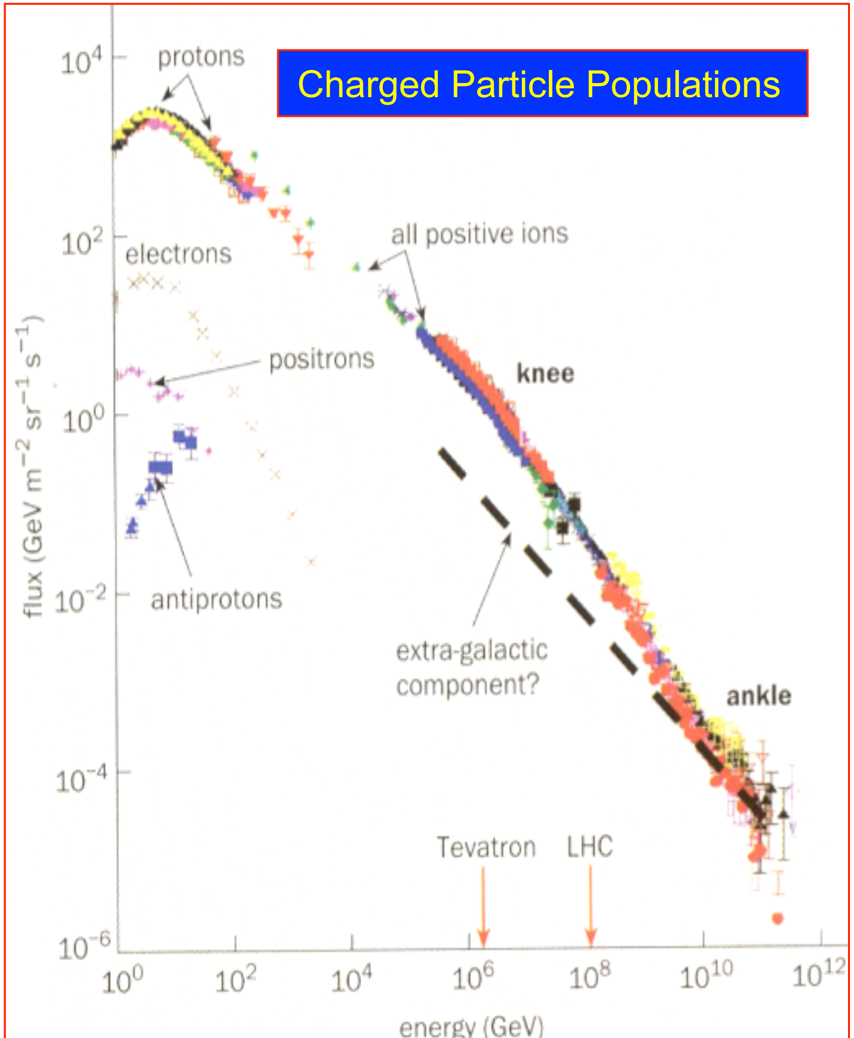
Heliospace



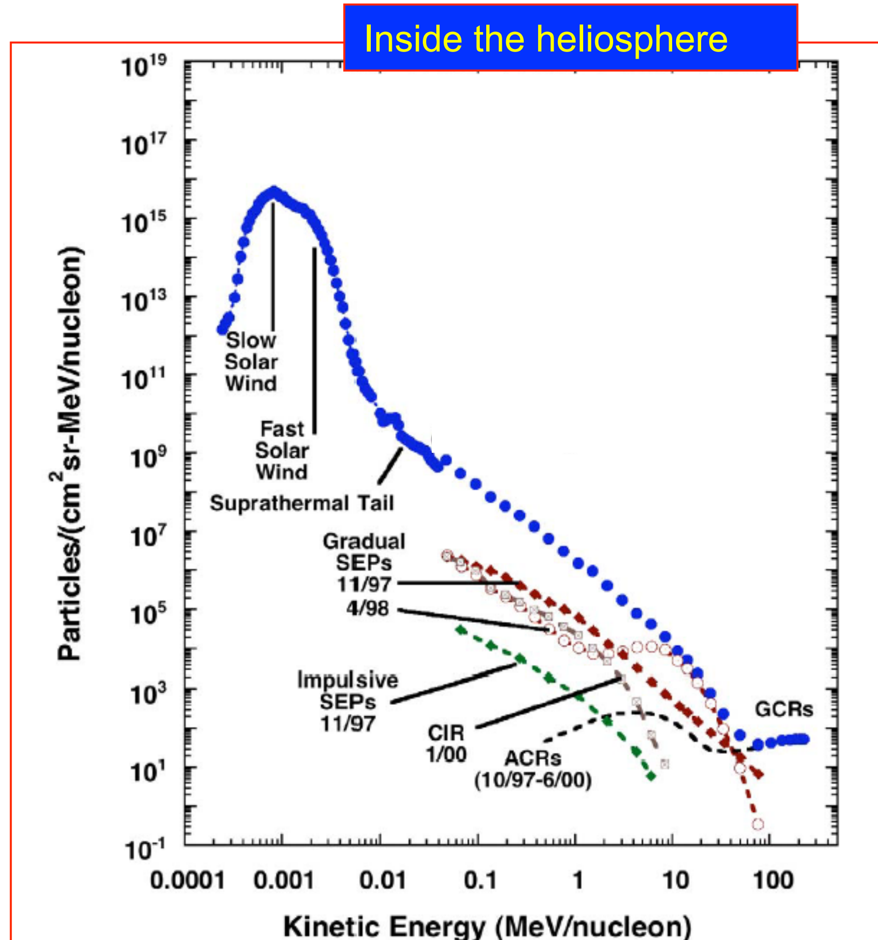
- Solar wind interacts with the interstellar medium, forming a blown bubble called heliosphere.
- Termination Shock(Solar wind speed largely decrease.)
- Heliosheath(region between termination shock and heliopause)
- Heliopause(boundary between solar wind and interstellar medium)

