

Cosmic Rays in the Heliosphere

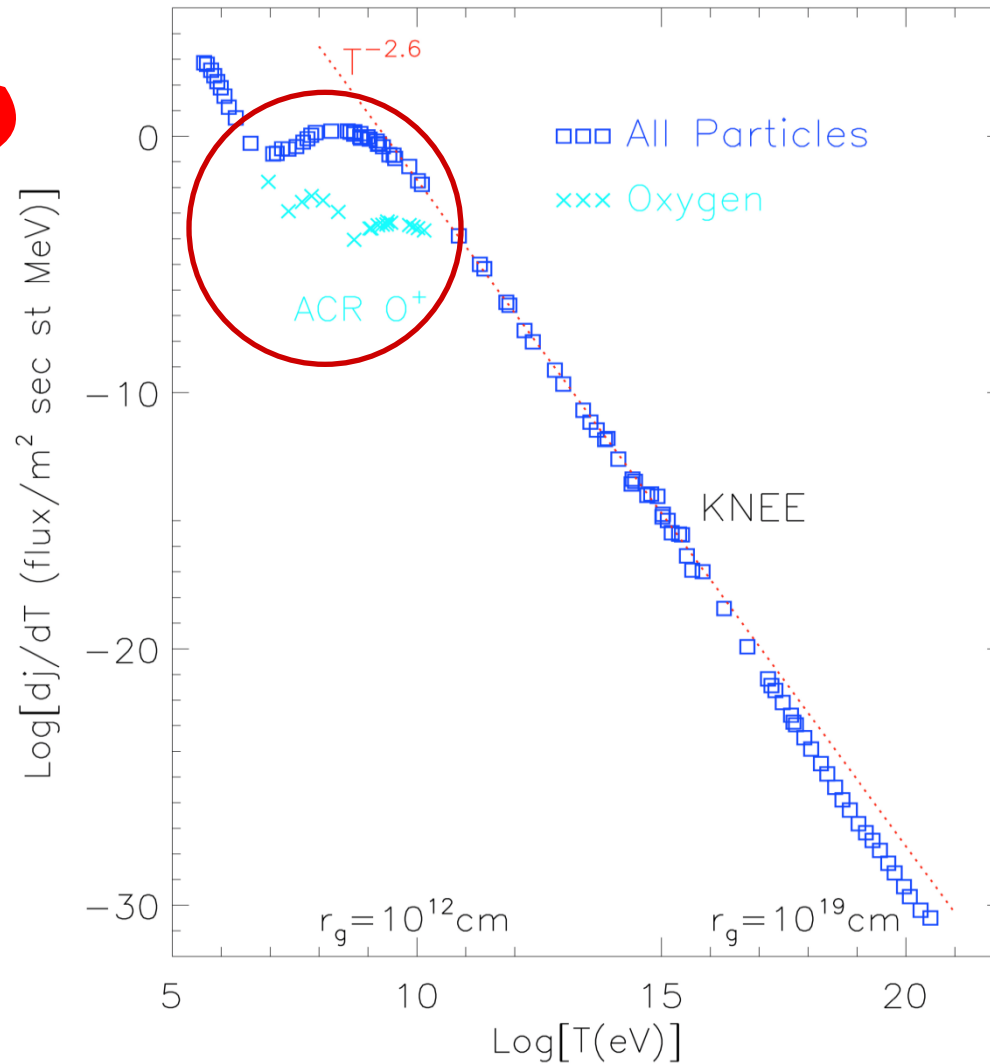
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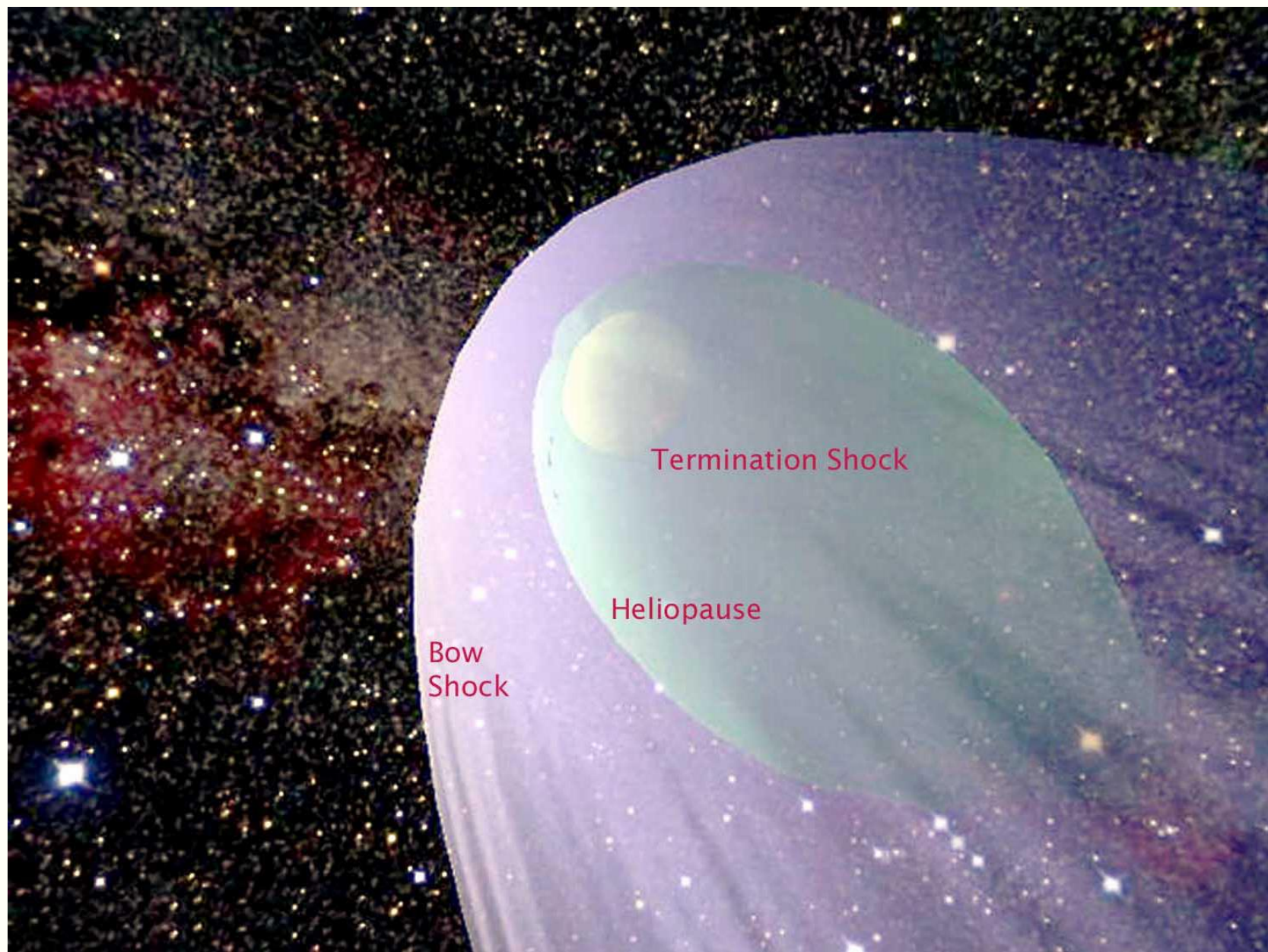
I acknowledge helpful discussions with J. Kóta and J. Glacalone.

*Presented at the TeV Particle Astrophysics Workshop,
Irvine, CA, 26-29 August, 2013*

