Cosmic-Ray Transport in the Heliosphere.

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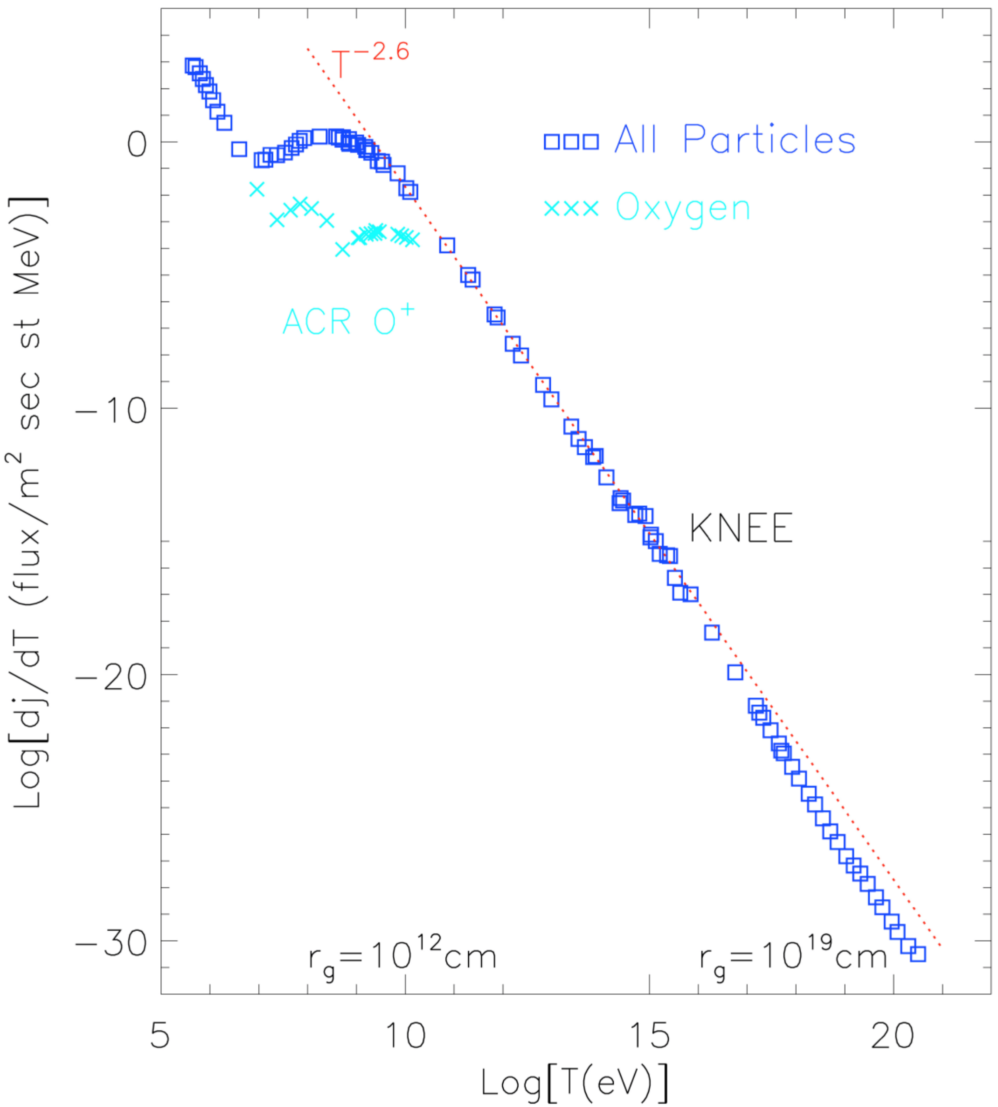
I acknowledge helpful discussions with J. Kóta and J. GIacalone.

Presented at Hess Symposium, Bad-Saarow, 2012

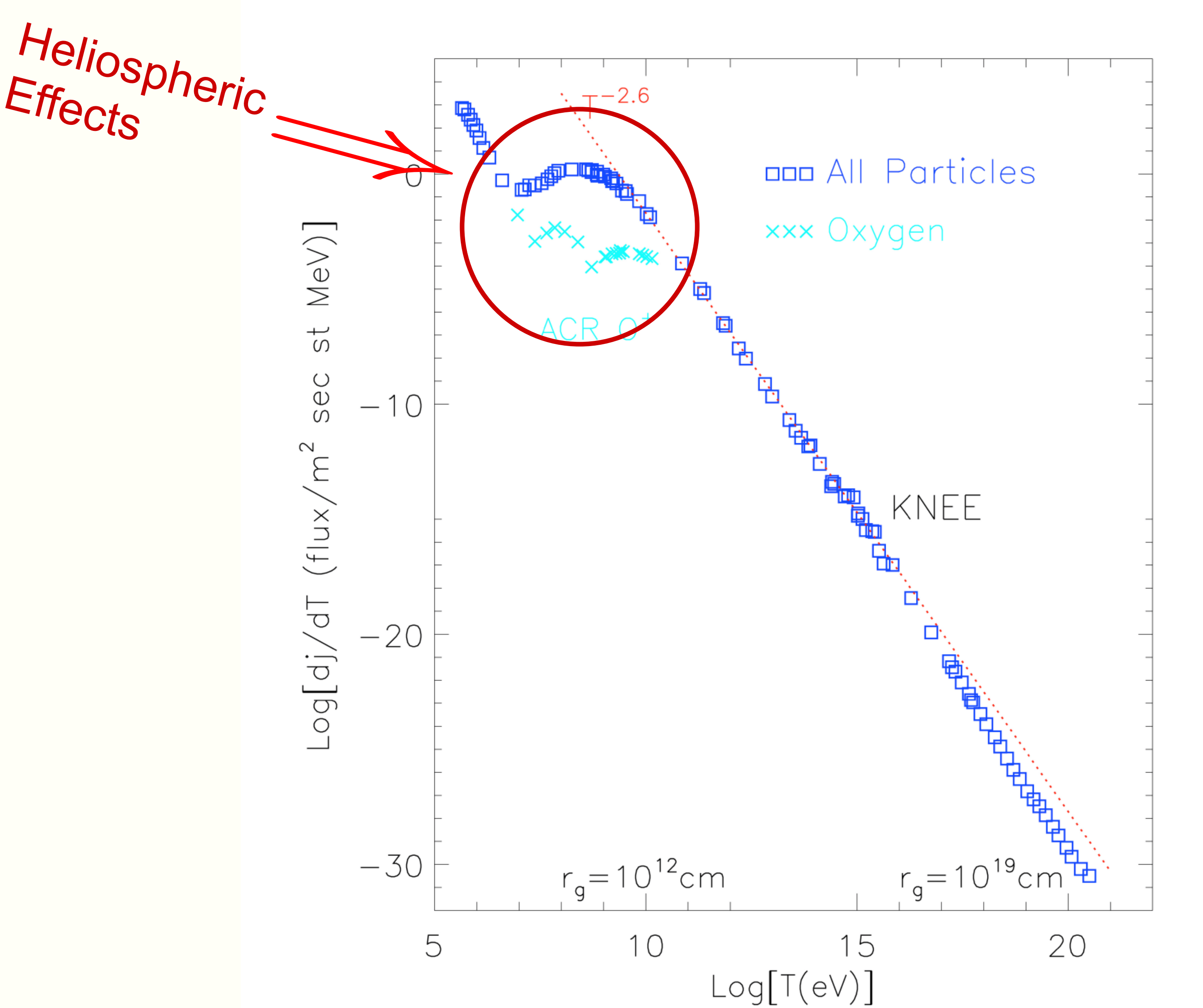
Outline of Talk

- **The Heliosphere and Energetic Charged Particles**
- **The discovery of the effects of the Sun and heliosphere on galactic cosmic rays.**
- **The transport of cosmic rays in the heliosphere.**
- **Anomalous Cosmic Rays.**
- **Some current issues – Voyager observations.**
- **Summary and conclusions.**

The Cosmic Ray Spectrum



Cosmic Rays



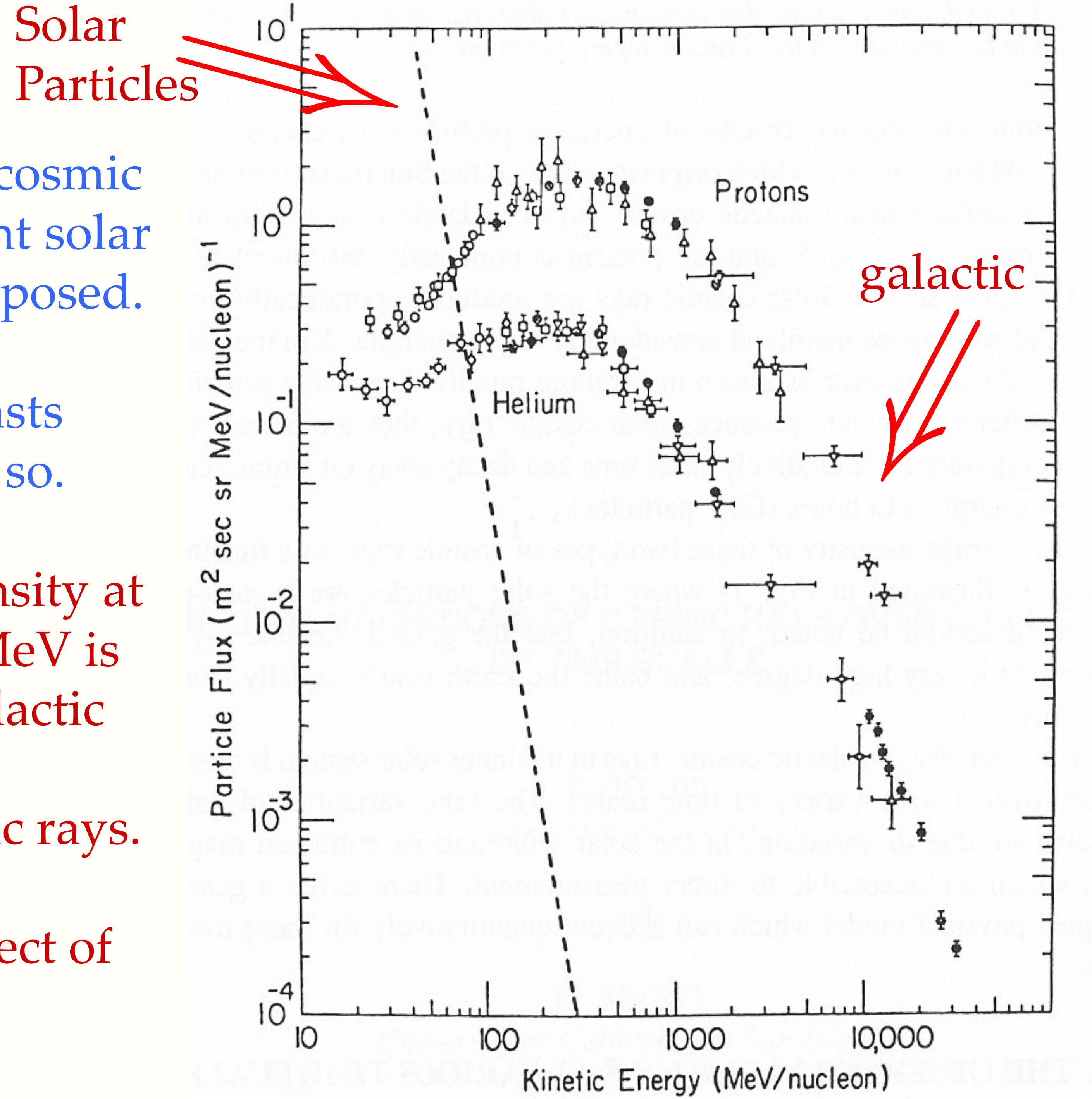
Heliospheric Effects
$T^{-2.6}$
All Particles
Oxygen
ACR O+
KNEE
$r_g=10^{12}$cm
$r_g=10^{19}$cm
Log[dj/dT (flux/m^2 sec st MeV)]
Log[T(eV)]
0
−10
−20
−30
5
10
15
20