The heliosphere

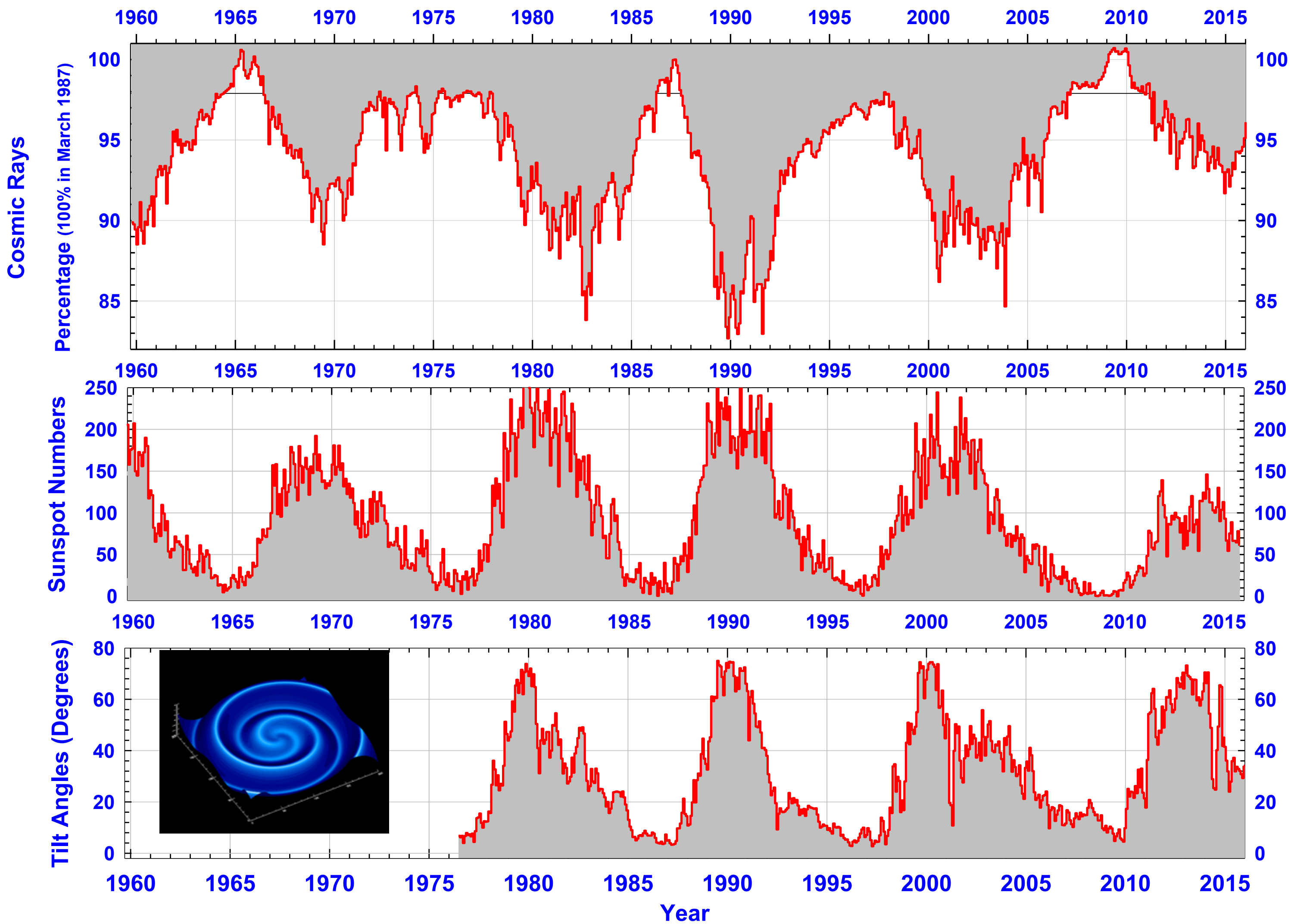
Cosmic Rays from the Galaxy



- Cosmic ray Particles with energy below about 10 GeV are subject to solar modulation