Cosmic Rays

Heliospheric
Effects

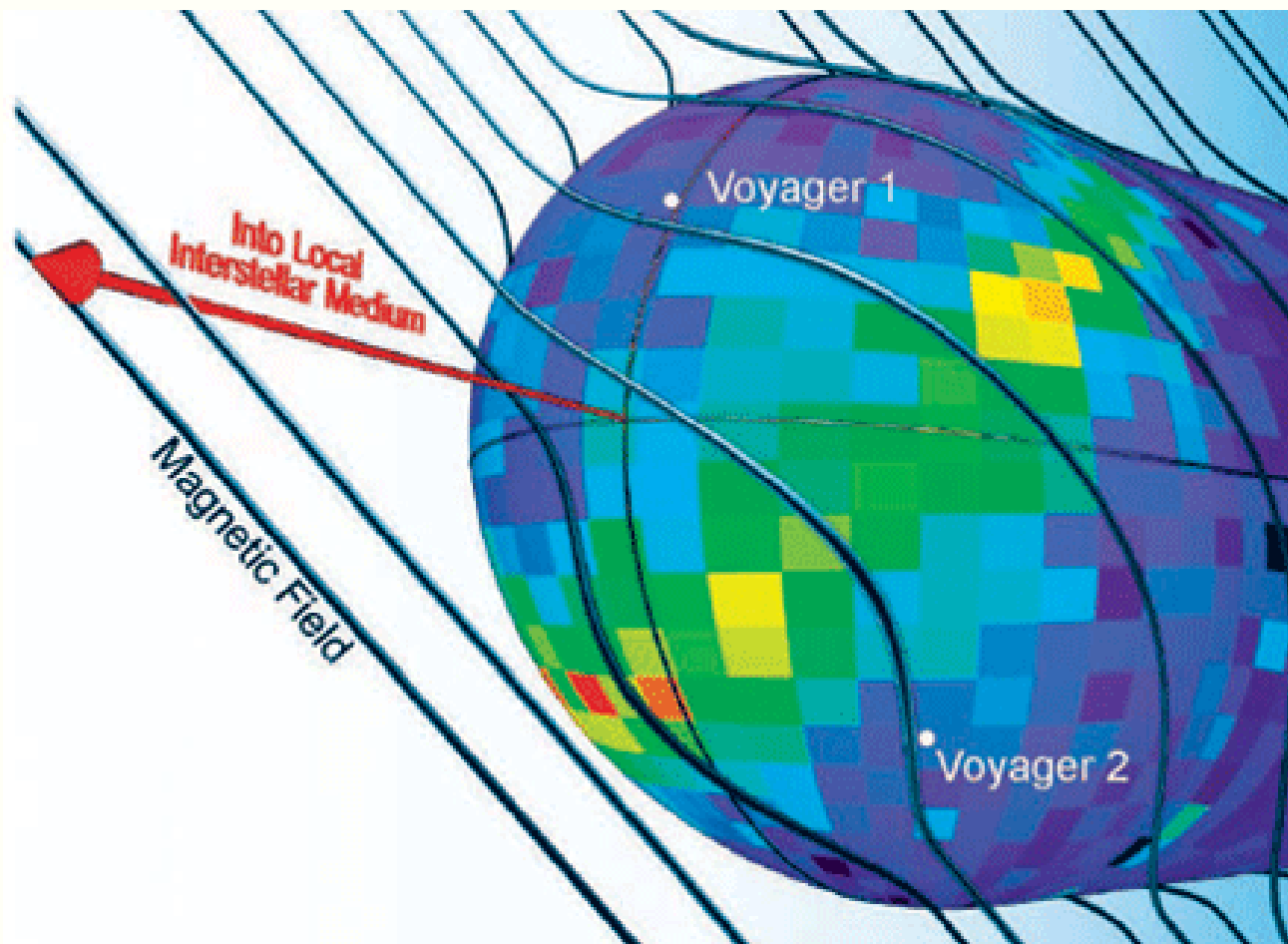




Termination Shock

Heliopause

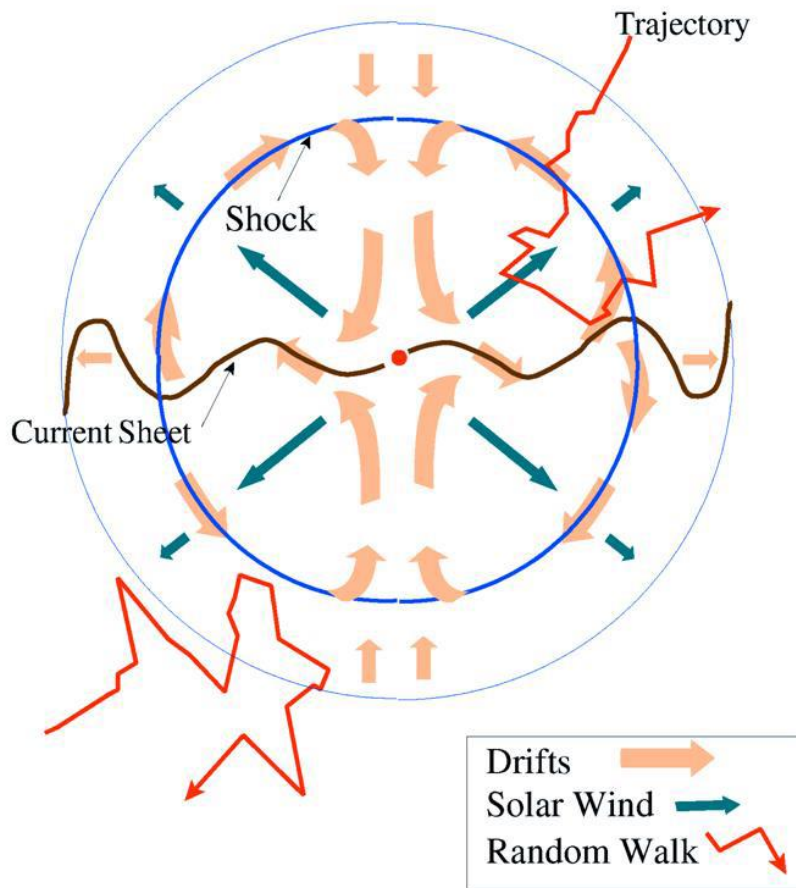
Bow
Shock



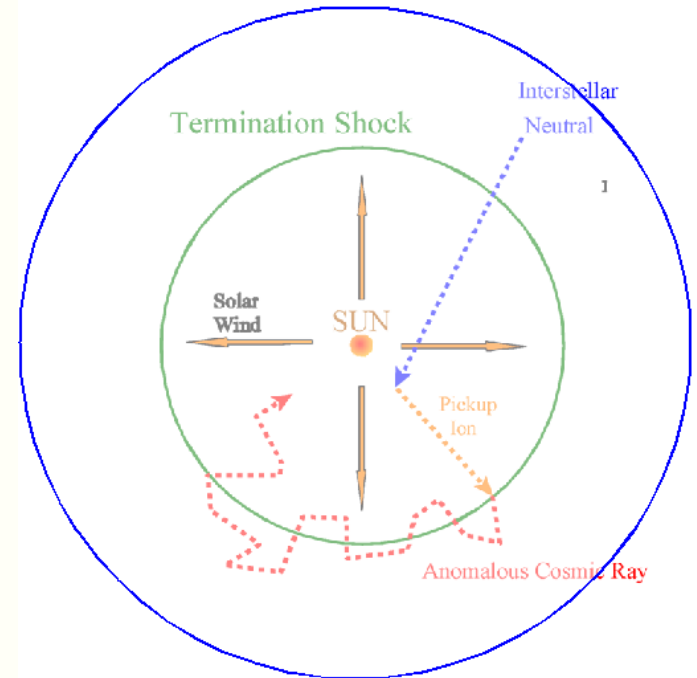
- I will concentrate on energies significantly lower than 1 TeV, as the effects of the heliosphere at 1 TeV are smaller (but still significant).
- The gyro-radius of a 1 TeV proton in the interstellar magnetic field is ~ 74 AU, which is significantly smaller than the heliosphere.
- The interstellar field is distorted in the flow around the heliosphere out to perhaps a few hundred AU, so there should be significant observable effects on cosmic rays up to 10 TeV or more.
- I do not have time to discuss this further here.

The standard paradigm for anomalous cosmic rays (ACR) and galactic cosmic rays (GCR).