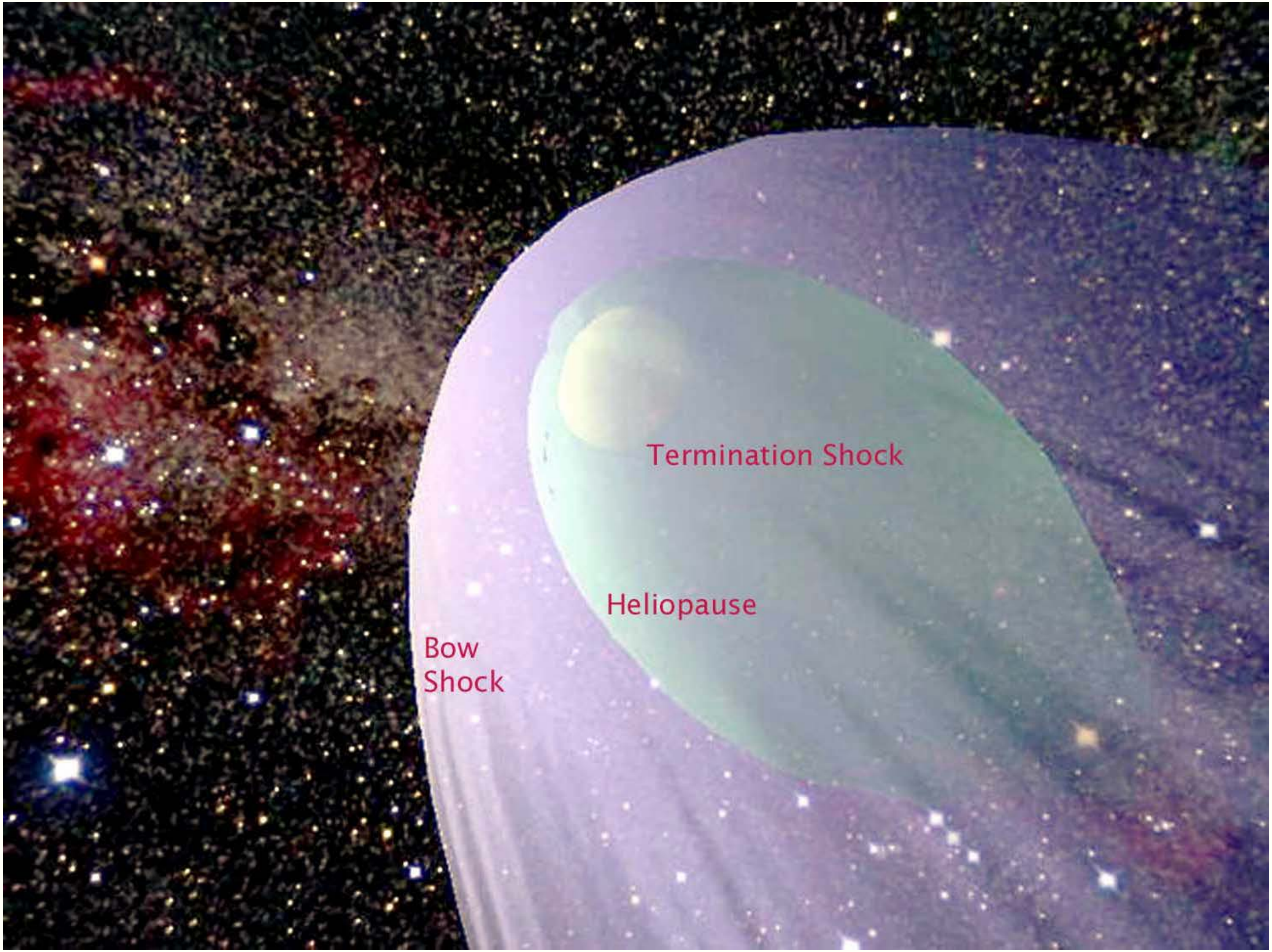
Average galactic cosmic rays with transient solar particles superimposed.

The solar event lasts hours to a day or so.

The average intensity at energies >≈ 100 MeV is dominated by galactic cosmic rays and anomalous cosmic rays.

They are the subject of this talk.




Termination Shock
Heliopause
Bow
Shock

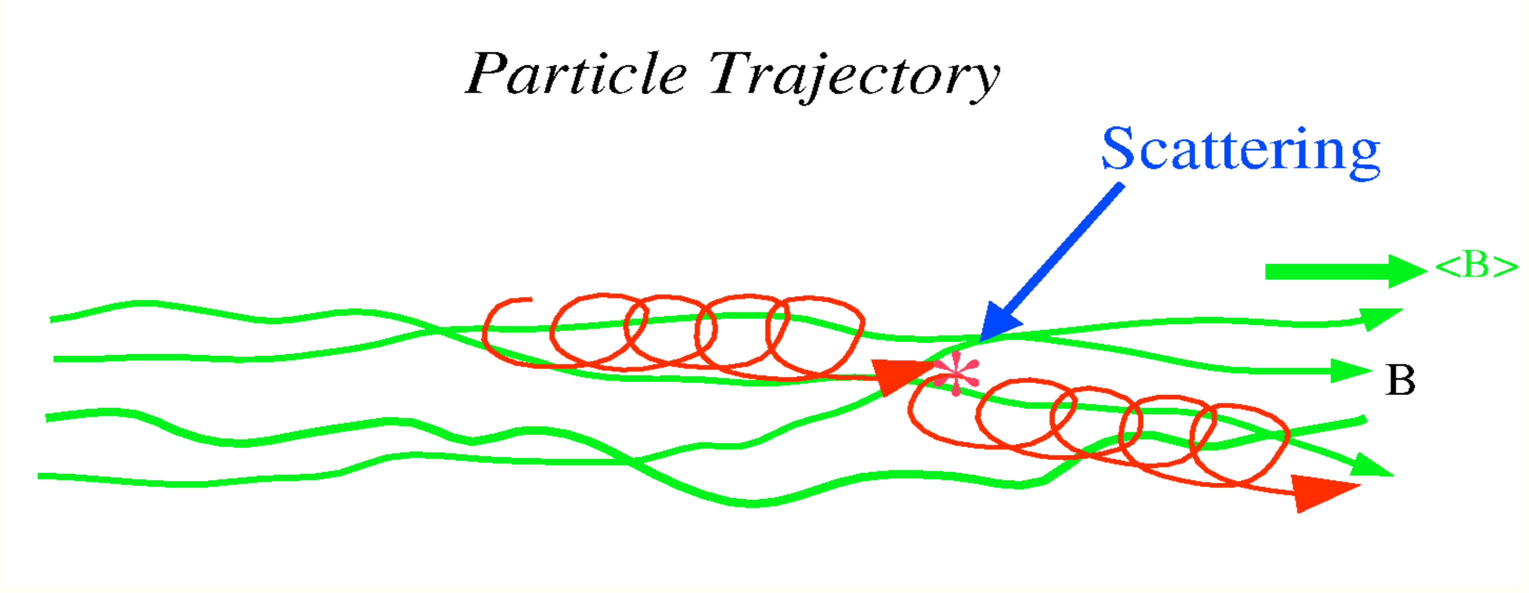
An instructive analog representation of the heliosphere.

There are a Variety of Cosmic-Ray Time Variations

- Irregular fluctuations on a continuum of time scales – from fractions of seconds to many years.
- Quasi-periodic 27-day, 11-year and 22-year variations.
- Longer-term variations, some apparently cyclic.
- There are also related *spatial* variations.
- Most variations are caused by the heliosphere and, eventually, the Sun.
- To understand these, we must understand cosmic-ray transport.

The magnetic field is fluctuating and turbulent.

Following Fermi's ideas for acceleration, the transport of cosmic rays in this turbulent magnetic field is described statistically. The particles are 'scattered' by magnetic fluctuations at ~ r_g. This leads to a diffusion, or random-walk equation.



The Transport Equation (first written down by Parker in 1965 – Krymsky, in 1964, presented a less-complete version):

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j}\right] \quad \Rightarrow \text{ Diffusion}$$

$$-\mathbf{U} \cdot \nabla f \quad \Rightarrow \text{ Convection w. plasma}$$

$$-\mathbf{V_d} \cdot \nabla f \quad \Rightarrow \text{ Grad \& Curvature Drift}$$

$$+\frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ell n p}\right] \quad \Rightarrow \text{ Energy change}$$

$$+Q \quad \Rightarrow \text{ Source}$$

Where the *diffusion coefficient* and *drift velocity* due to the large scale curvature and gradient of the average magnetic field are:

$$\kappa_{ij}^{(S)} = \kappa_\perp \delta_{ij} + (\kappa_\| - \kappa_\perp)\frac{B_i B_j}{B^2} \qquad \mathbf{V_d} = \frac{pcw}{3q}\nabla \times \left[\frac{\mathbf{B}}{B^2}\right]$$

This equation is *amazingly general*, and is still the one used. It only requires scattering to near-isotropy to be valid

First: Can the Interstellar Medium Cause Cosmic-Ray Variations?

- These could be of two types: the Earth could pass through cosmic-ray *spatial* variations in its motion through the interstellar medium, or *dynamical* variations in the interstellar medium could cross the solar system.

- For spatial variations to exist long enough for the motion of the solar system to bring the Earth through them, the transport of galactic cosmic rays would have to be much *less rapid* than is currently thought to be possible.

- Diffusive transport: Consider a fluctuation in the cosmic-rays of scale L, which has a diffusive lifetime $\tau \approx L^2/\kappa$, where κ is the cosmic-ray diffusion coefficient. If the solar system is moving at a speed V_E, it will take a time L/V_E to cross this fluctuation. Therefore, we require $L^2 / \kappa >> L / V_E$.

- Setting $V_E \approx 20$ km/sec and $\kappa = (1/3)\,\lambda\, c$, where λ, the diffusion mean free path >> cosmic-ray gyro-radii, we find that $L >> 3 \times 10^{17}$ cm, which would be crossed by Earth in $>> 10^4$ yrs.

- $\Rightarrow$ **Shorter than 10^4 year variations must be heliospheric (solar) in origin.**

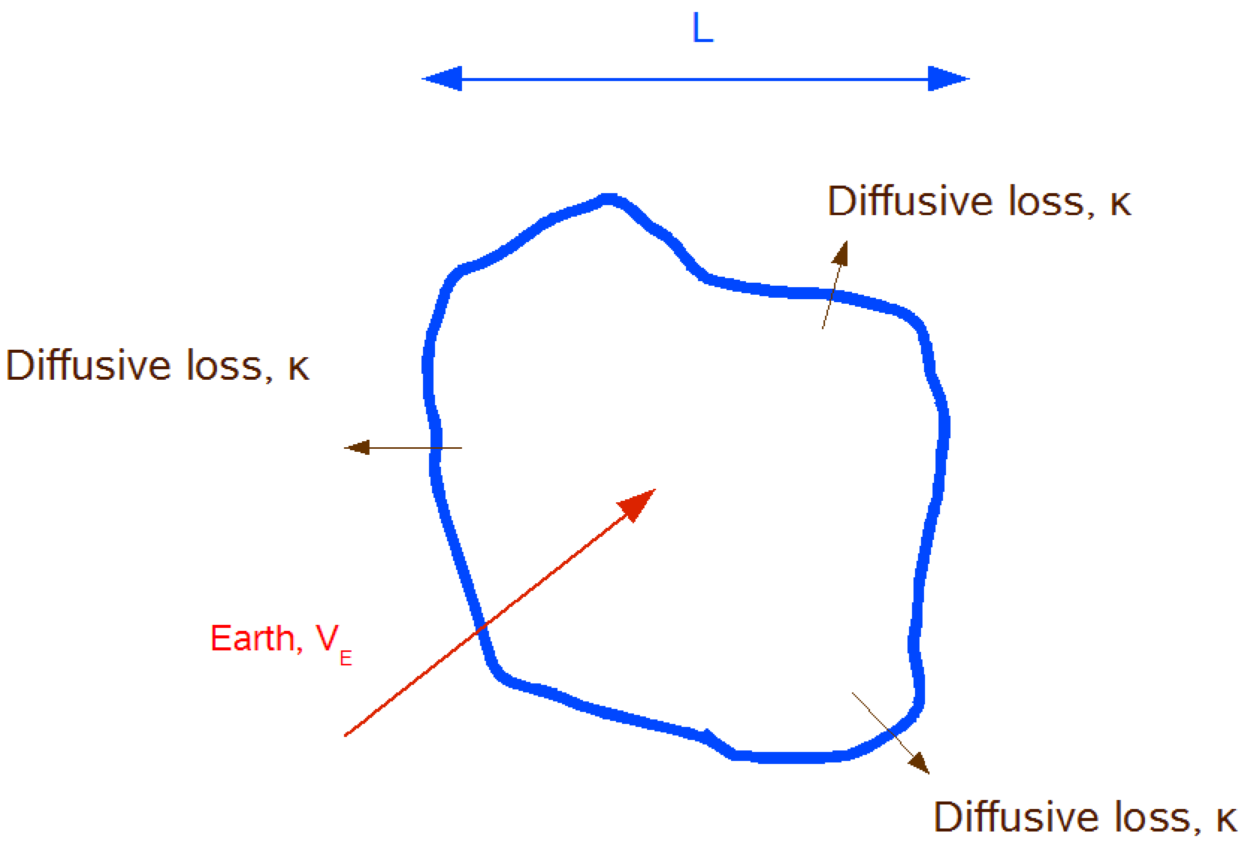
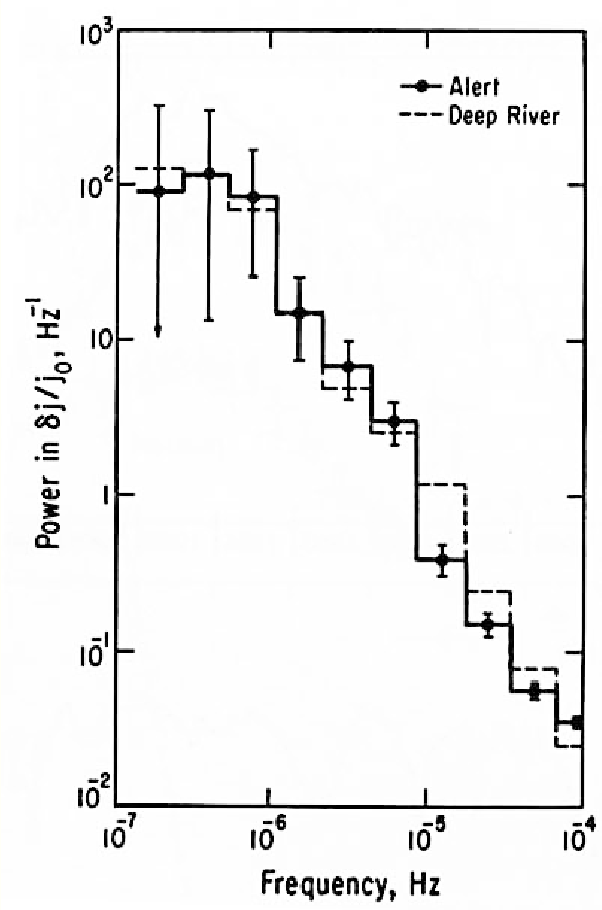
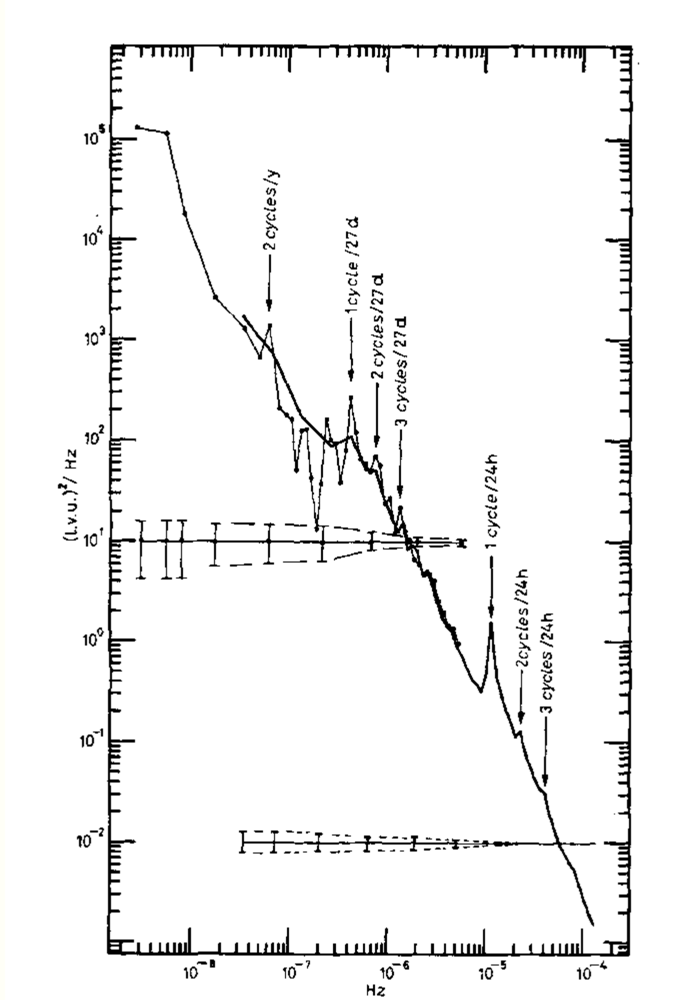