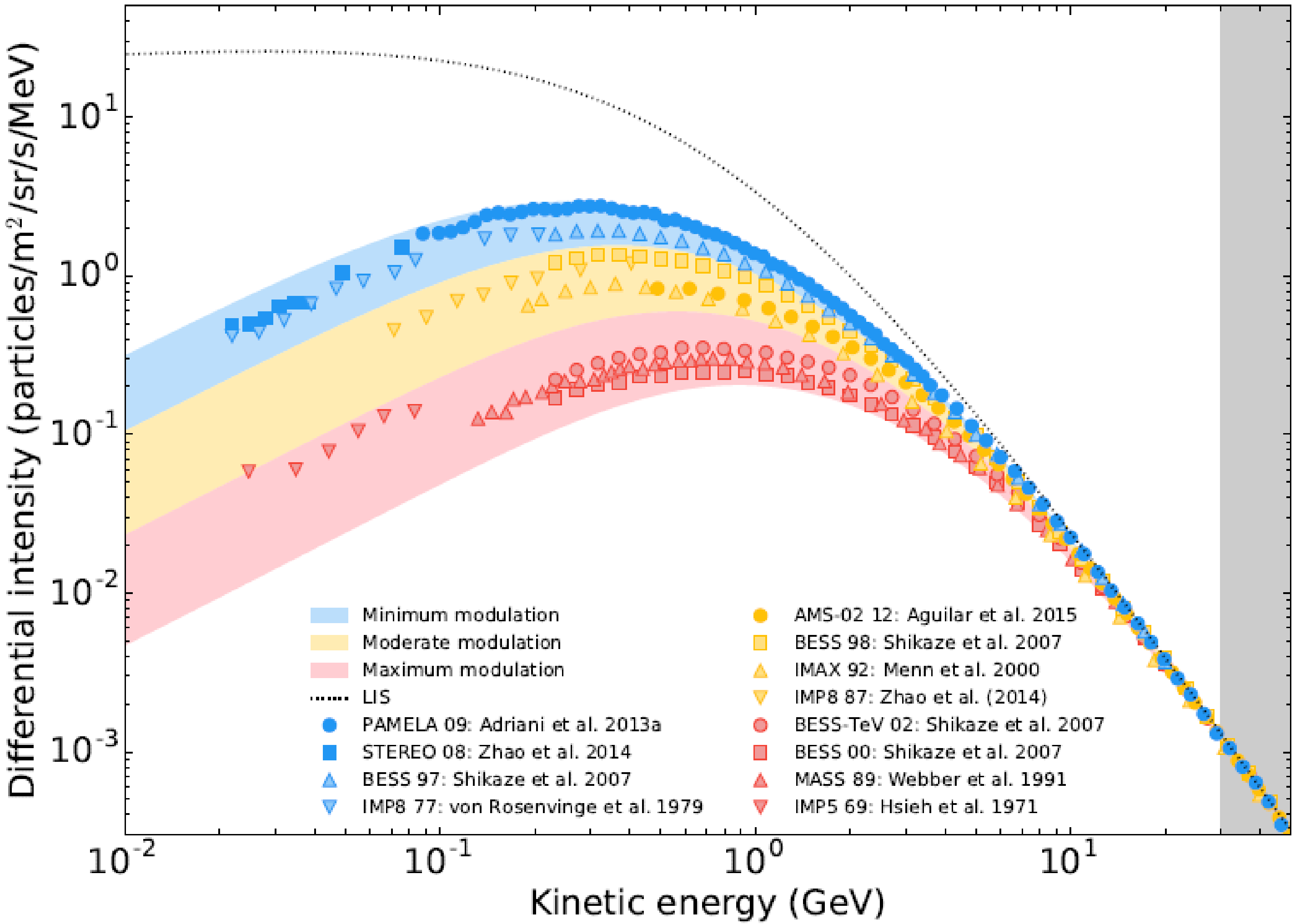


Cosmic Ray Modulation Observed From Earth



Hermanus
Neutron
Monitor,
South Africa
(4.6 GV)

Cosmic Ray Modulation Observed From Space



Transport equation for the transport, modulation and acceleration of cosmic rays in the heliosphere

$$\underbrace{\frac{\partial f}{\partial t}}_{} = \underbrace{\nabla \cdot [\mathbf{K} \cdot \nabla f]}_{} - \underbrace{V \cdot \nabla f}_{} - \underbrace{\langle \boldsymbol{v}_D \rangle \cdot \nabla f}_{} + \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial \ln p} + \underbrace{Q(r,p,t)}_{}$$