Galactic Cosmic Rays



ANOMALOUS COSMIC RAYS



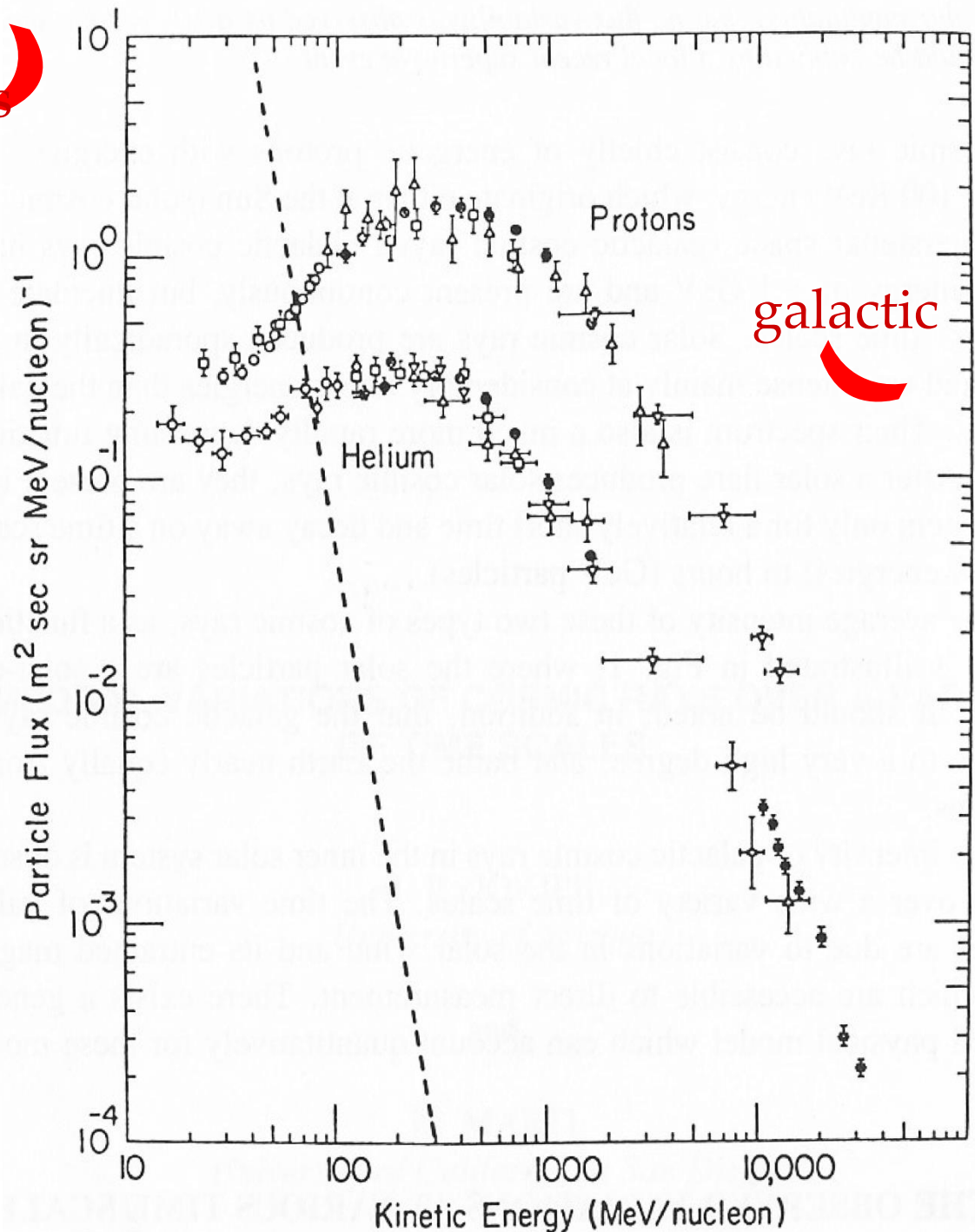
Solar Particles

Showing the average GCR intensity at Earth with very transient solar particles superimposed.

A solar energetic-particle event lasts hours to a day or so.

The average intensity at energies $>\approx 100$ MeV/nuc is dominated by GCRs and anomalous cosmic rays.

Until the past year, we had no knowledge of the GCR flux below some 100 MeV/nuc.



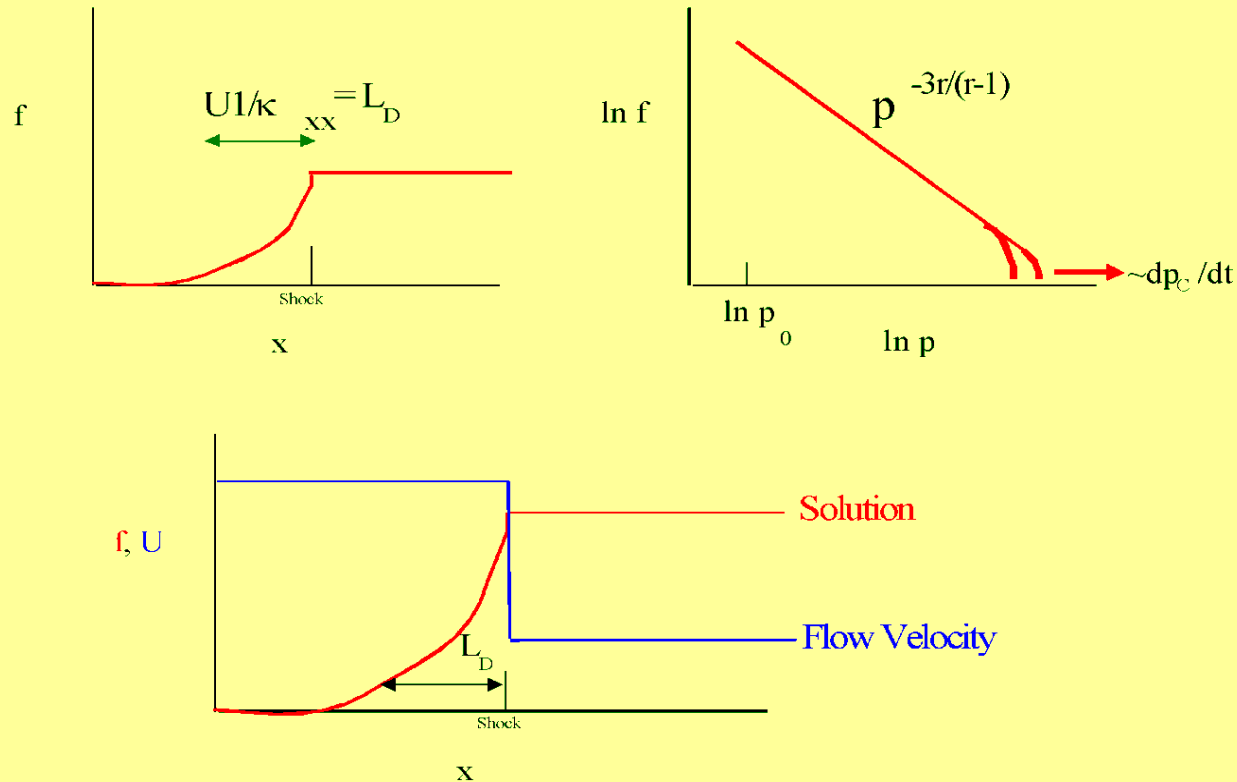
The Parker Transport Equation:

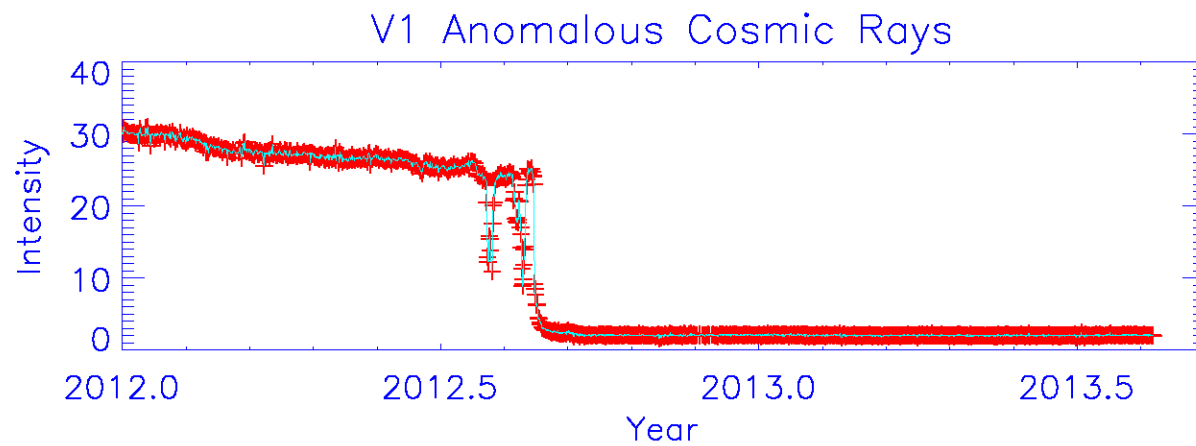
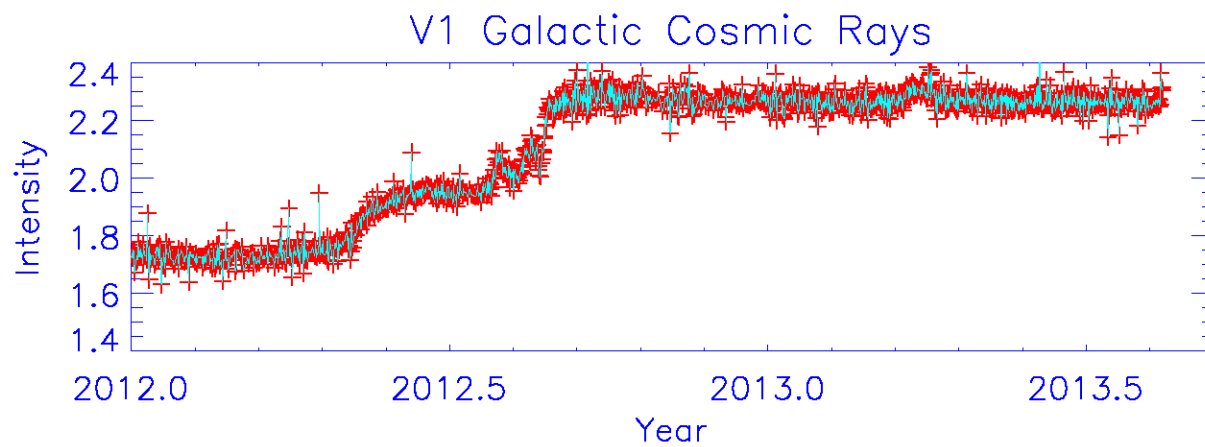
$$\begin{aligned}
 \frac{\partial f}{\partial t} = & \frac{\partial}{\partial x_i} \left[\kappa_{ij}^{(S)} \frac{\partial f}{\partial x_j} \right] &&) \text{ Diffusion} \\
 & - \mathbf{U} \cdot \nabla f &&) \text{ Convection w. plasma} \\
 & - \mathbf{V}_d \cdot \nabla f &&) \text{ Grad \& Curvature Drift} \\
 & + \frac{1}{3} \nabla \cdot \mathbf{U} \left[\frac{\partial f}{\partial \ln p} \right] &&) \text{ Energy change} \\
 & + Q &&) \text{ Source}
 \end{aligned}$$

Where the drift velocity due to the large scale curvature and gradient of the average magnetic field is:

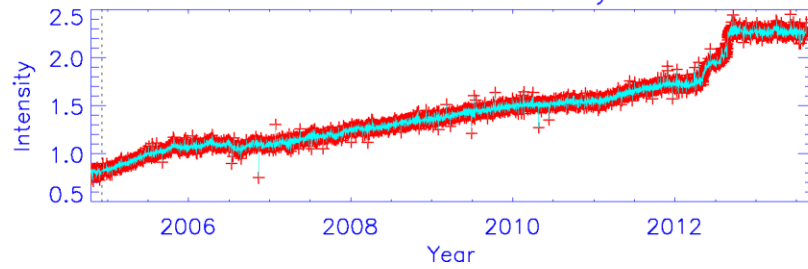
$$\mathbf{V}_d = \frac{pcw}{3q} \nabla \times \left[\frac{\mathbf{B}}{B^2} \right]$$

Let us look at the paradigm of diffusive shock acceleration for a simple planar shock. Solve Parker's equation at a flow discontinuity.