Illustration of the Earth passing through a quasi-static region of spatial scale L. The diffusive loss time is $\approx L^2/\kappa$. The Earth passes through the region in $\approx L/V_E$.

Cosmic-Ray variations are seen at all time scales.

They can be observed using a variety of techniques and over a variety of time scales. In this lecture, the relation to the basic physics of cosmic-ray transport will be discussed.





The Sun Produces ‘Cosmic Rays’ (now called SEPs)

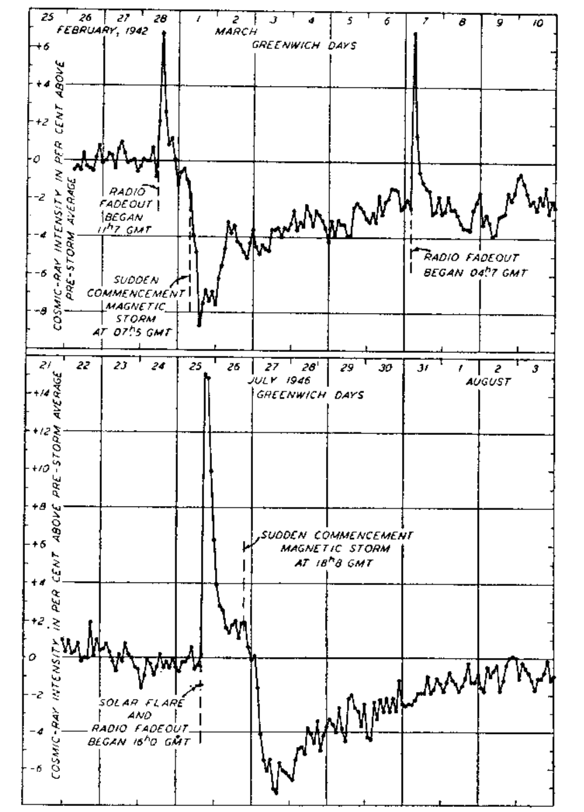


FIG. 1. Three unusual increases in cosmic-ray intensity at Cheltenham, Maryland, during solar flares and radio fadeouts.

SOLAR COSMIC RAYS OF FEBRUARY, 1956 771

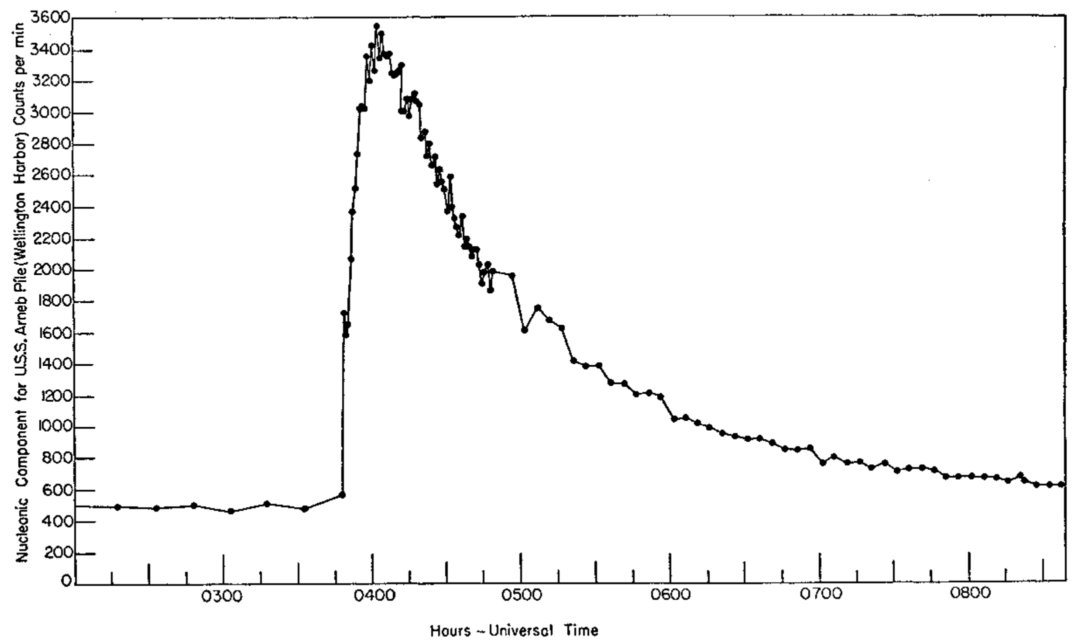
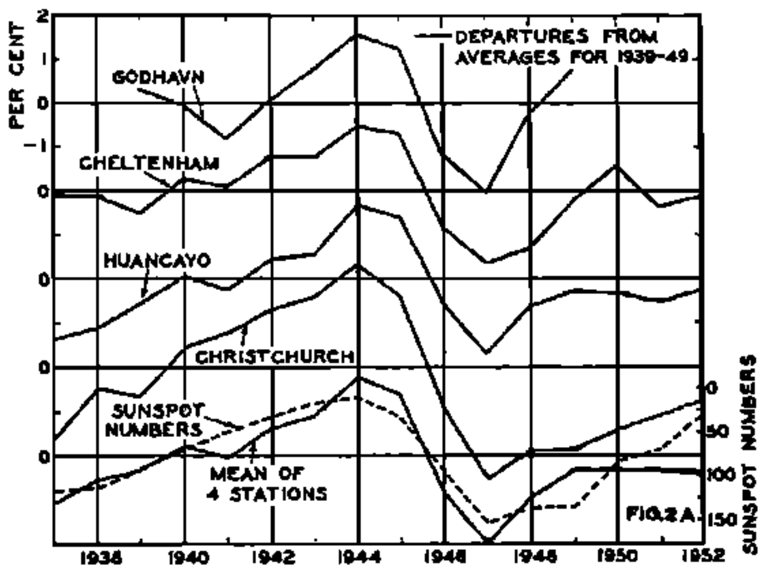


FIG. 3. Nucleonic component intensity as a function of time for neutron monitor *A*-2 located on board the U.S.S. *Arneb* anchored in Wellington Harbor, New Zealand at the time of the flare. One-minute intervals are shown between 0348 and 0445 U.T. The change in rate of rise of intensity appears to be real.

I will not discuss these solar particules further here.

At higher energies, an 11-year variation, correlated with sunspots, was observed.