Time-dependent, pitch-angle-averaged distribution function

Diffusion

Convection with solar wind

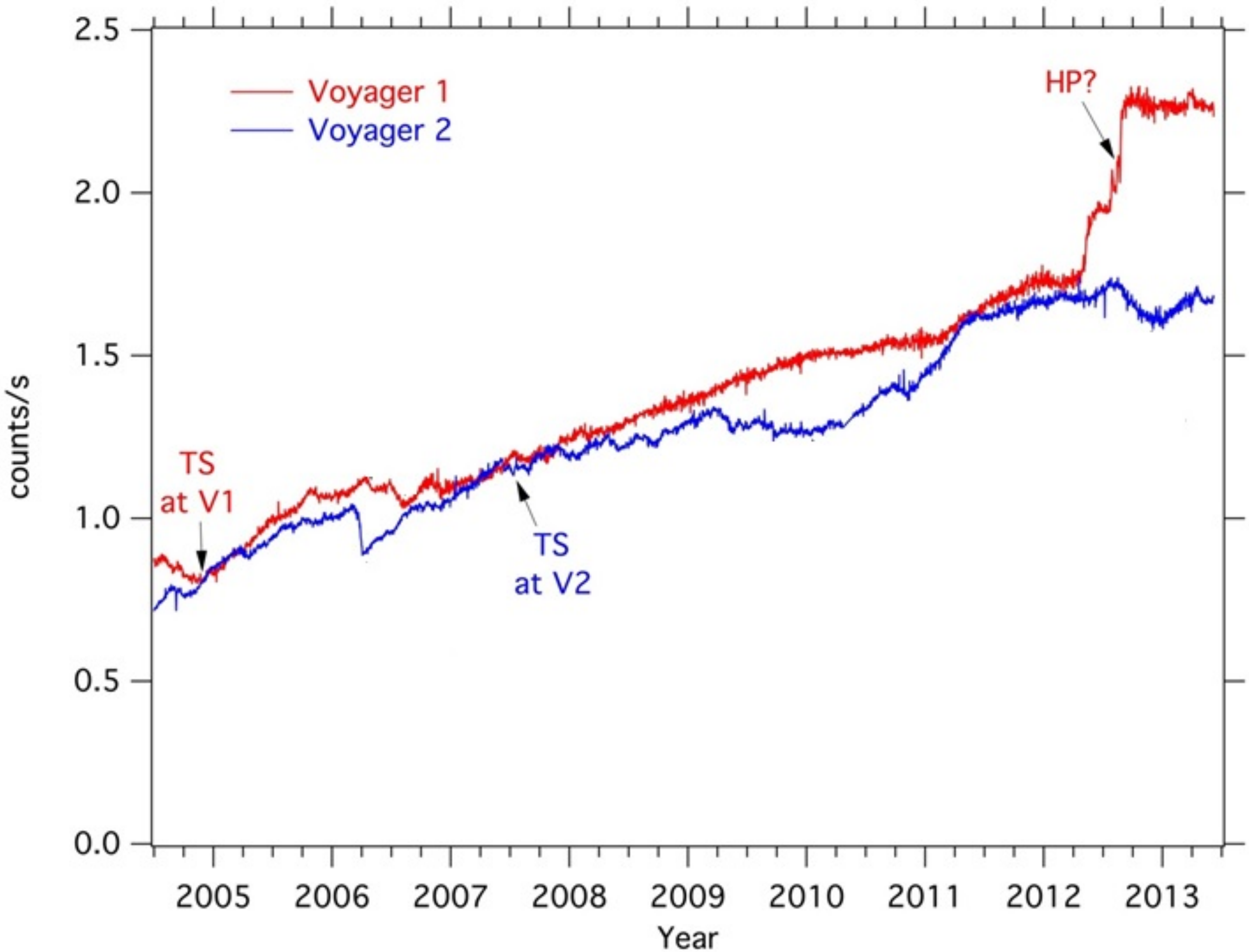
Particle Drifts

Adiabatic energy changes

Any local source

Study GCR modulation near the HP

Voyager observations of >70 MeV GCR intensity



V-PLS

Some Questions

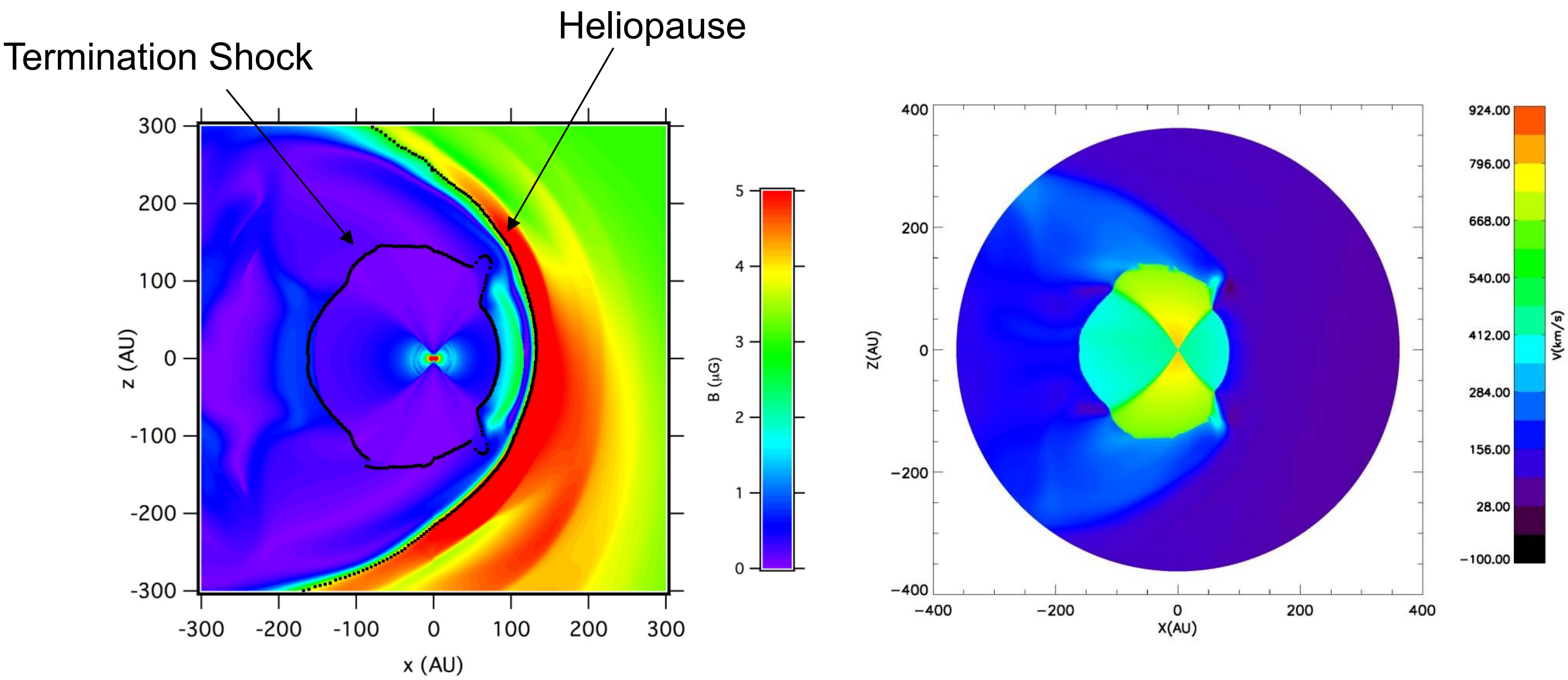
- Is heliopause the boundary for cosmic ray modulation as we set it in the computer simulation? What causes the radial flux jump as observed by Voyager 1?
- Does Voyager 1 observe the cosmic rays' interstellar spectrum, since it crossed HP in Aug. 2012?

My work is to use numerical method to contribute our answers for these questions.

Outline

Cosmic ray modulation in a realistic Global MHD heliosphere

Global Heliosphere Simulation-MHD Simulation Results



The interplanetary magnetic field and solar wind speed data from MHD simulation. The left panel shows the magnetic field magnitude in the X-Z plane; while the right panel shows the solar wind speed in the same plane.

Numerical Method For the transport Equation- Markov Stochastic Method

Cosmic Ray transport equation is equivalent to the following Ito

Stochastic Differential Equations

$$d\vec{\mathbf{x}} = \sqrt{2\vec{\vec{\kappa}}} \cdot d\vec{\mathbf{w}}(s) + (\nabla \cdot \vec{\vec{\kappa}} - \vec{\mathbf{V}}_{sw} - \vec{\mathbf{V}}_{d})ds$$