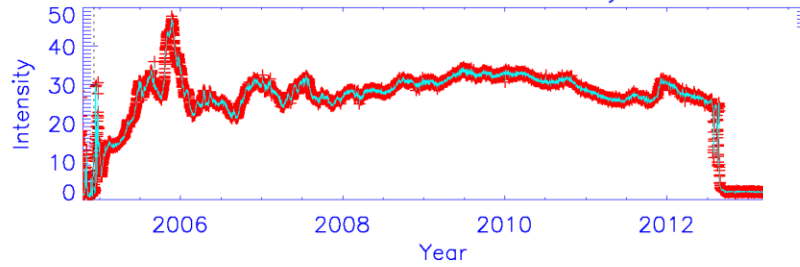




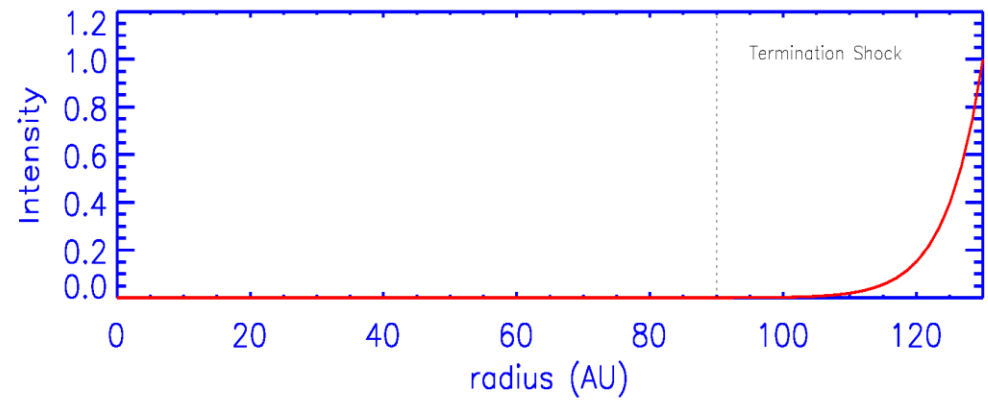
V1 Galactic Cosmic Rays



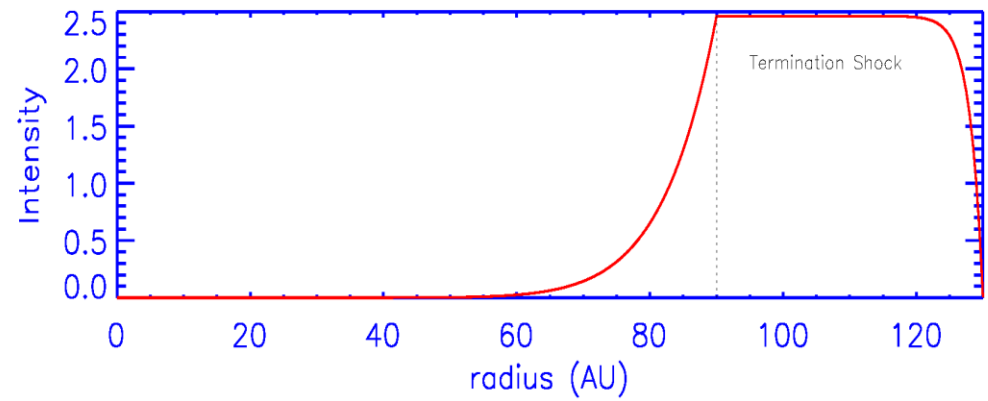
V1 Anomalous Cosmic Rays



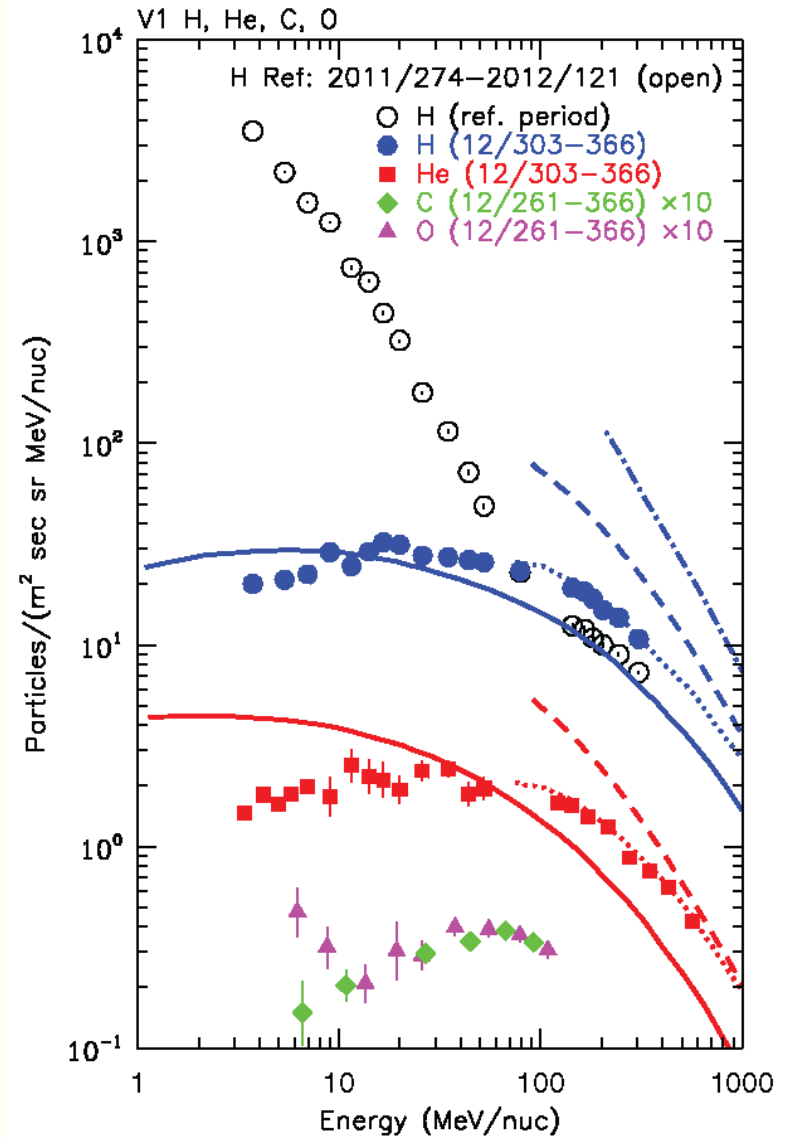
Galactic



Anomalous



We believe that V1 is now observing the interstellar GCR intensity below 200 MeV for the very first time!