From Forbush, JGR 59, 525
1954



ANNUAL MEANS COSMIC-RAY INTENSITY AT FOUR STATIONS

From Forbush, JGR 63, 657,
1958

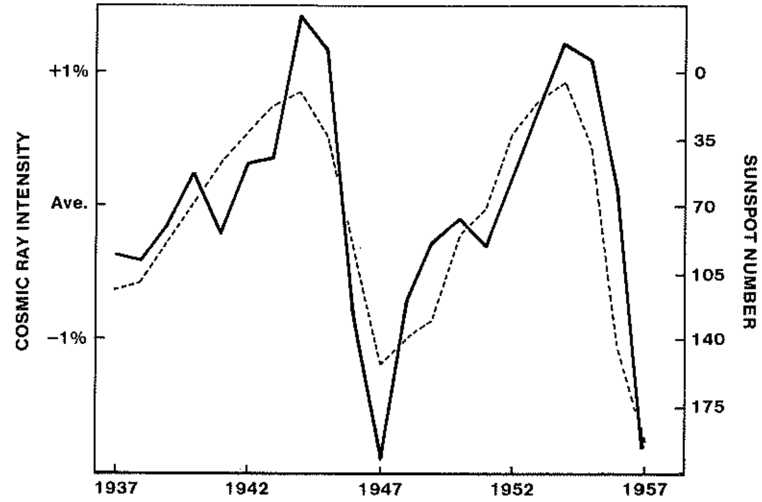
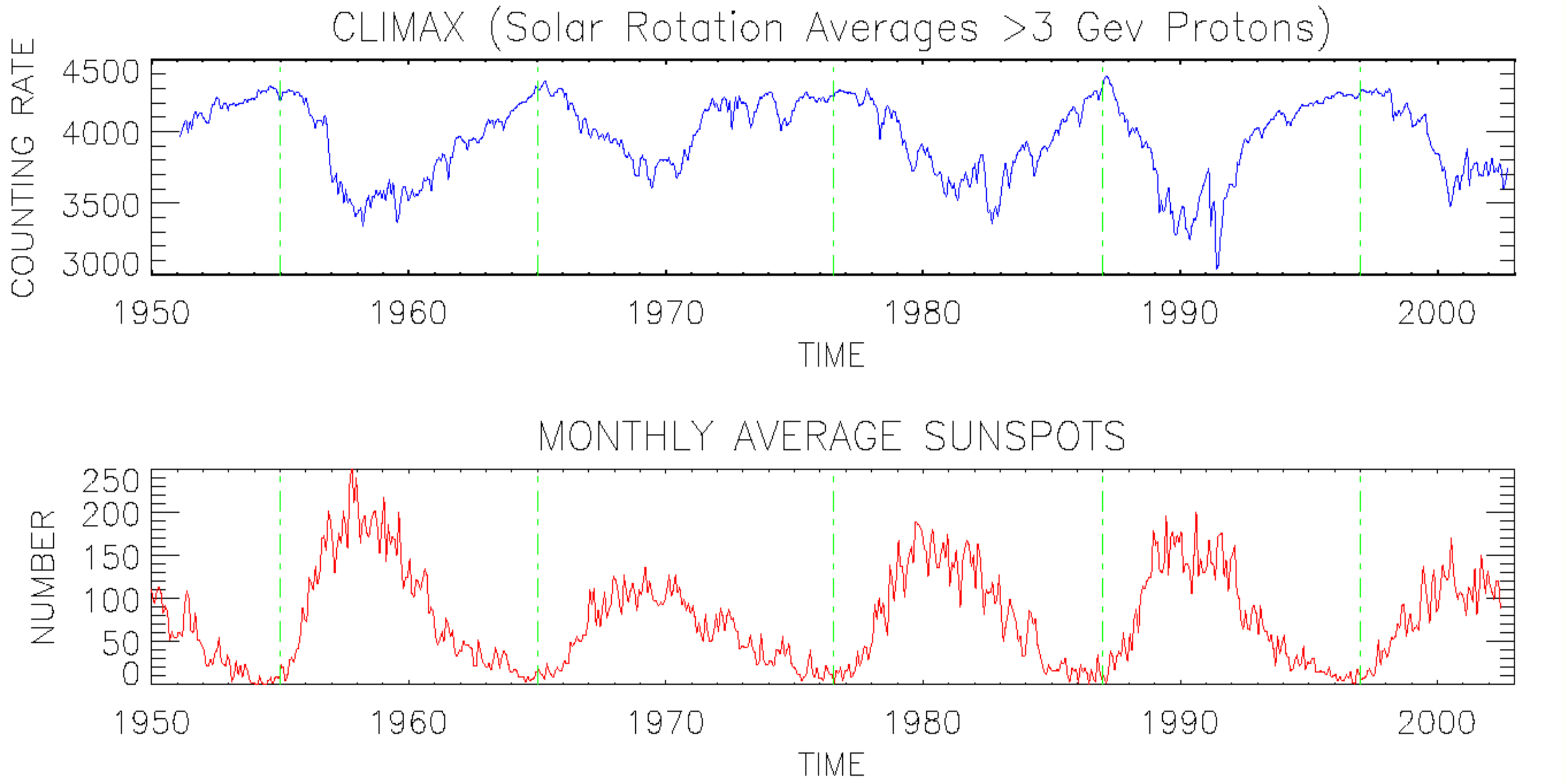
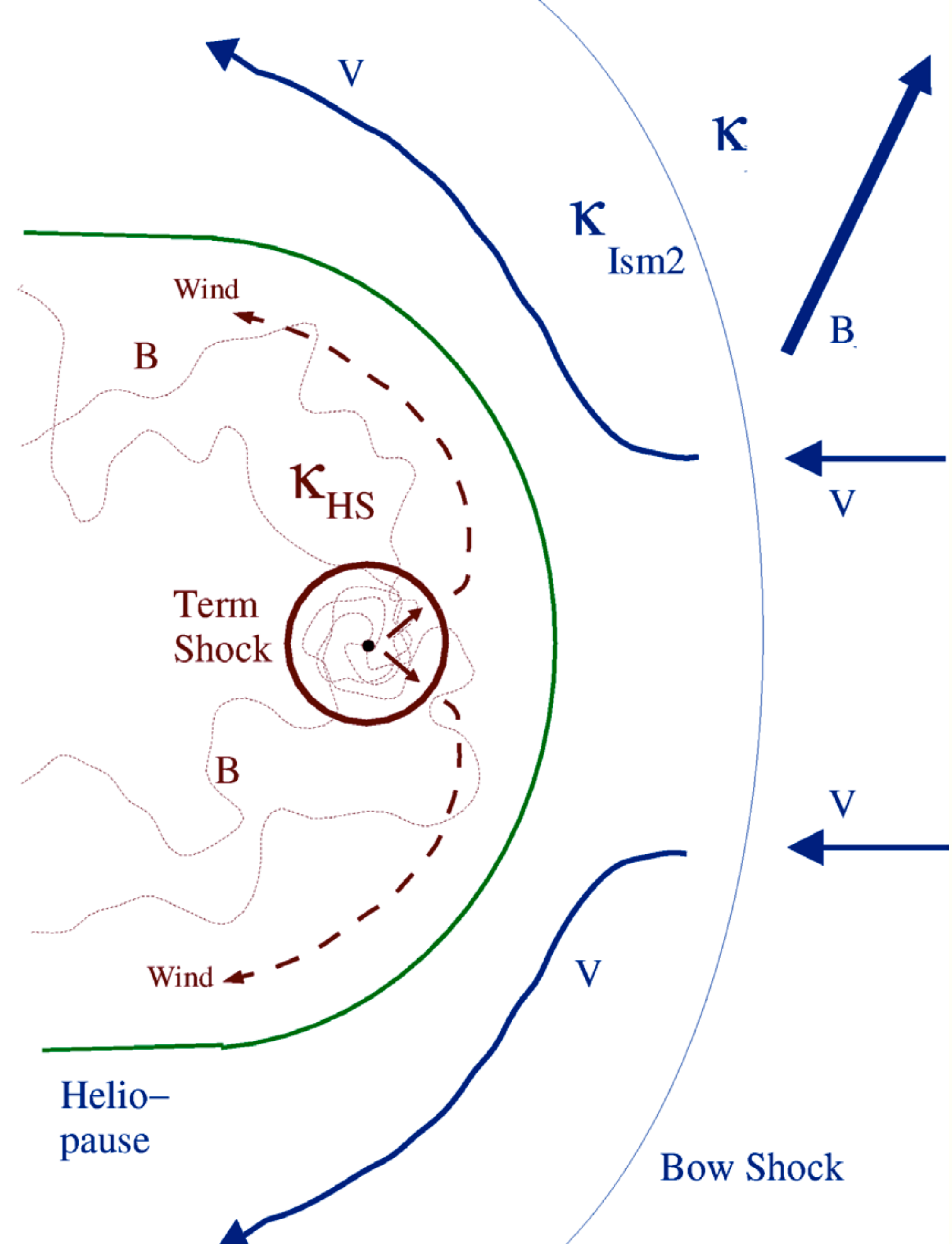


Figure 4.2 *Correlation between cosmic ray intensity (solid line, scale at left) and sunspot number (dashed line, scale at right) through two solar cycles. Increased solar activity produces a decrease in the cosmic ray intensity at Earth. (Adapted from Scott Forbush,* Journal of Geophysical Research *63 [1958]: 657, © American Geophysical Union.)*

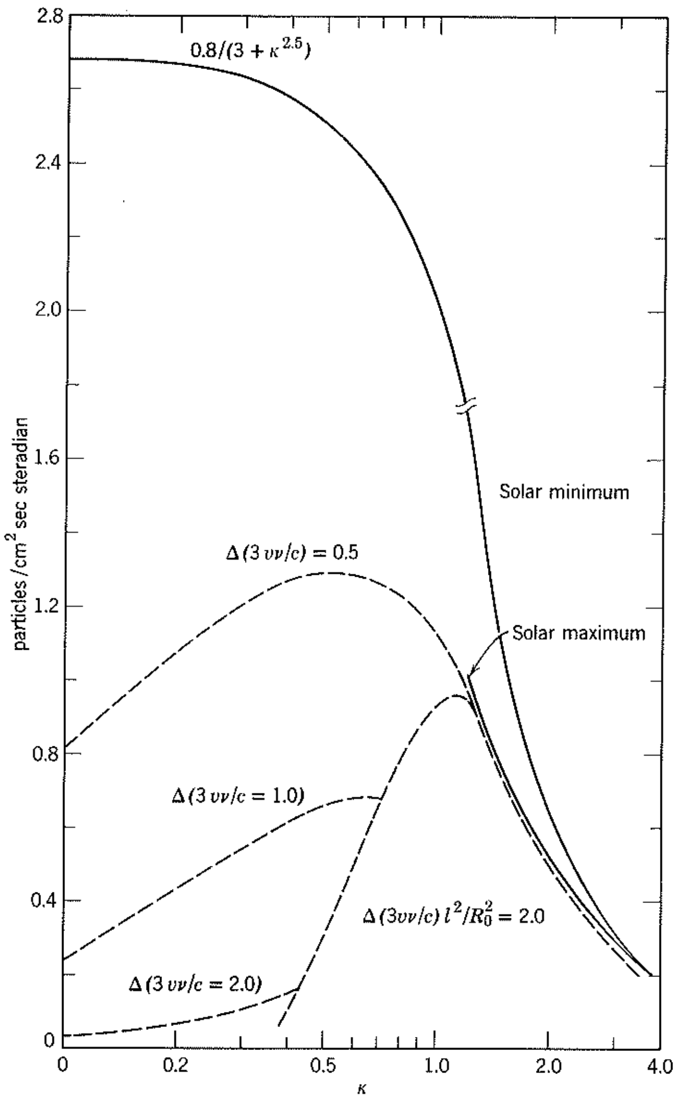
Originally, a magnetospheric origin of thes was proposed, but observations in the solar wind showed that they were caused by the Sun and solar wind -- what we now call the heliosphere.

The variation of > 3 Gev protons at Earth and sunspots since 1950 seen by the Climax neutron monitor.




V
κ
κ
Ism2
B
Wind
B
κ
HS
Term
Shock
V
V
B
Wind
V
Helio–
pause
Bow Shock

Early crude illustration of effect of solar wind on galactic cosmic rays, from Parker (1963). We must do more detail.

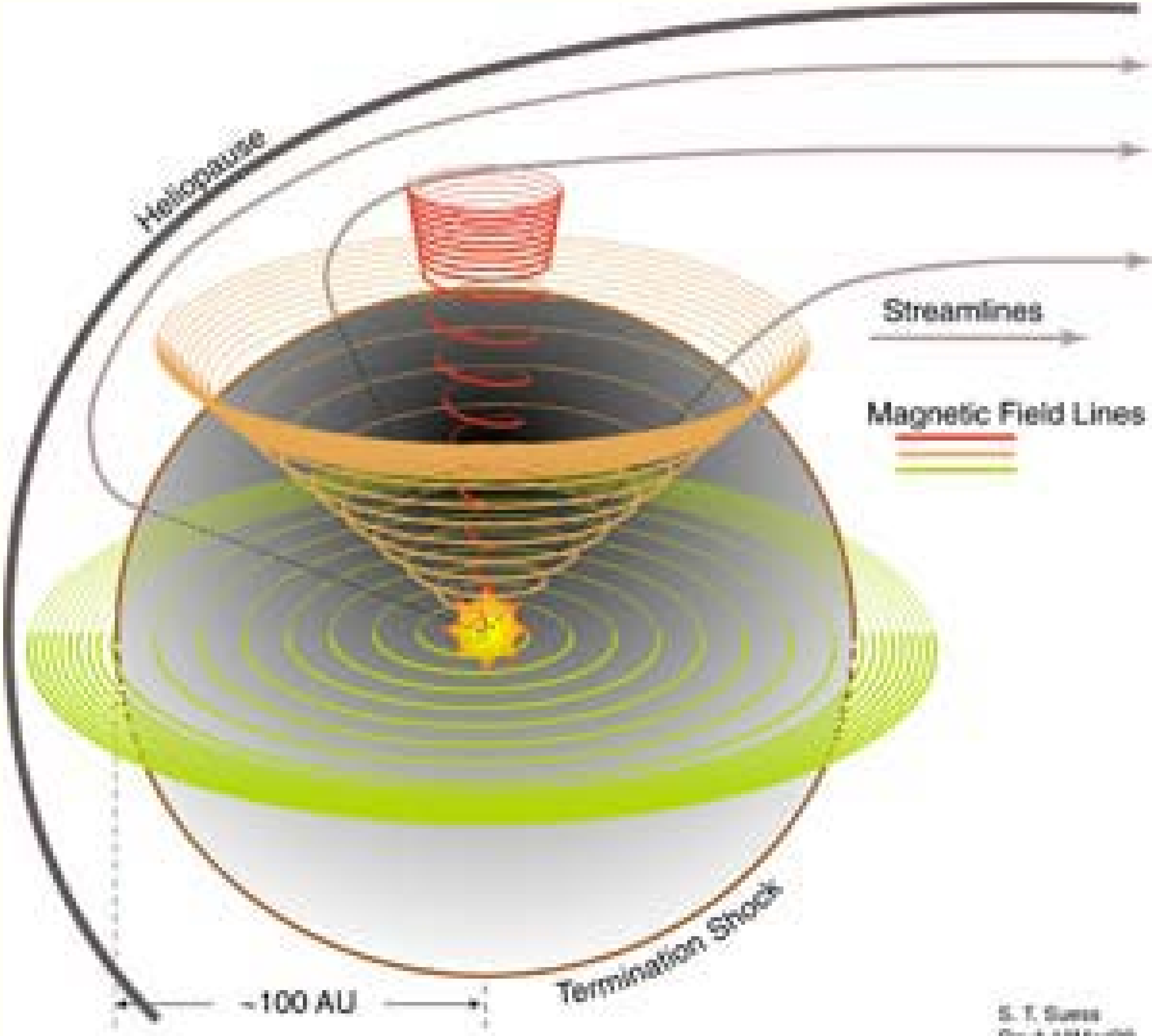


Spiral Magnetic Field of Parker

- The solar wind drags out the solar magnetic field. Because of the large radial acceleration (expansion) near the Sun, the field is very nearly radial near the Sun. Solar rotation leads to a spiral shape. We can write:

$$\mathbf{B}(r,\theta) = A\left(\frac{r_0}{r}\right)^2\left[\mathbf{e}_r - \frac{r\Omega_\odot sin(\theta)}{V_w}\mathbf{e}_\phi\right]$$

Here, A is generally nearly constant in magnitude around the Sun, but changes from positive to negative at a current sheet, called the heliospheric current sheet.