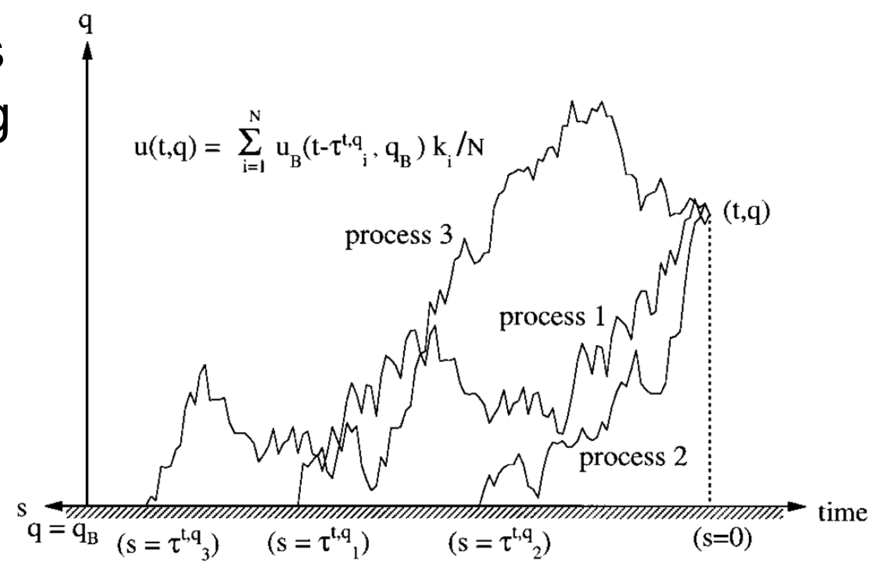
$$dp = \tfrac{1}{3}\nabla \cdot \vec{\mathbf{V}}_{sw} p ds$$

Demonstration of solving the cosmic ray equation in 1-D case.

dW satisfies a Wiener process, which is a nonstationary Markov process having a Gaussian Distribution.

$$p(dw_i) = \frac{1}{\sqrt{2\pi dt}} e^{[-\frac{(dw_i)^2}{2dt}]}$$

Gaussian distribution Random Number with standard deviation of dt



Cosmic ray modulation in a realistic Global MHD heliosphere

Incorporating MHD data into cosmic ray transport code

The MHD simulation $\vec{B}$ $\vec{V}_{sw}$

Diffusion Tensor

$$\vec{\vec{\kappa}} = \kappa_\perp \vec{\vec{I}} + (\kappa_\parallel - \kappa_\perp)\hat{b}\hat{b}$$

$$\kappa_\parallel = \left(\kappa_\parallel\right)_0 \beta \left(\frac{p}{1GeVc^{-1}}\right)^{0.5} \left(\frac{B_e}{B}\right)$$

$$\kappa_\perp = (\kappa_\perp)_0 \beta \left(\frac{p}{1Gevc^{-1}}\right)^{0.5} \left(\frac{B_e}{B}\right)$$

Drift Speed

$$\vec{V}_d = \frac{pv}{3q} \vec{\nabla} \times \left(\frac{\vec{B}}{B^2}\right)$$