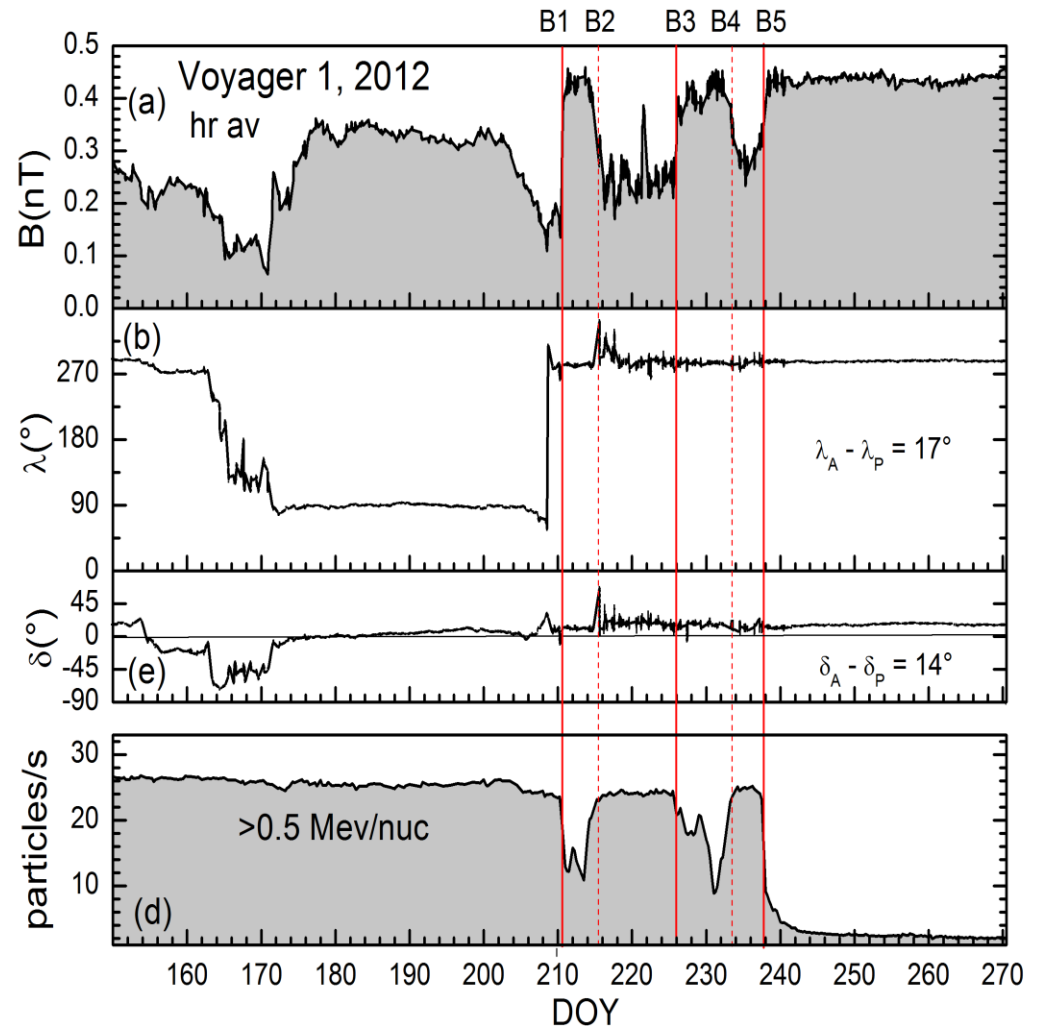
What is the interpretation of these recent changes in the energetic particles?

- Given the general agreement with the expected behavior at the heliopause, the observations prompted speculation that the heliopause was indeed crossed.
- The magnetometer data was eagerly anticipated. It was expected that the magnetic field would show a change in direction at the same time as the intensity changes in ACR and GCR.

However, the V1 magnetometer showed no significant change in direction.

Hence, the Voyager SSG has decided that this is a new region of space – the ‘magnetic highway’.

Some feel that V1 crossed the heliopause and others that V1 has not. This is currently being debated.



Galactic cosmic rays have been observed in many observations over the last several decades to be very nearly isotropic. At several TeV energies, the anisotropies observed are less than 10^{-3} .

At lower energies, one must use modeling, as the heliosphere distorts the trajectories of the lower-energy particles.

This analysis has been done by many authors.

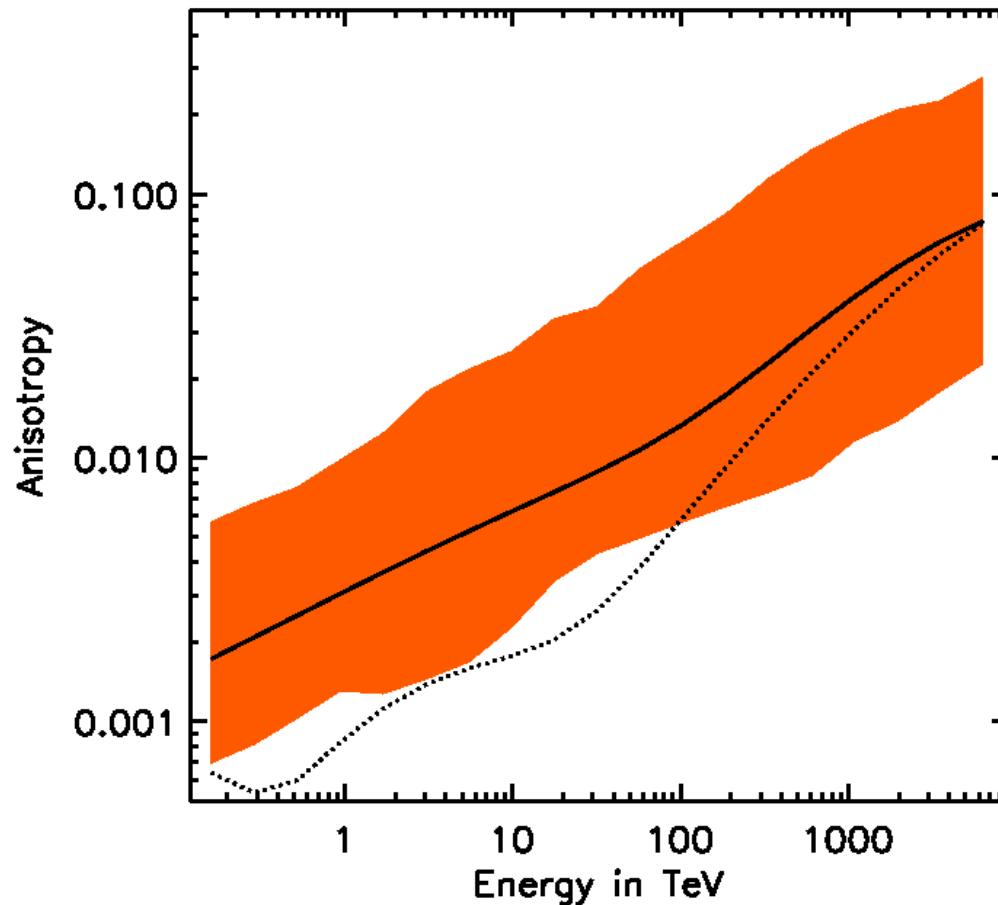
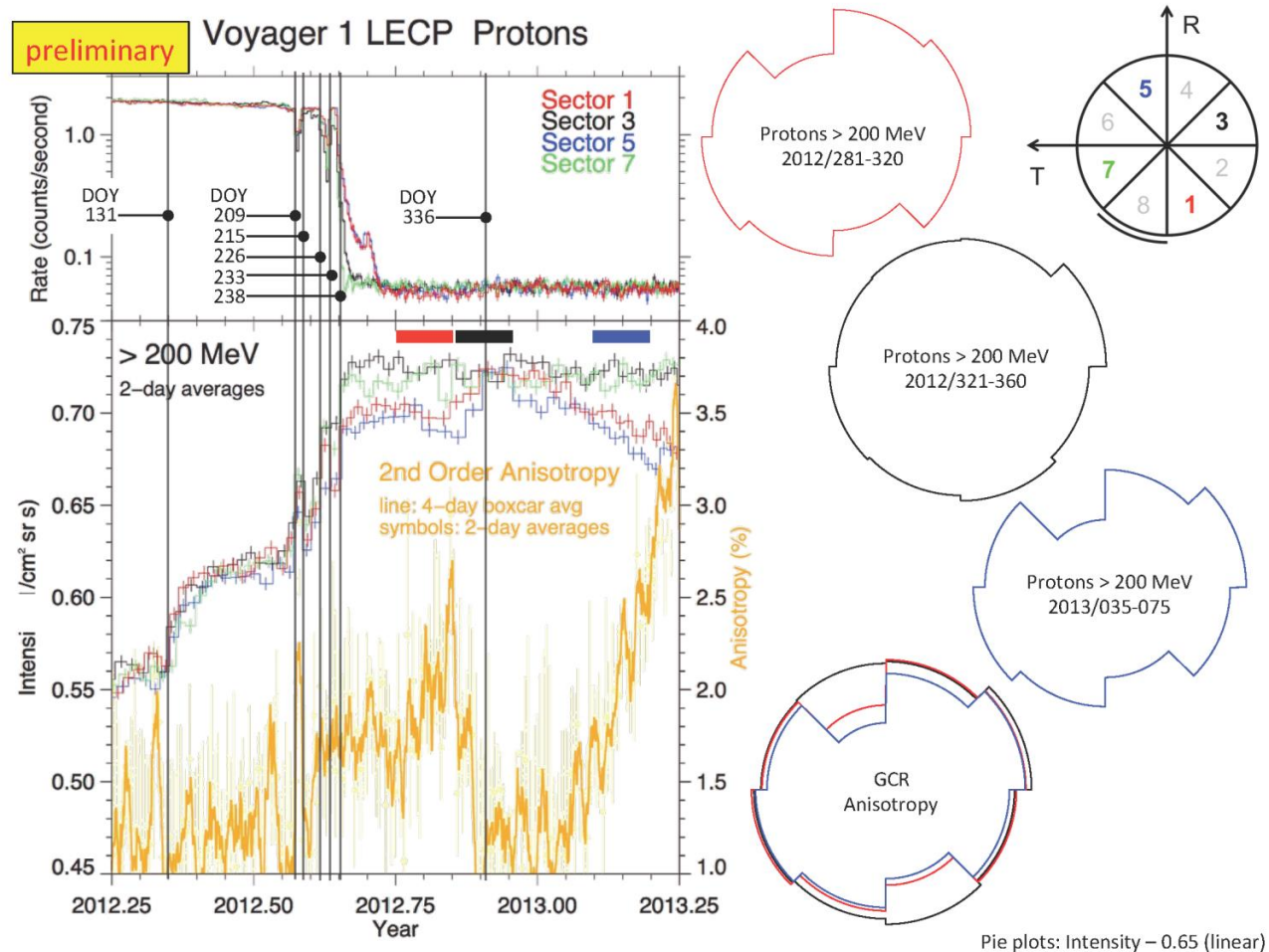


Figure 2. Anisotropy for standard parameters (Trotta et al.) and $H = 5$ kpc. The red band indicates the central 90% of the fluctuation range. The solid line marks the median of the distribution and the dotted line describes the anisotropy amplitude in a randomly selected run.