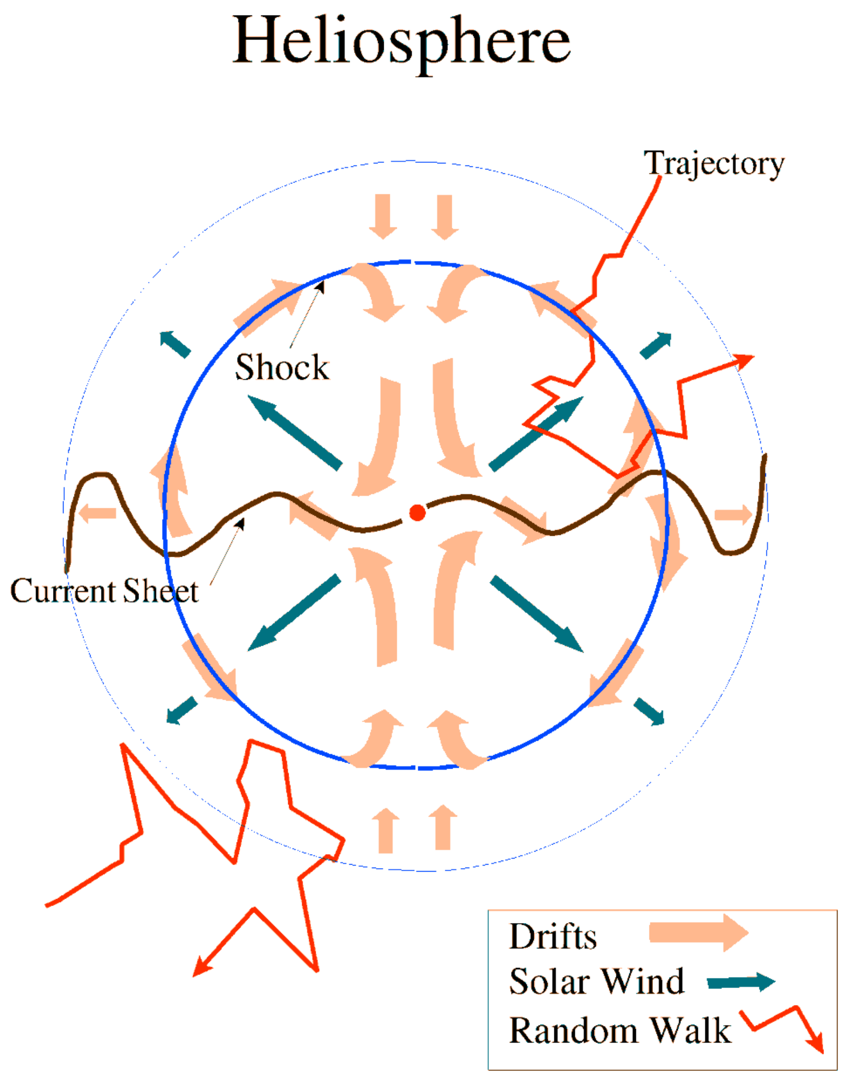


Heliopause
Streamlines
Magnetic Field Lines
Termination Shock
~100 AU
S. T. Suess
Rev1.18Mar'99

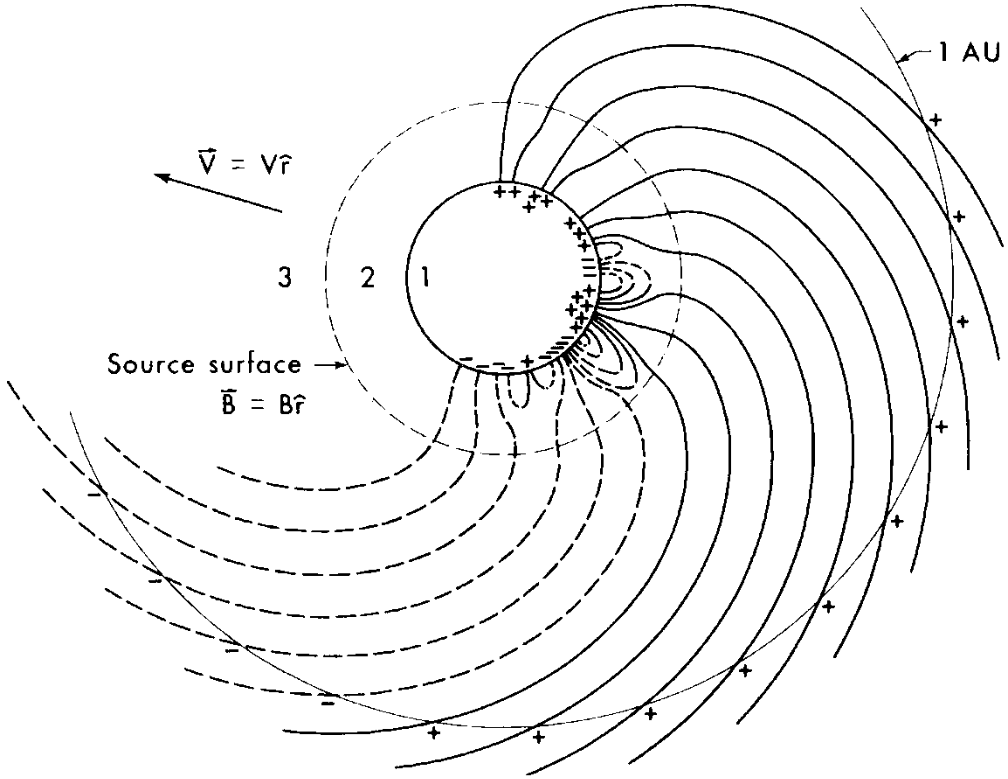
The galactic cosmic rays enter the heliosphere through a combination diffusion (random walk) and drift.

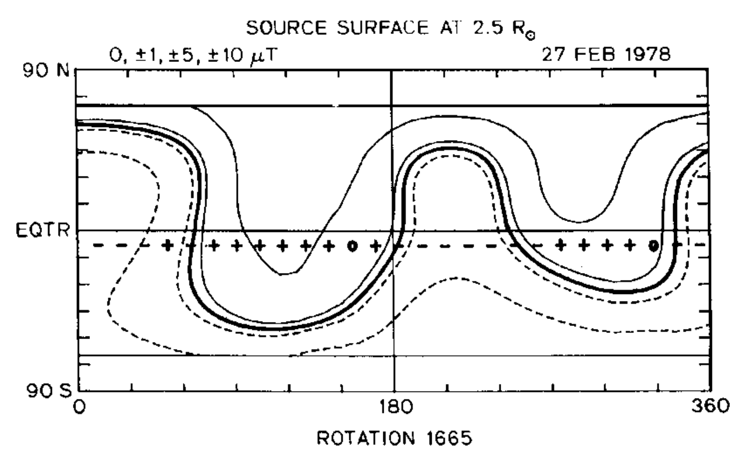
These motions are counteracted by outward convection and the associated cooling by the expansion of the wind.

The drift motions are very significant. They change sign every solar maximum– 22-year cycle.

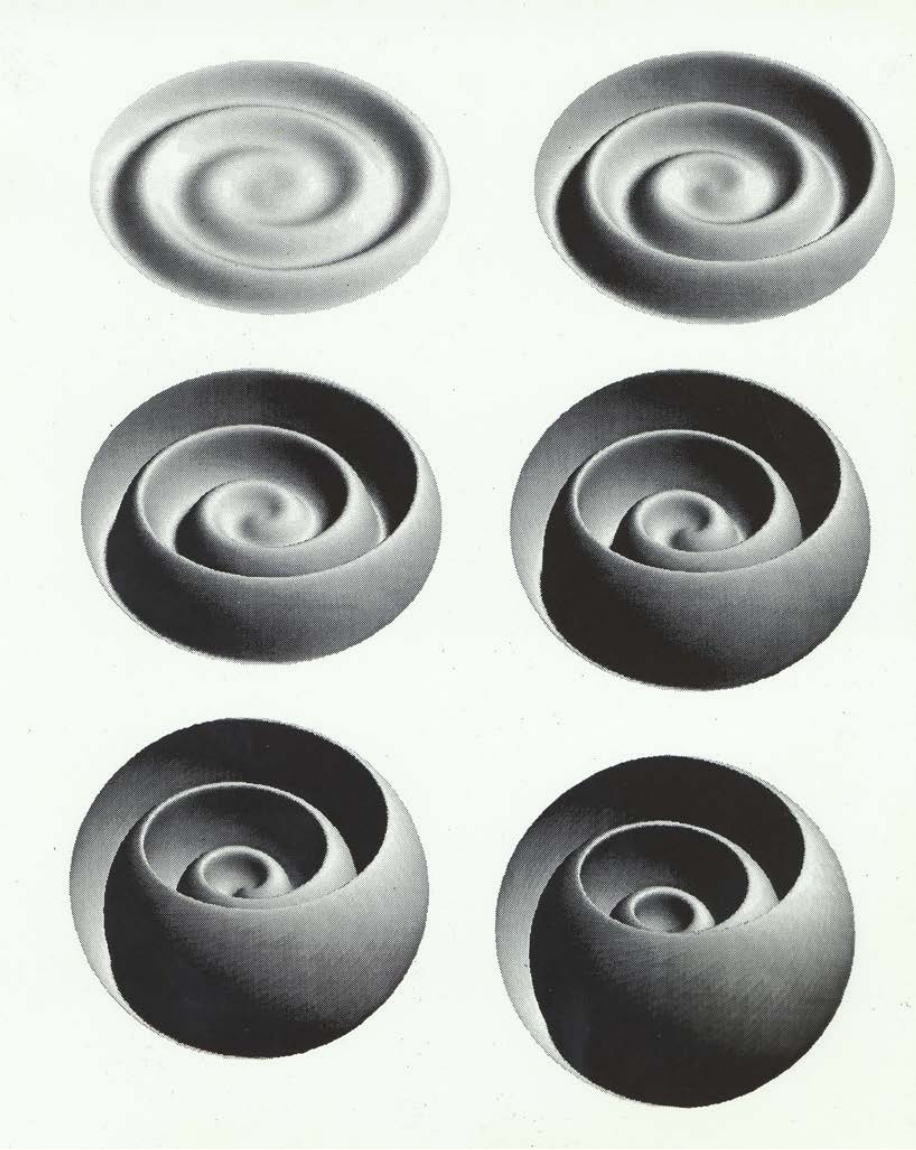


Magnetic sector structure.