Solar Wind Speed

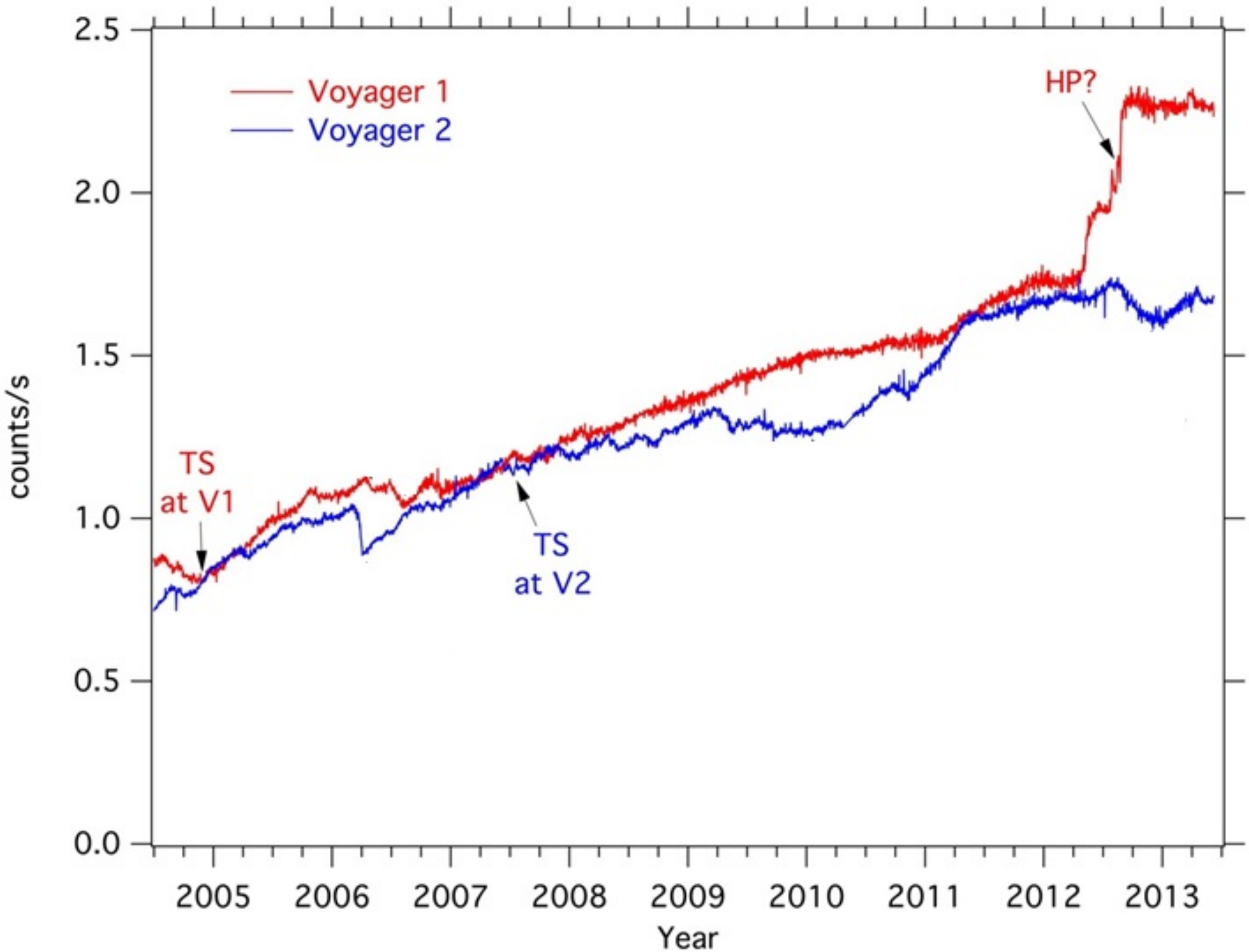
$$\vec{V}_{sw}$$

$$d\vec{\mathbf{x}} = \sqrt{2\vec{\vec{\kappa}}} \cdot d\vec{\mathbf{w}}(s) + (\nabla \cdot \vec{\vec{\kappa}} - \vec{\mathbf{V}}_{sw} - \vec{\mathbf{V}}_d)ds$$

$$dp = \tfrac{1}{3} \nabla \cdot \vec{\mathbf{V}}_{sw} p\, ds$$

Study GCR modulation near the HP

Voyager observations of >70 MeV GCR intensity



[V-PLS](V-PLS)

Study GCR modulation near the HP

Setting simulation model: Magnifying Diffusion Coefficients ratio

Motivation: the fact that parallel diffusion should be much more effective than the perpendicular diffusion in the outer heliosheath.

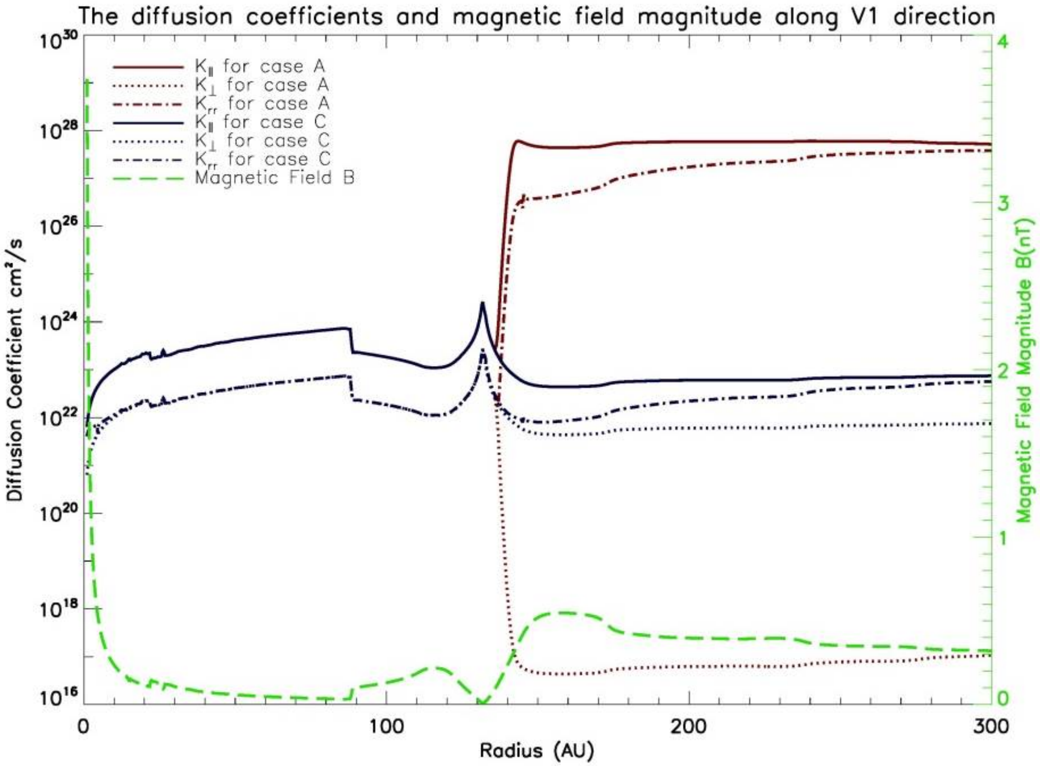
$$\kappa_{\parallel}^{ISM} = 10^{28} cm^2 / s$$

$$\kappa_{\parallel}^{Helio} = 10^{23} cm^2 / s$$

$$\kappa_{\parallel} = \left(\kappa_{\parallel}\right)_0 \beta \left(\frac{p}{1GeVc^{-1}}\right)^{0.5} \left(\frac{B_e}{B}\right) \times fac$$

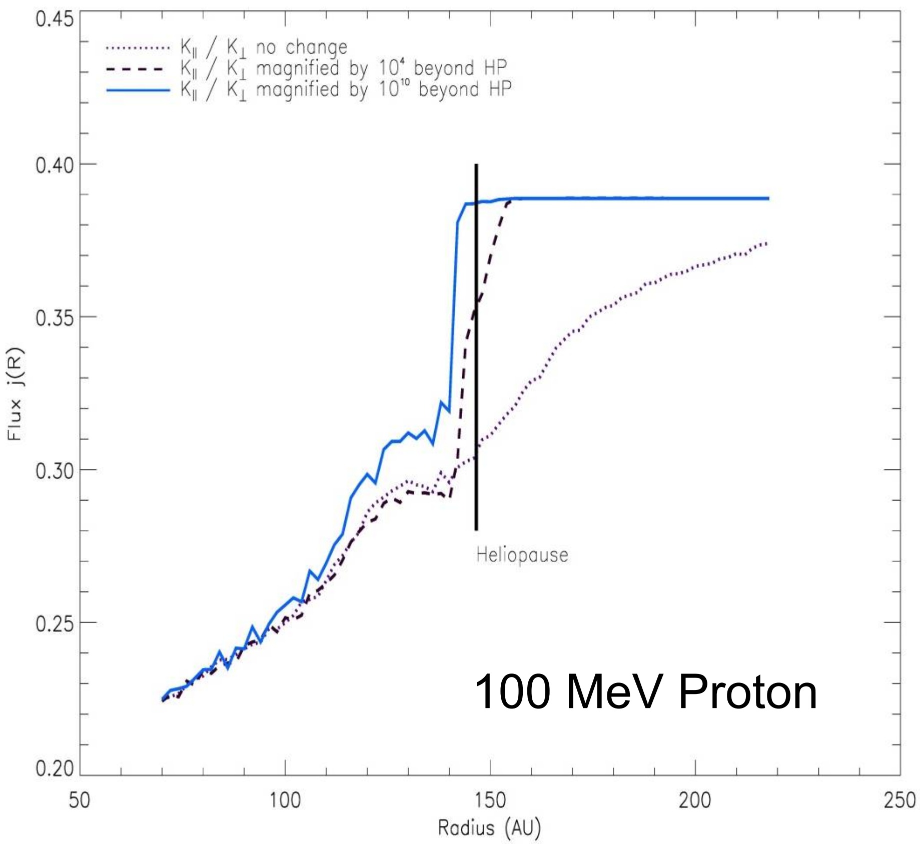
$$\kappa_{\perp} = (\kappa_{\perp})_0 \beta \left(\frac{p}{1Gevc^{-1}}\right)^{0.5} \left(\frac{B_e}{B}\right) / fac$$