Pohl and Eichler 2013 *ApJ* **766** 4 [doi:10.1088/0004-637X/766/1/4](https://doi.org/10.1088/0004-637X/766/1/4)

Extrapolating to \sim GeV energies yields a very small anisotropy $\sim 10^{-4}$

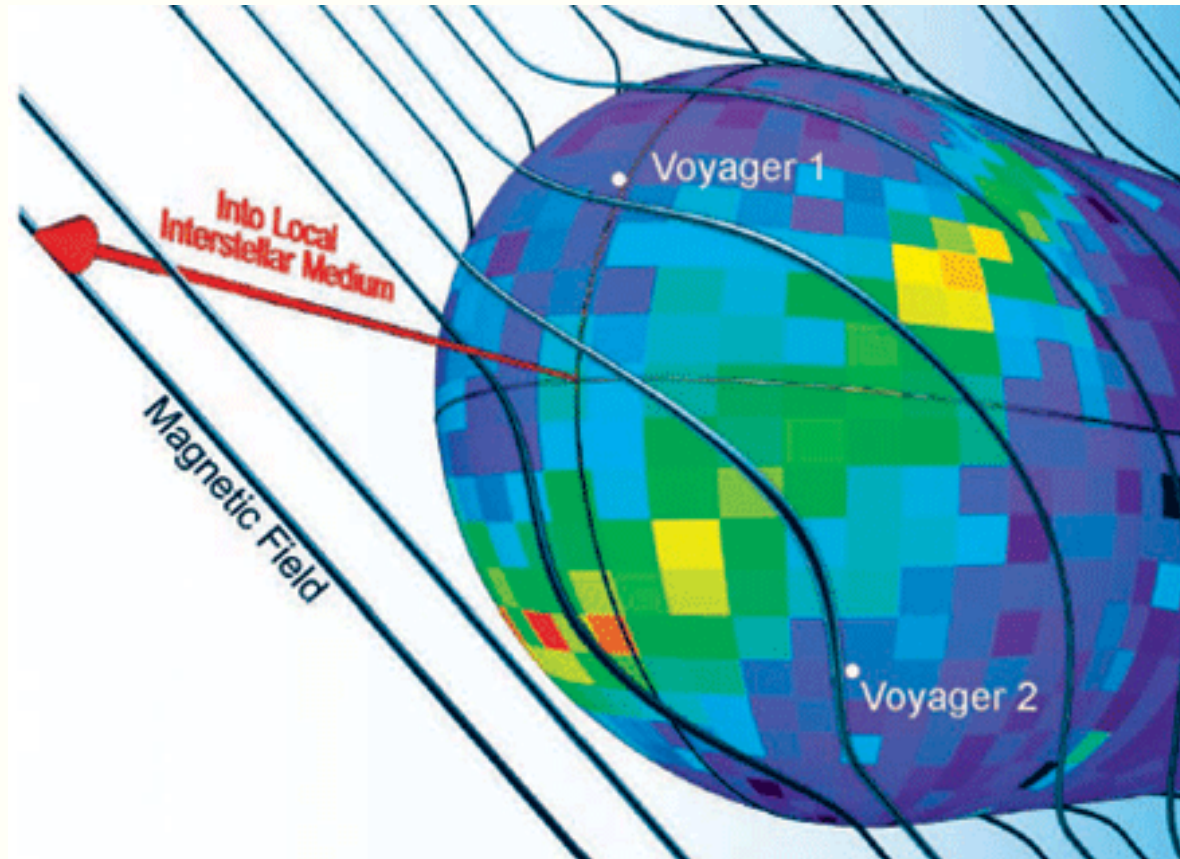
Hill (private communication) reports significant anisotropies.



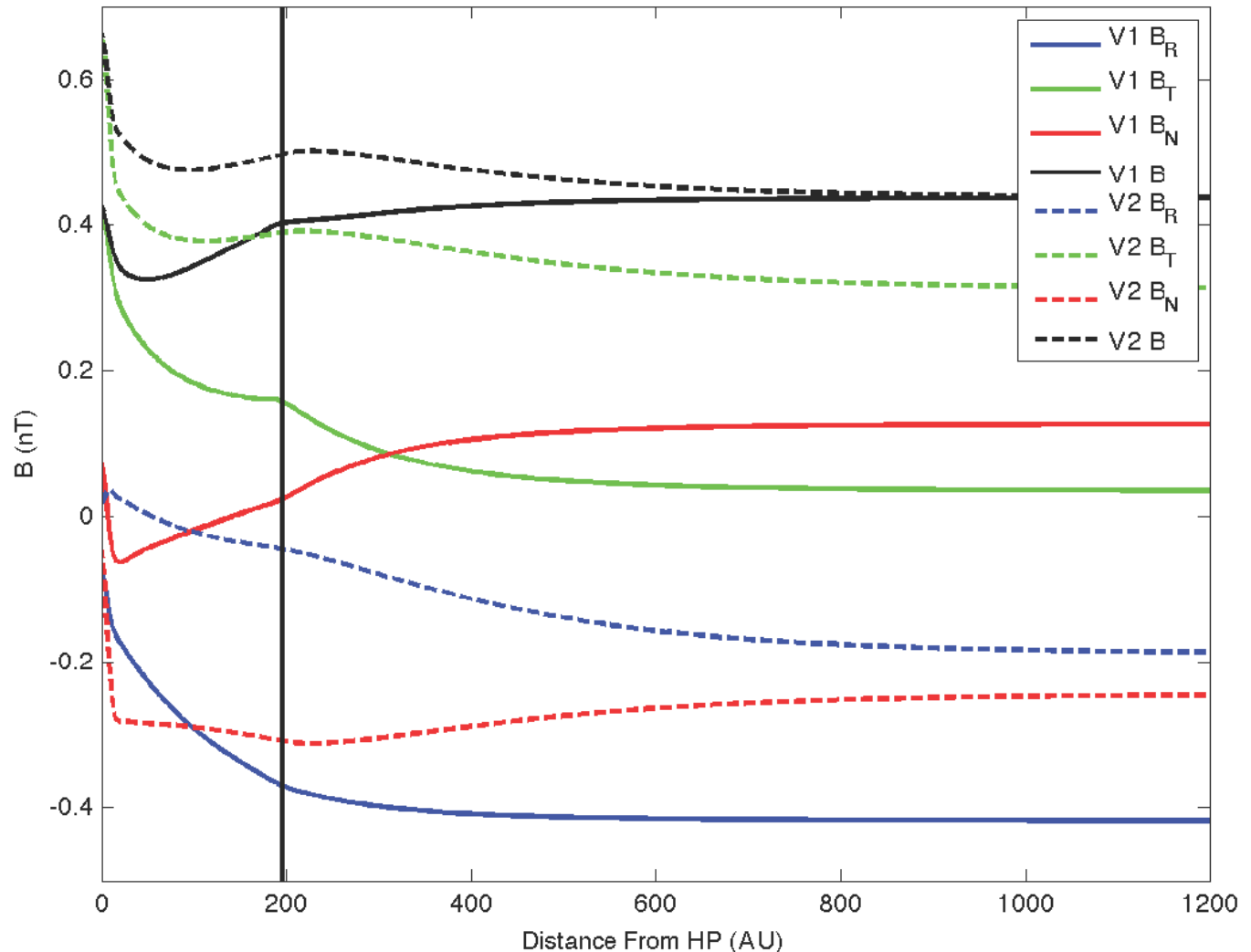
The anisotropy is \sim few % and persists for several months. This is the largest GCR anisotropy ever observed.

What can be the cause of this large anisotropy?

Almost certainly it is not of interstellar origin. It must come from the interaction of the interstellar medium with the heliosphere.



V1/V2 Magnetic Field Components Beyond the Heliopause



Note the decrease in $|B|$ near the heliopause.