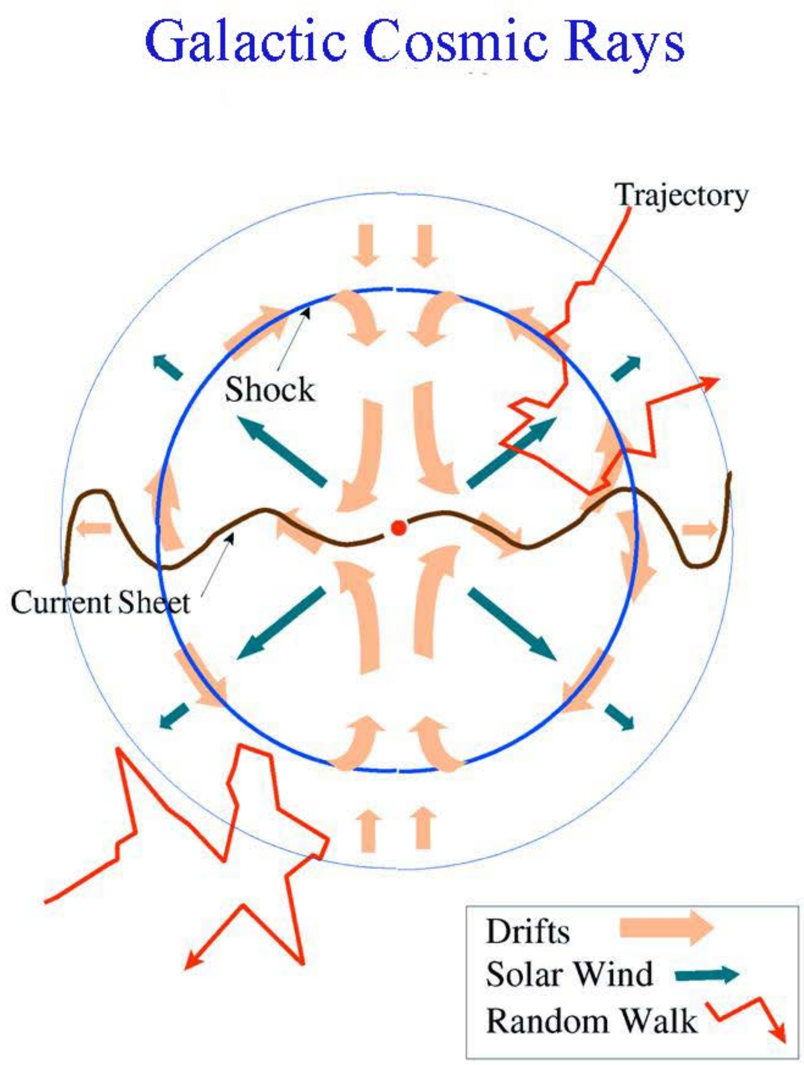


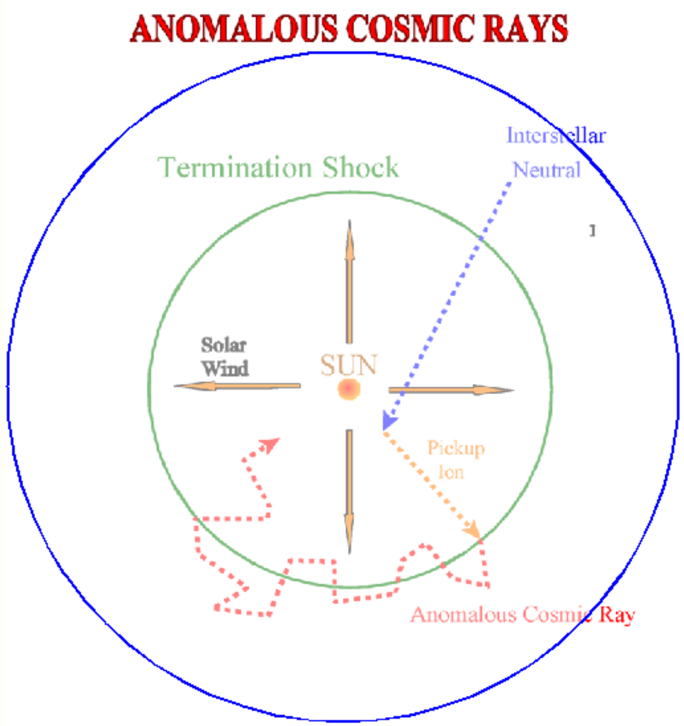


The current sheet changes from sunspot minimum to sunspot maximum

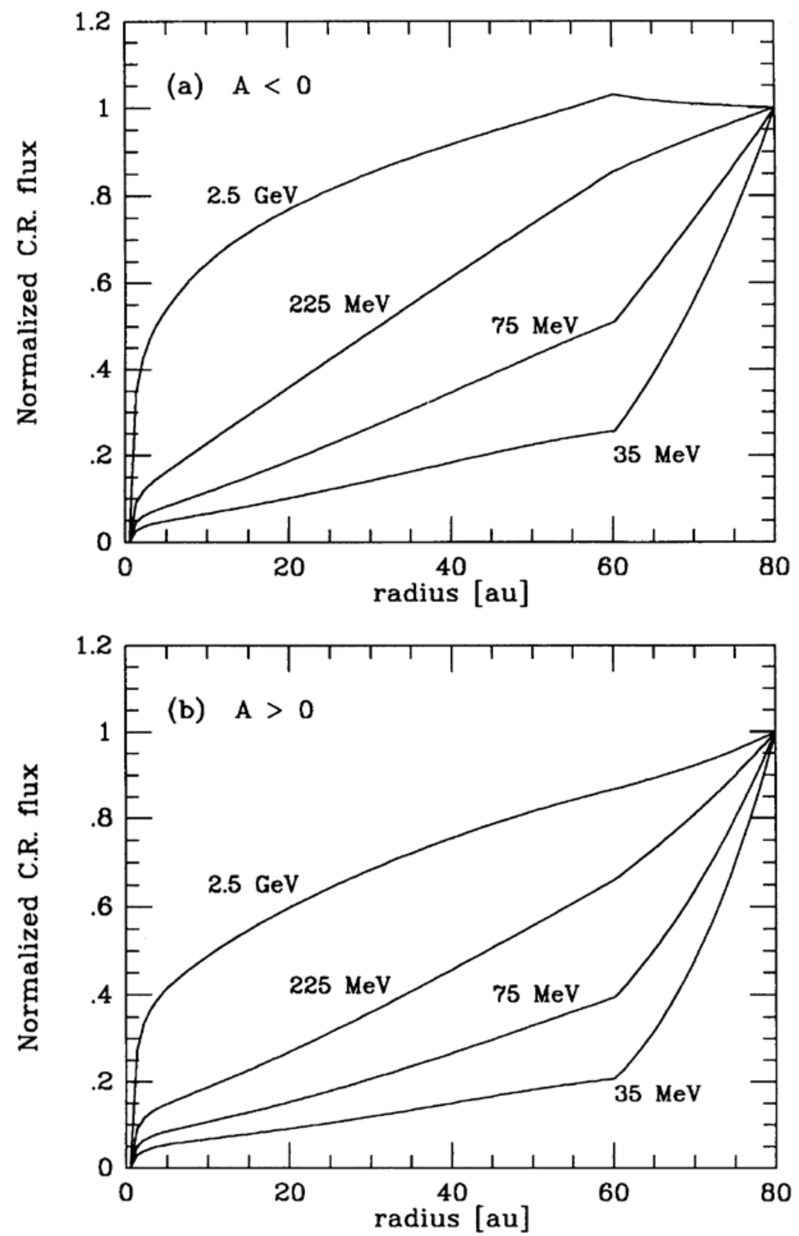


The standard paradigm for galactic and anomalous cosmic rays in the outer heliosphere





Early results from model calculations



Results from quasi-steady termination shock transport models of ACR and GCR.

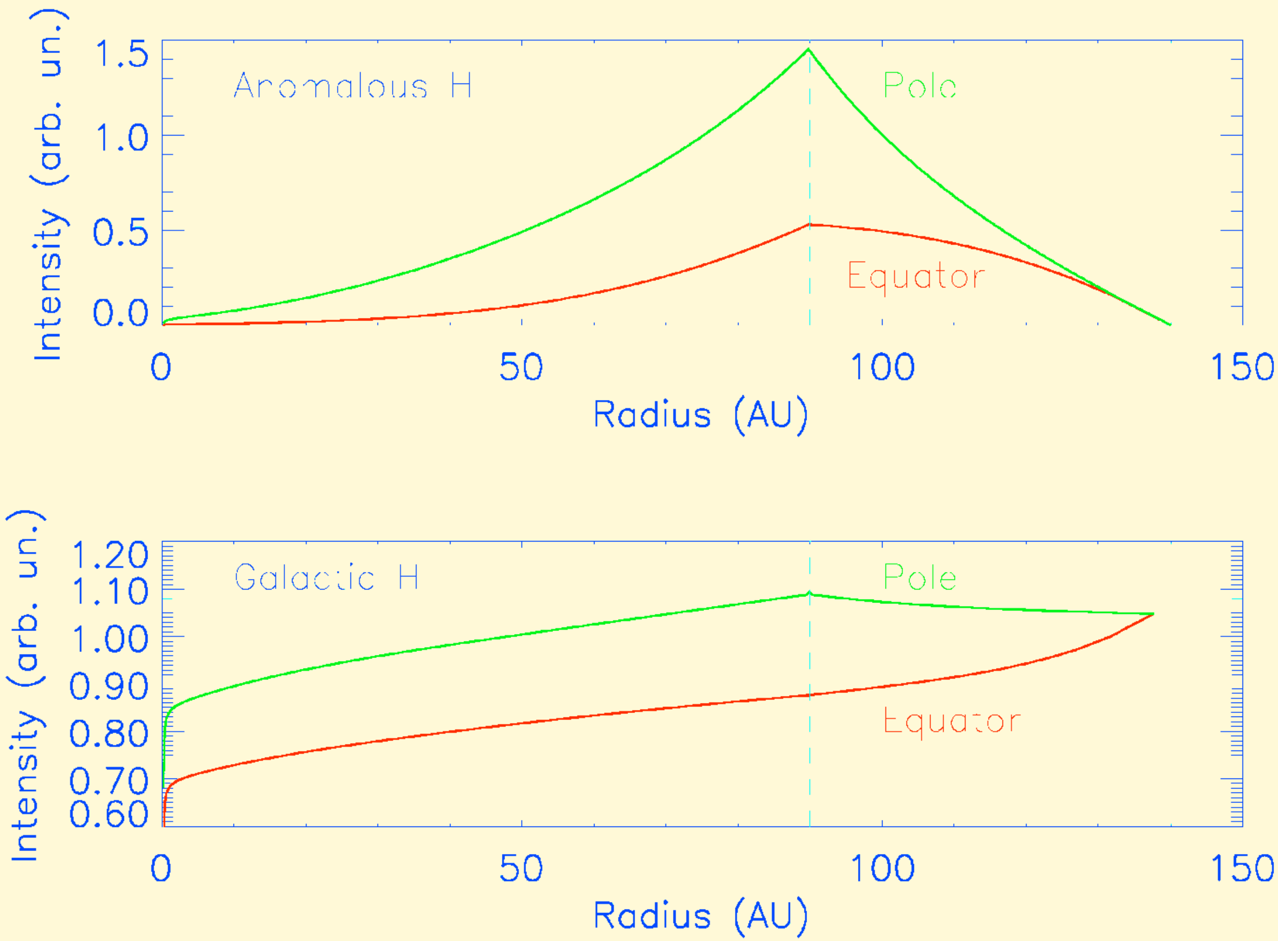
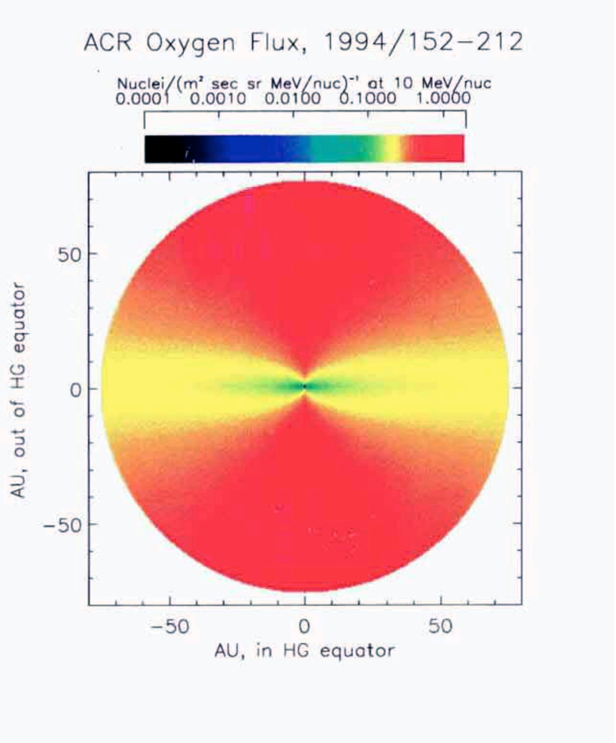
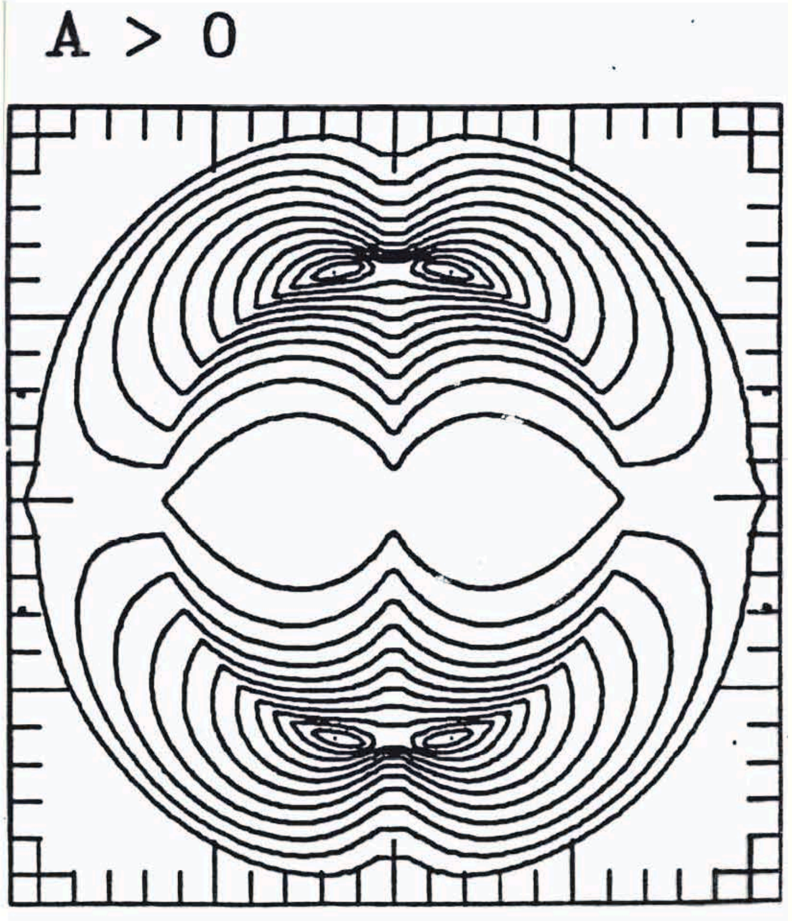


Illustration of the latitudinal gradients for 1994 (A<0)