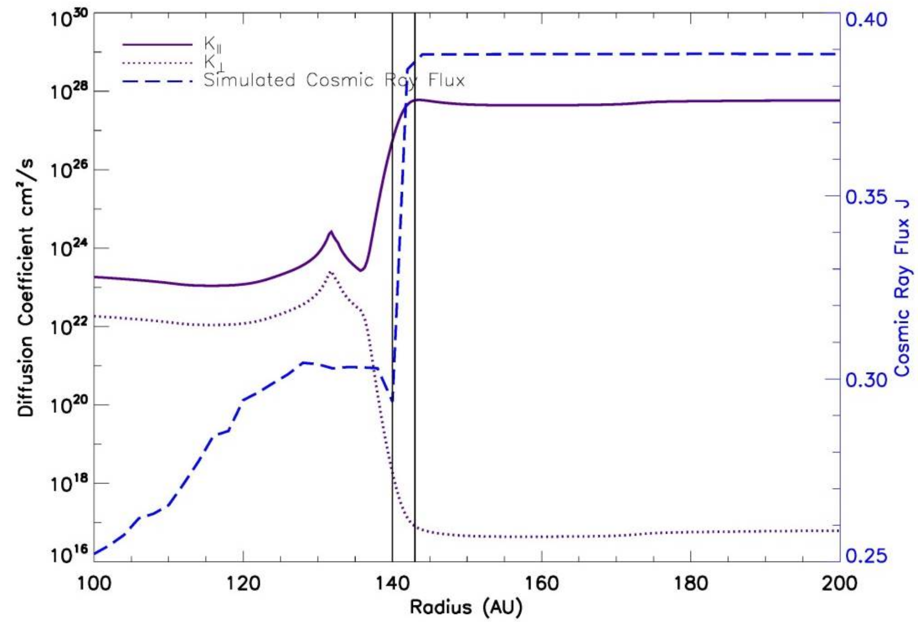
$$fac = \frac{1+M_k}{2} + \frac{M_k - 1}{2} \times \frac{(B/B_{ism})^6 - (B_{ism}/B)^6}{(B/B_{ism})^6 + (B_{ism}/B)^6}$$