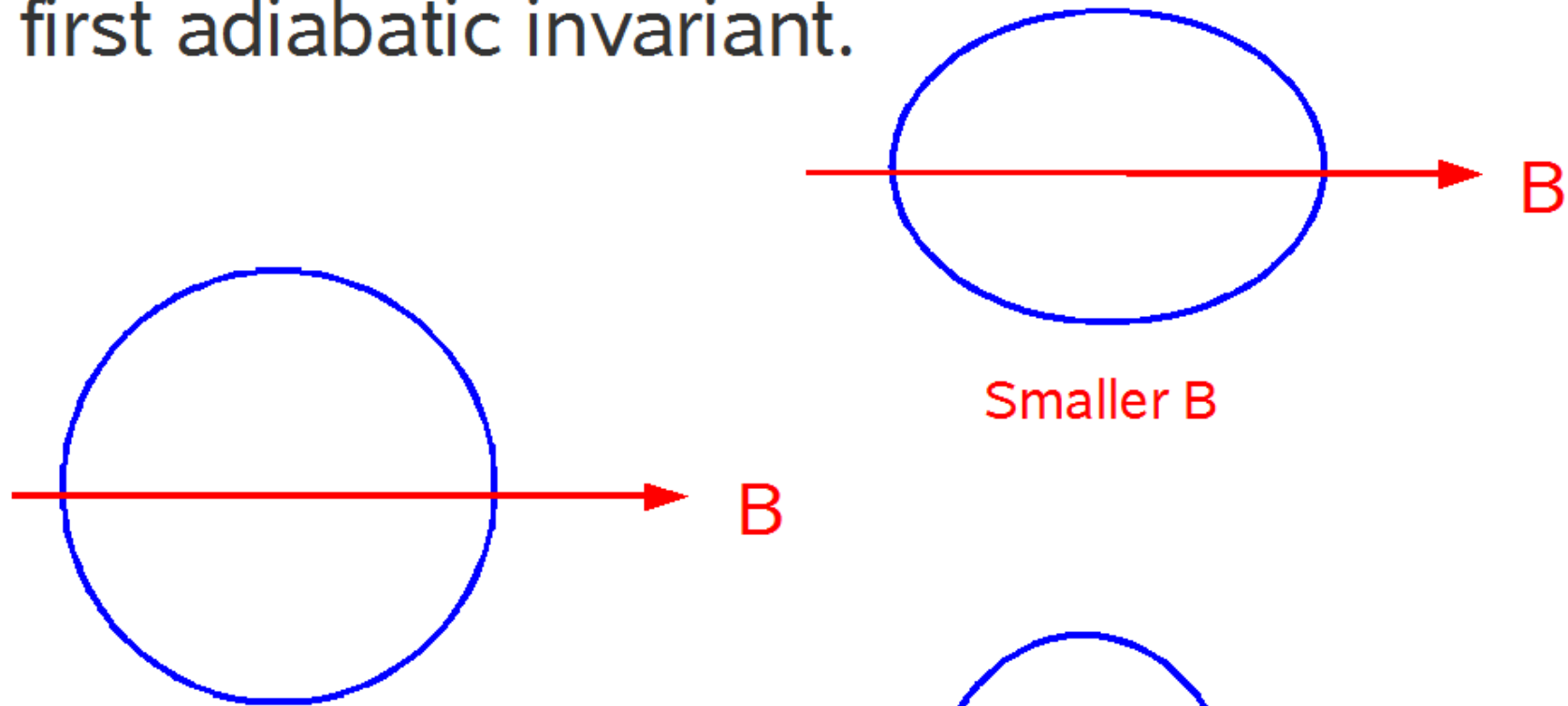
This is the result of a simulation sent to me by M. Opher. (Pogorelov shows similar curves.)

Effects of variation in the magnetic-field intensity on isotropy

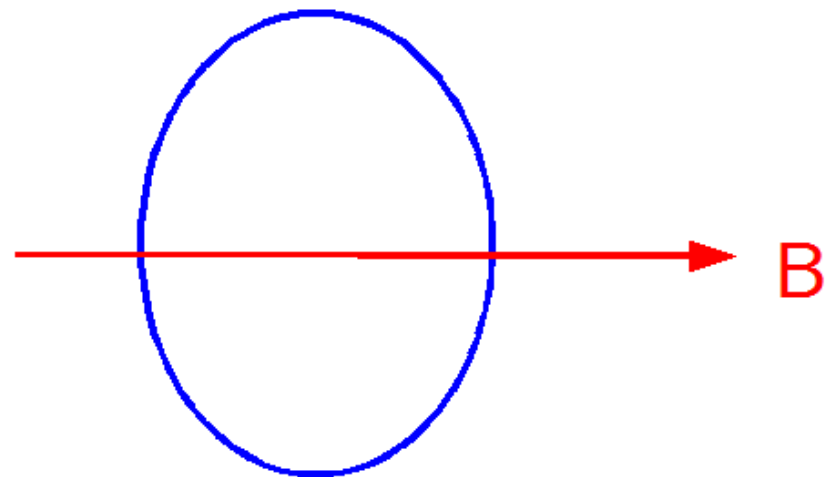
- We consider 200 MeV galactic cosmic rays.
- Their gyroradius in the 3 nT local interstellar magnetic field is $r_g = m v c / (q B) = .033 \text{ AU}$ and their gyro-period is $\tau_g = 2\pi / \omega_g = 125 \text{ sec.}$
- The corresponding scales in the local ISM flow around the heliopause are $L \approx 1 \text{ AU}$, and $\tau_{\text{flow}} = L / U_{\text{flow}} \approx 2.5 \text{ yr.}$
- Hence, on scales less than the scattering mean free path, the cosmic-ray motion conserves the first adiabatic invariant $\mu_{\text{ad}} = T_{\text{perp}} / B$, where T_{perp} is the perpendicular *kinetic energy*.
- Changes in the magnetic field magnitude B will therefore induce anisotropies in an originally isotropic distribution, unless scattering by the turbulence isotropizes the distribution faster, on a shorter time scale.

Effect of conservation of first adiabatic invariant.

Similar to observation



Initial nearly isotropic distribution



Bigger B

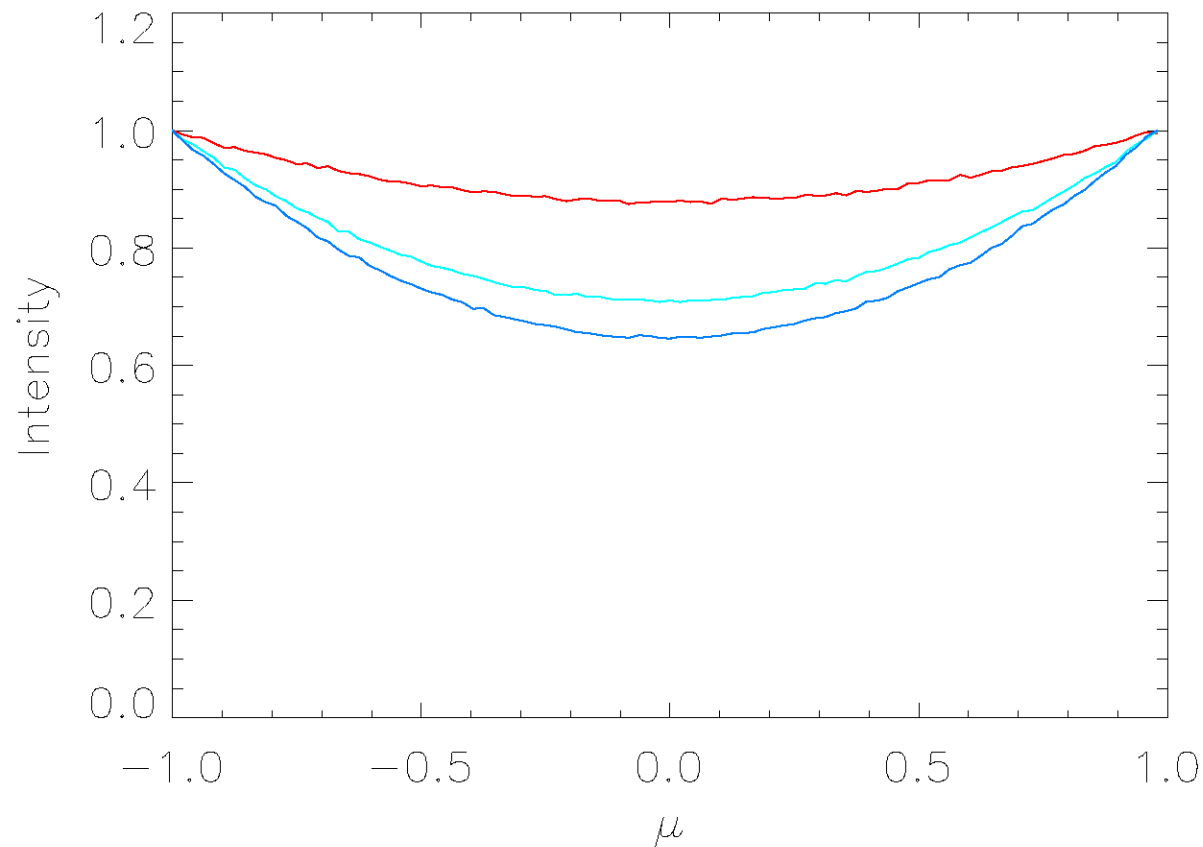
Effect of scattering.