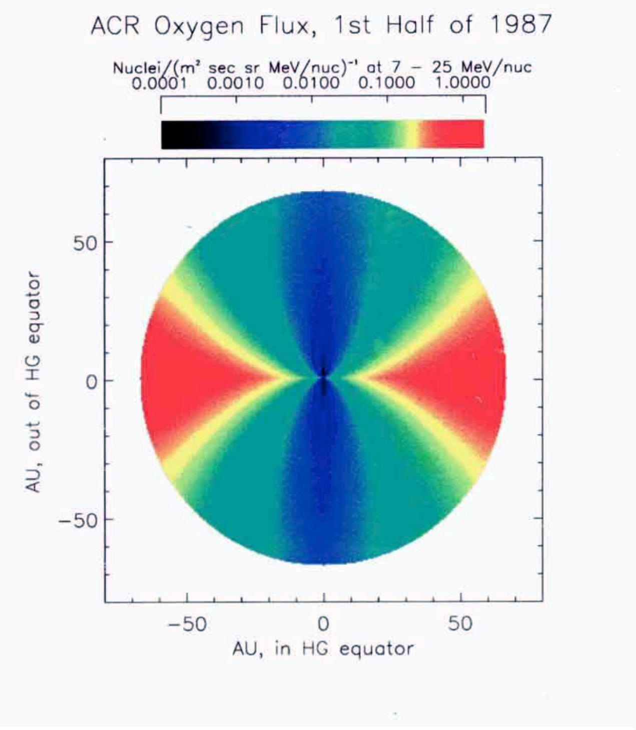
Multi-spacecraft observations



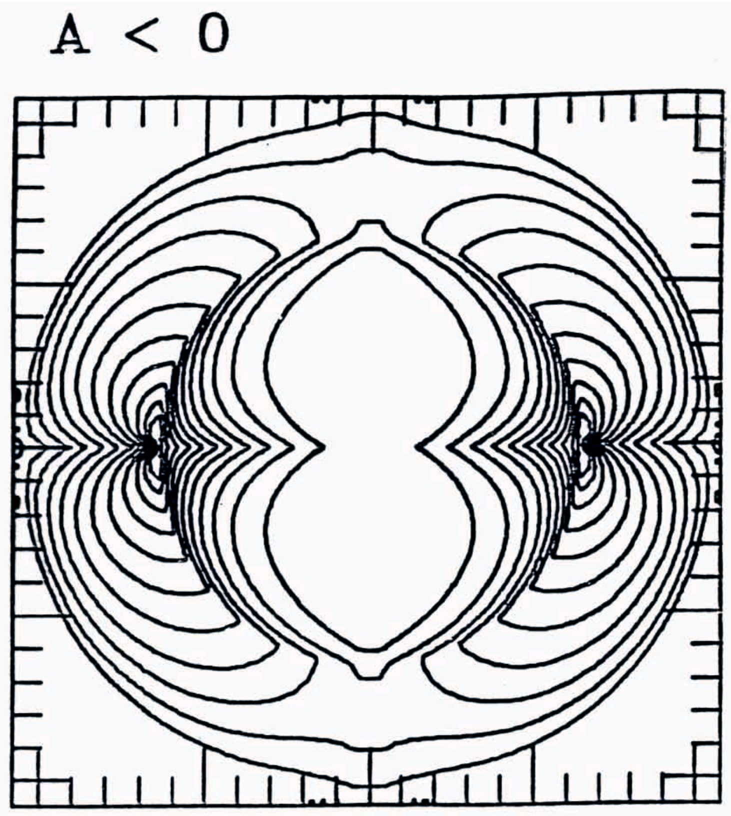
Model Calculation



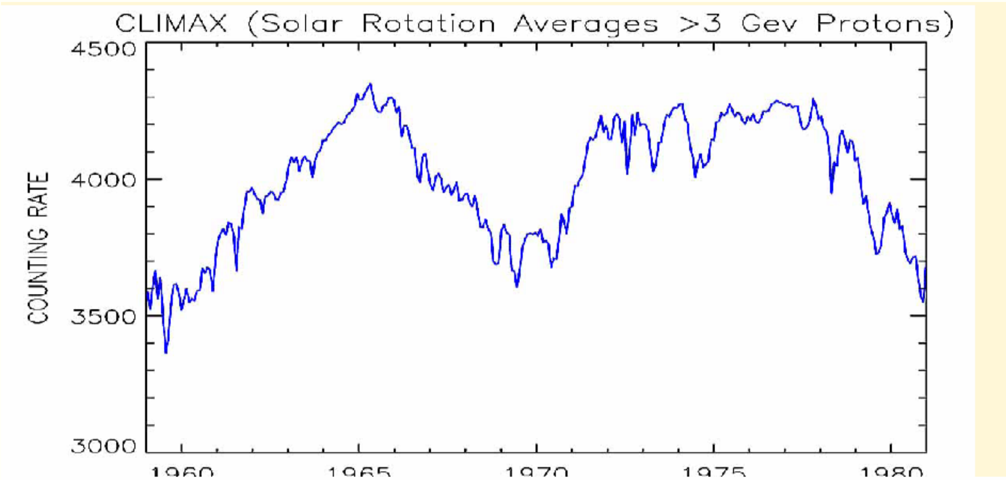
The latitudinal distribution for A>0

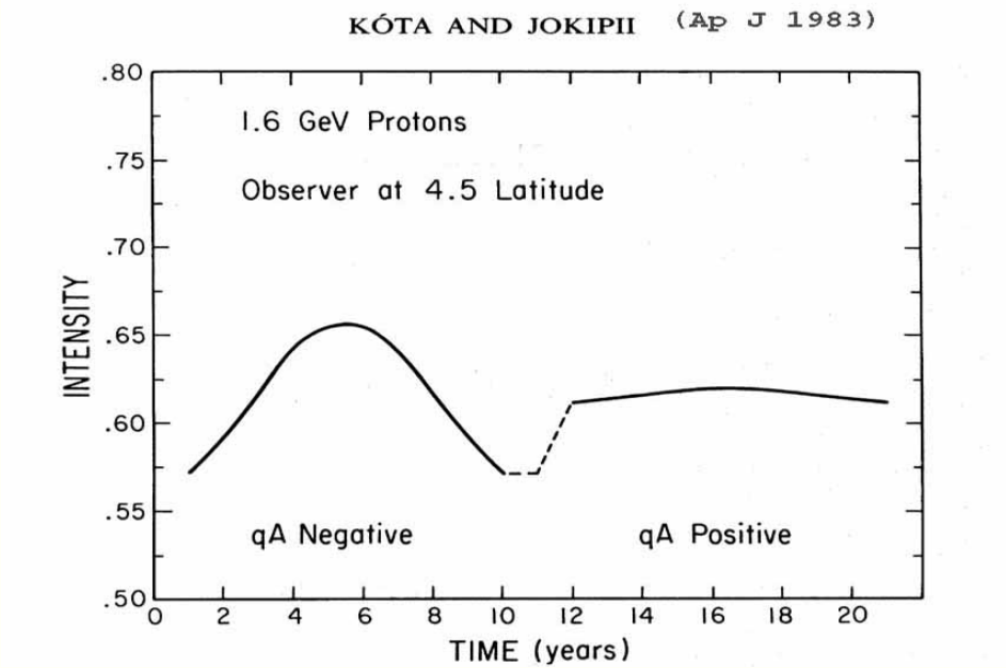


Model Calculation



The models predict a 22-year cycle in cosmic rays, as is observed.

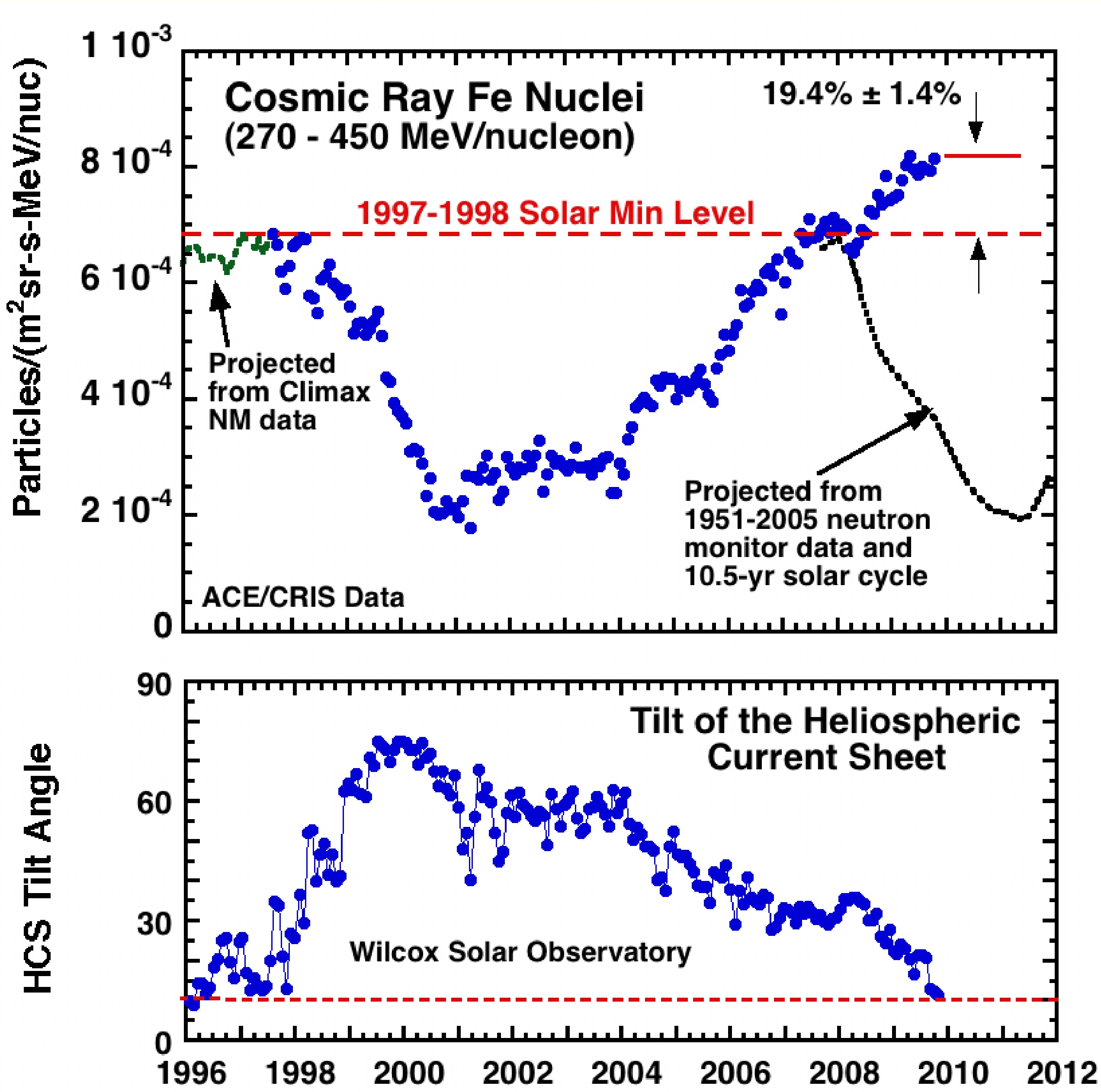




The Recent Sunspot Minimum

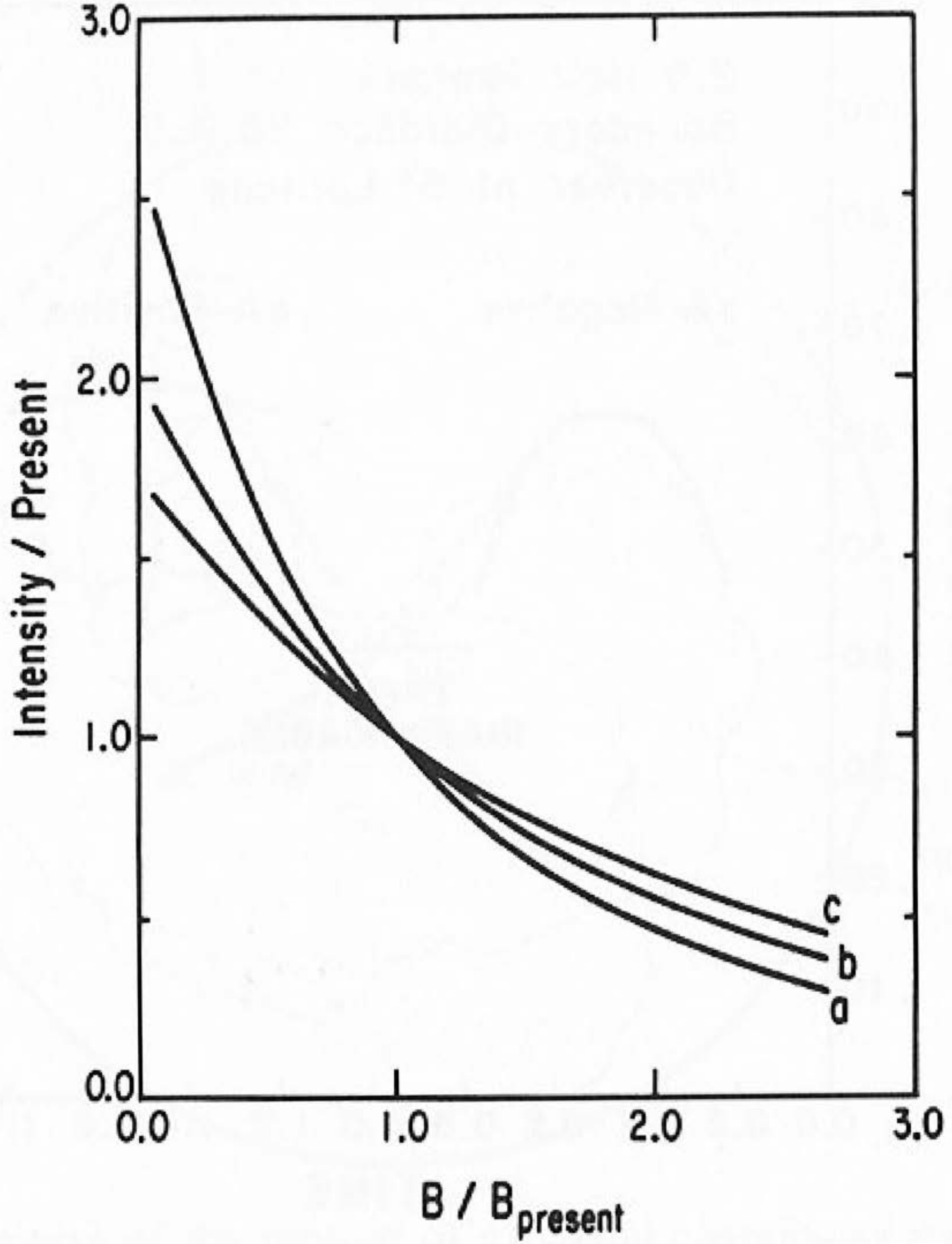
- The current minimum is anomalous, with many parameters at historic levels.
- This has affected both ACR and GCR.
- This provides an opportunity to increase our understanding of the variations of galactic cosmic rays.