Study GCR modulation near the HP

Simulation Results by Magnifying Diffusion Coefficients ratio

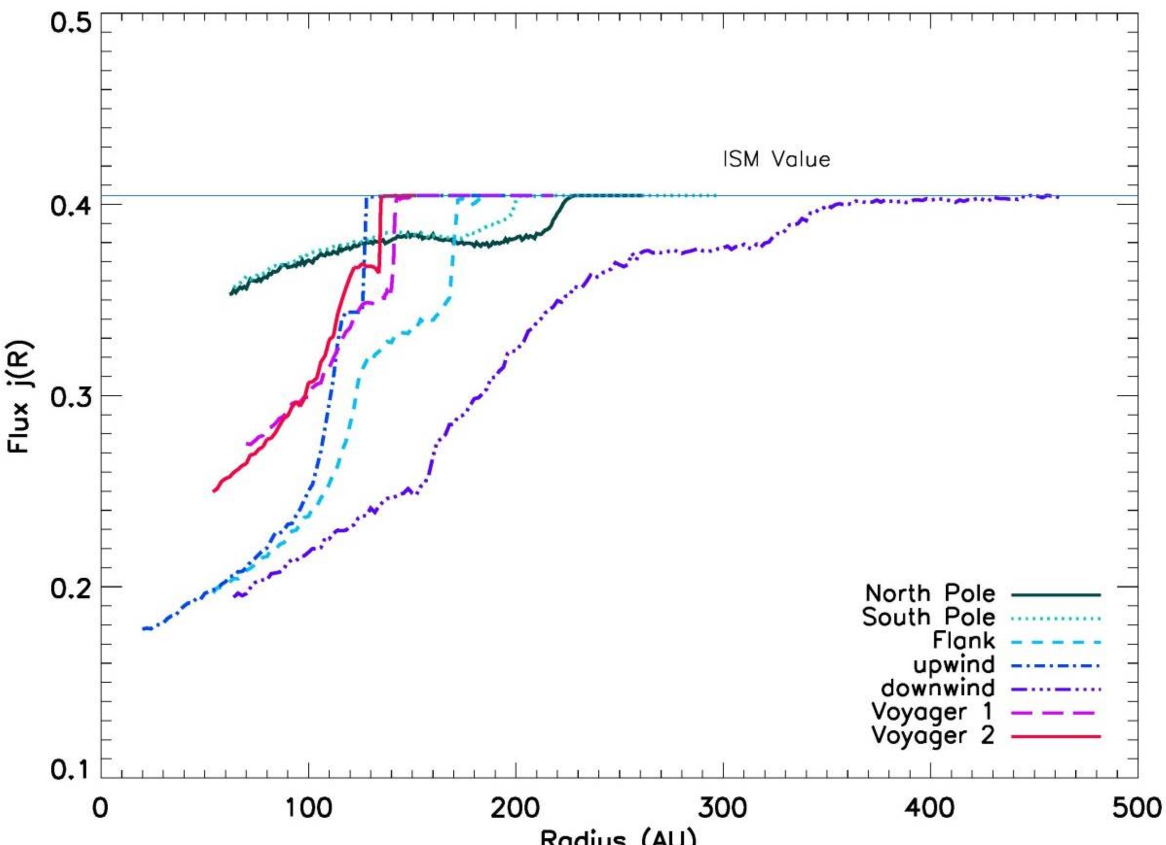




- The cosmic ray radial gradient sharply increase near the HP as the ratio increase.
- By increasing the ratio to 10^{10} , we reproduce the cosmic ray intensity jump as Voyager 1 observed in Aug. 2012.

Study GCR modulation near the HP

Simulation Results for different directions



No sharp jump along the polar, and tail direction.

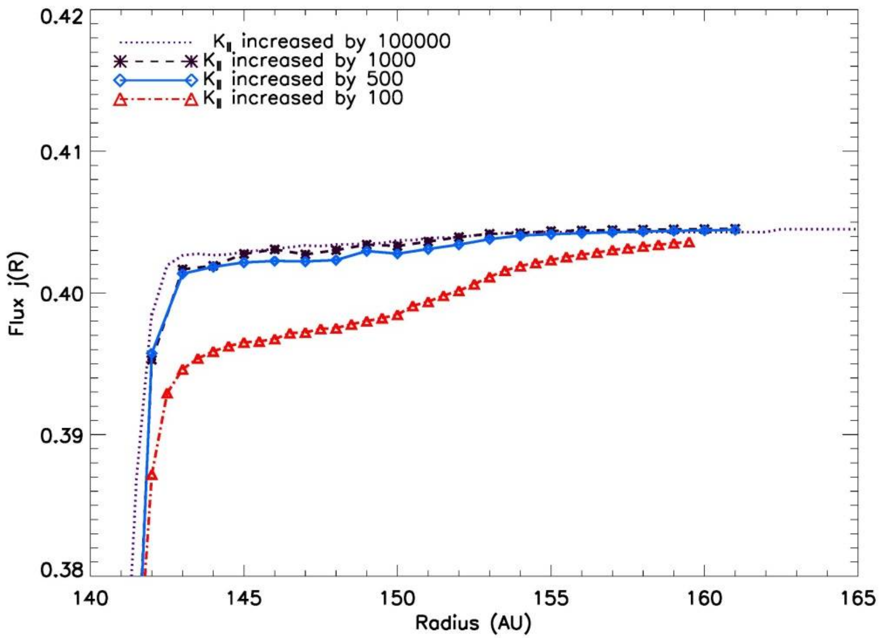
There is still jump along the Voyager 2 direction. Based on the location of this jump, the HP crossing time of Voyager 2 can be estimated.

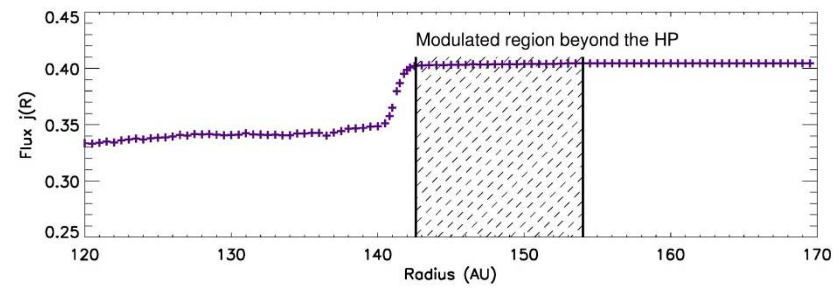
$$time = [(radius_{MHD} - 19AU) - 83.7AU] / 3.3year + 2007.66 = 2017.14$$

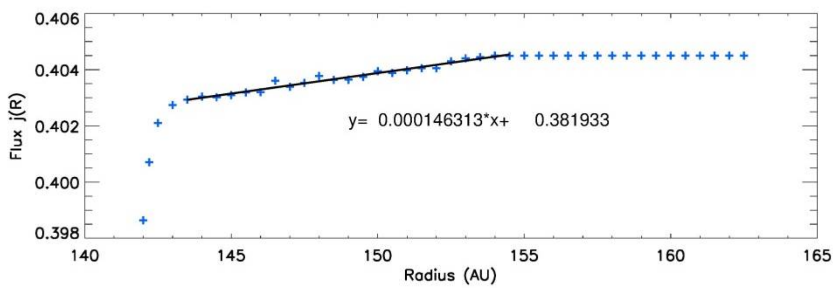
$$HP_{V2} = 134AU$$

Study GCR modulation near the HP

Modulation Boundary: Heliopause







Diffusion Coefficients affects the radial gradient beyond the HP.

There is seldom modulation exists(<0.1% per AU) if using the diffusion coefficients sets inferred from Voyager 1 CR observation.

Conclusions

Study Galactic Cosmic Ray Modulation near the Heliopause(HP)

- Cosmic Ray intensity jumps as the parallel diffusion coefficient and the ratio of the diffusion coefficients are magnified.
- There is still jump along the Voyager 2 direction. Based on the location of this jump, the HP crossing time of Voyager 2 can be estimated.
- There is seldom modulation exists if using the diffusion coefficients sets inferred from Voyager 1 CR observation.
- For cosmic ray particles arriving at the assumed Voyager 1 location, most of them entering the tail region and diffuse along spiral line to the nose region.

Outline

Solar wind velocity profiles in the heliosphere