- Interstellar turbulence scatters the cosmic rays.
- The time scale for this may be estimated from the interstellar diffusion coefficient deduced from a number of different observations.
- One finds $D_{\text{ism}} \sim 10^{27} - 10^{28} \text{ cm}^2/\text{sec}$ for 200 MeV protons.
- In this case, $L_{\text{sc}} \sim 1.5 \times 10^{18} \text{ cm}$ or $\tau_{\text{sc}} \sim 2.5 \text{ yr}$.
- Thus the scattering time and the flow time scale are comparable, so scattering plays a role.
- We expect some anisotropy, but not as much as that given by adiabatic invariant conservation.
- We must carry out a numerical analysis.

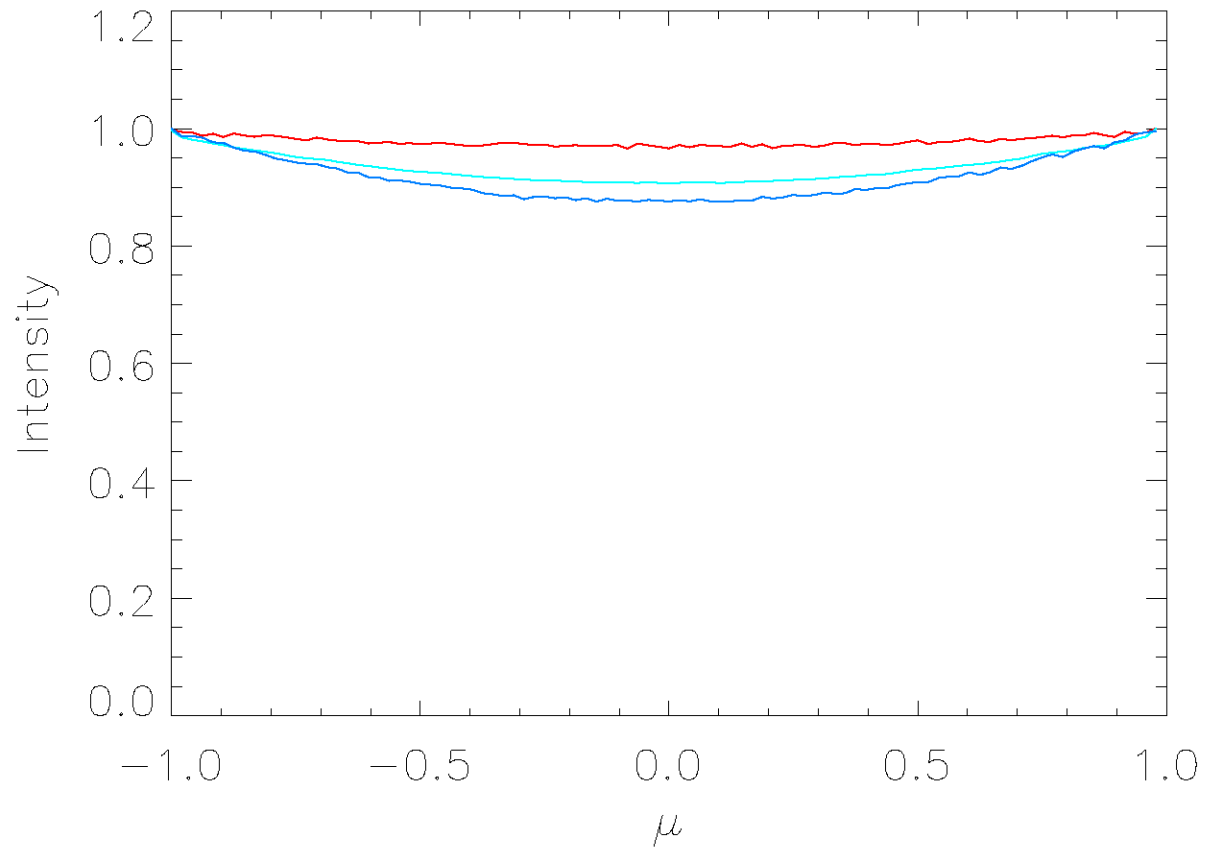
Solve for the distribution function

- Use Liouville's equation.
- Apply to an initially isotropic distribution with a dependence on momentum given by $f_0(p) = Ap^{-\alpha}$ with $\alpha = -2.6$.
- Scattering is taken to be simple isotropization with a scattering time τ_{sc} .
- The magnetic field decreases or increases, causing an anisotropy. Scattering counters this.

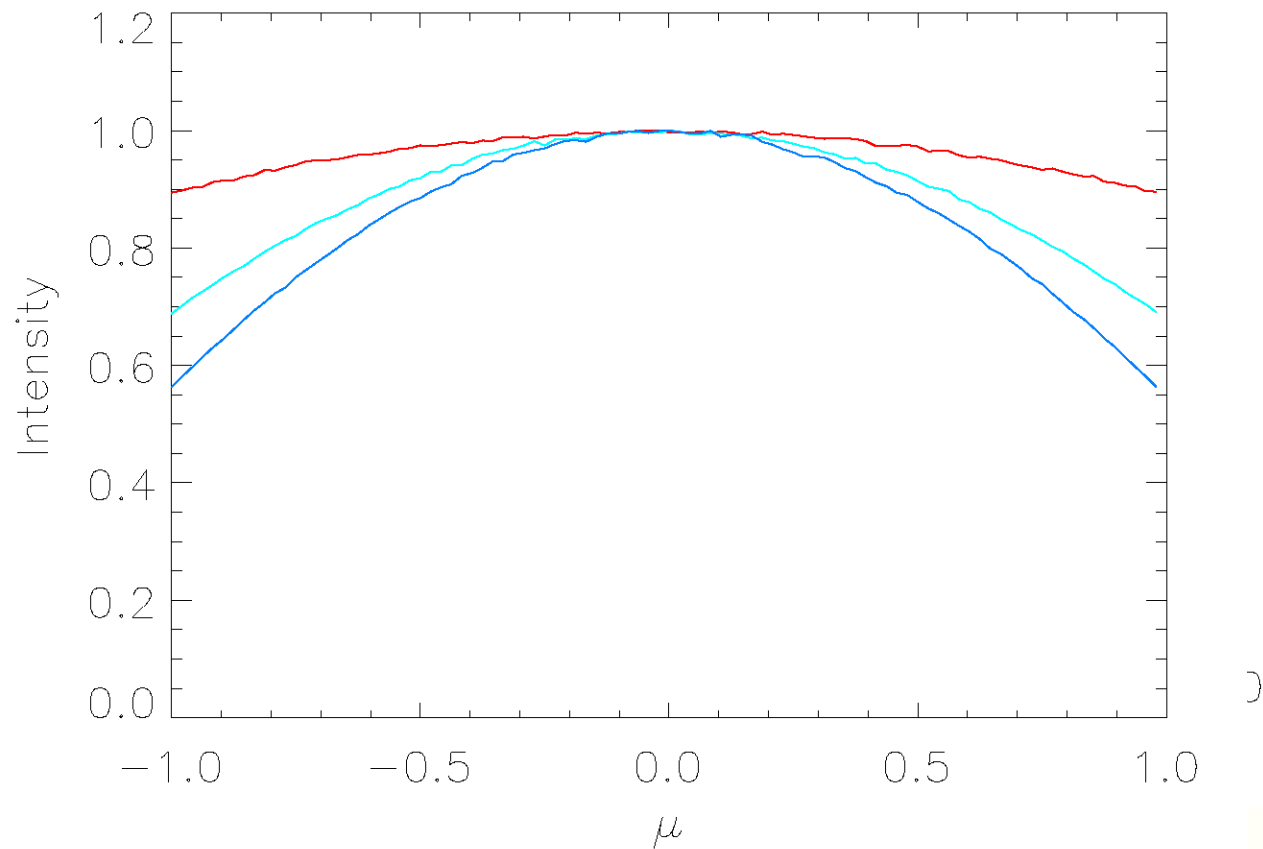
Solution for a magnetic field *decreasing* to 0.7 of its original value, with various values of ζ_{sc} approximately that of interstellar scattering. The magnitude of the anisotropy is not far from what is observed.



Solution for a magnetic field *decreasing* to 0.9 of its original value, with various values of ζ_{sc} .



Effect of an *increasing* magnetic field. This is not what is observed.



Conclusions

- The effects of the flow of the around the heliosphere on cosmic rays and the consequent change in magnetic-field magnitude produces either bi-directional field-aligned or pancake anisotropies.
- Whether the anisotropy is field-aligned or pancake depends on whether the field increases or decreases.
- These anisotropies are consistent with recent preliminary observations of ~ 200 MeV galactic cosmic rays.
- Further analysis should provide valuable information concerning the transport of galactic cosmic rays.