The observations of GCR until quite recently.



The interplanetary magnetic-field magnitude also decreased to historically low values. It is known that this generally implies larger diffusion coefficients.

The effect of changing the magnetic field magnitude in a simulation of cosmic-ray modulation.



The low magnetic field strength would be expected to change the cosmic ray intensity, and it clearly has.

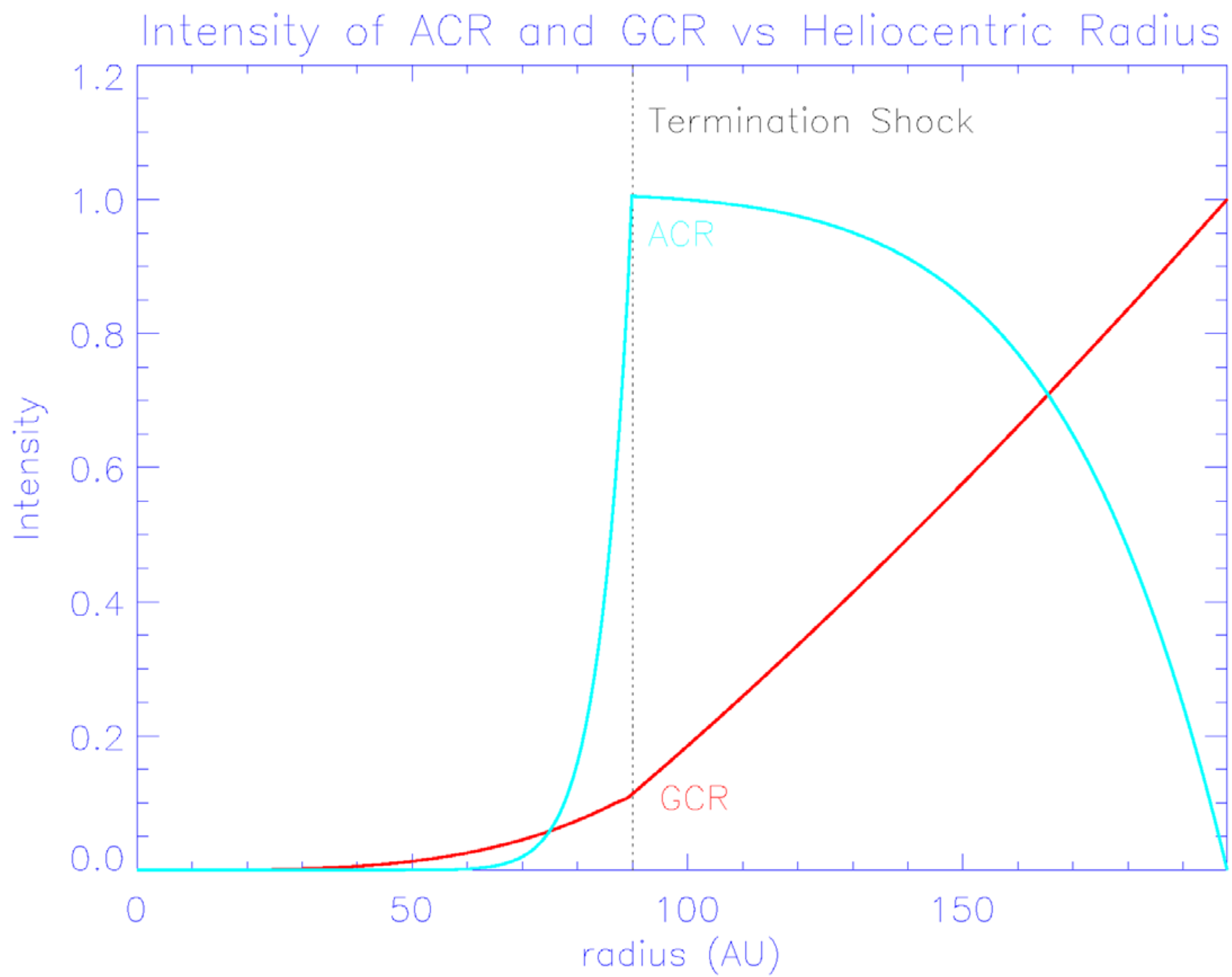
One possibility is that, since both the rate of diffusion and the drift velocity vary inversely with B, we would expect the low magnetic field to result in a higher cosmic-ray intensity.

The solar wind velocity also became very low, which would also be expected to increase the intensity.

Hence we can readily understand the high GCR intensities. But what causes the difference between ACR and GCR?

The Physics of Shock Acceleration

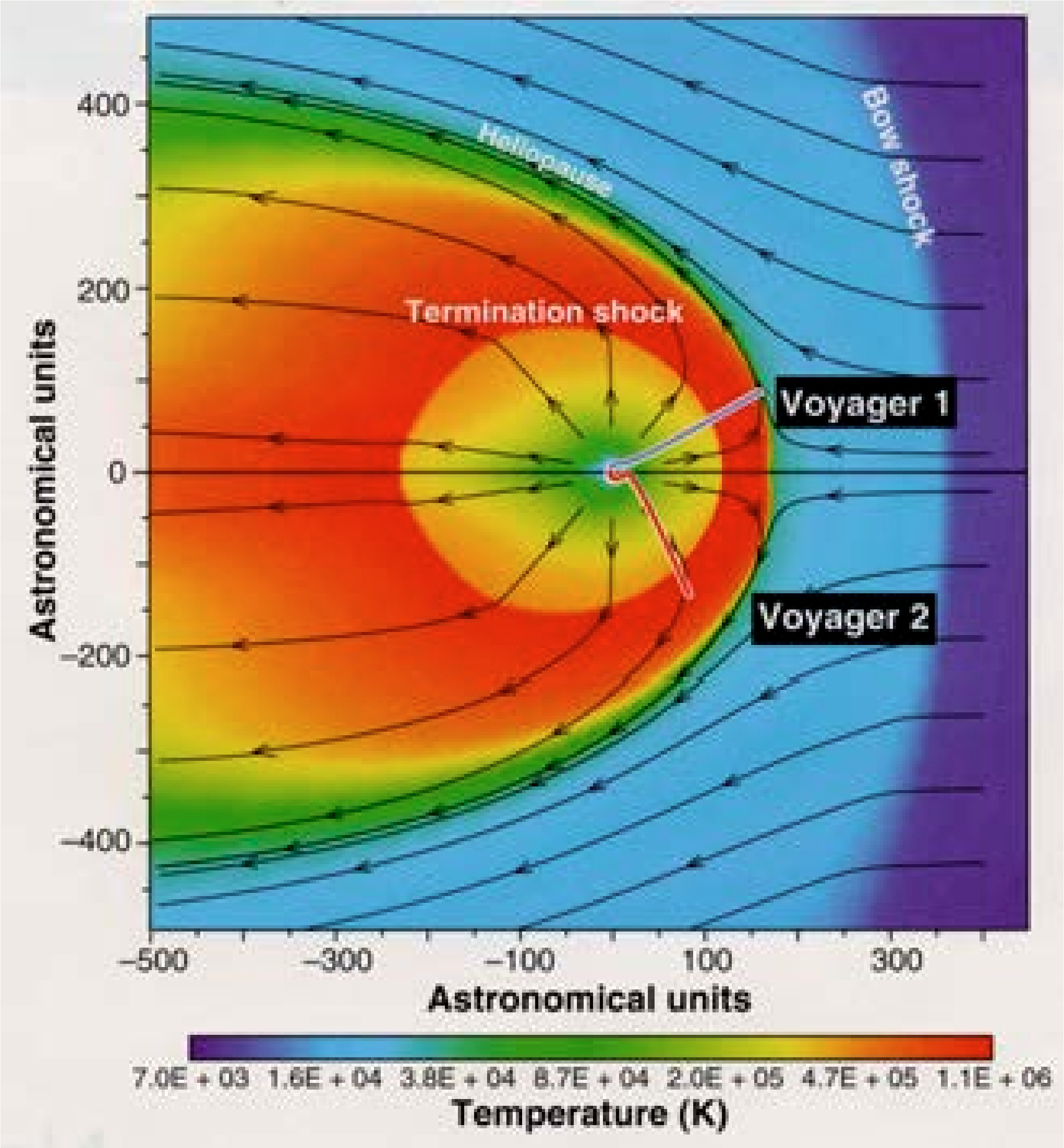
- Acceleration charged particles at shocks is called diffusive shock acceleration.
- The acceleration is remarkably insensitive to the parameters. In particular, the spectrum at the shock does not depend on the diffusion coefficient unless some additional physics is included.
- In the heliosphere, the adiabatic cooling upstream the shock introduces a dependence of the intensity on the diffusion coefficient.



Intensity of ACR and GCR vs Heliocentric Radius
Termination Shock
ACR
GCR
Intensity
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
radius (AU)

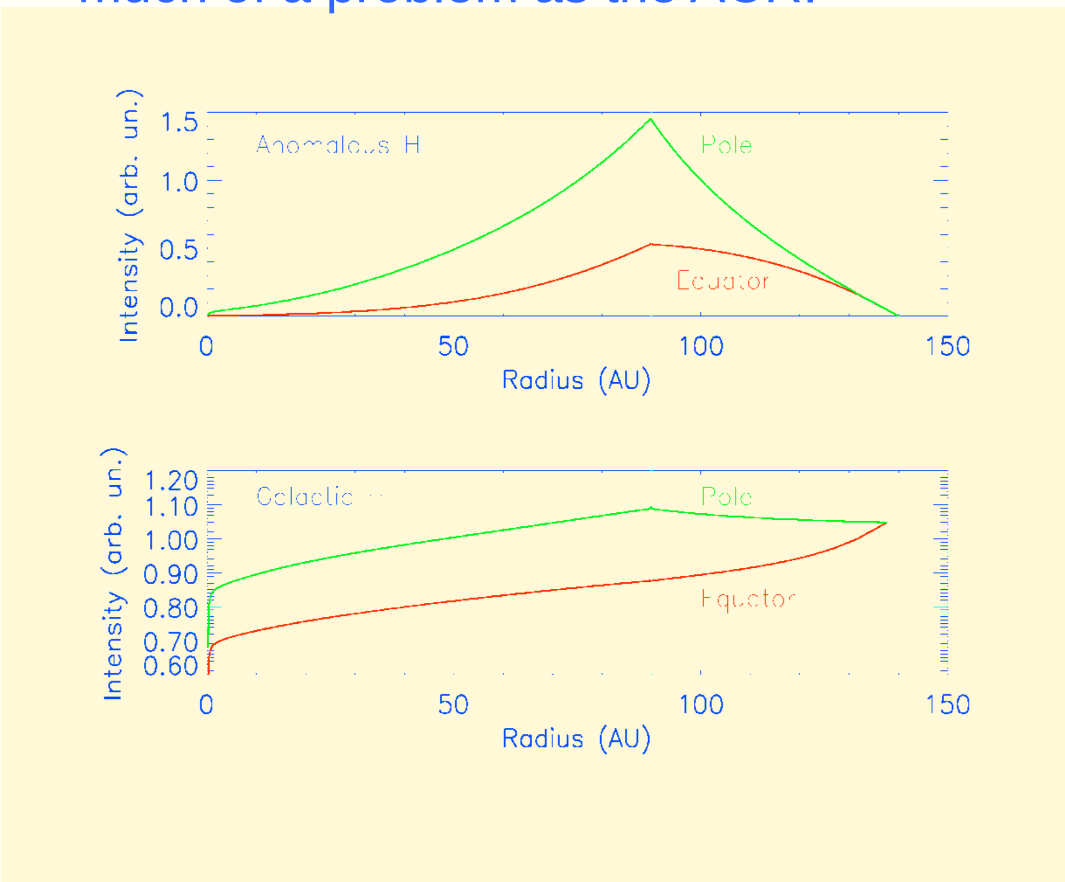
The Observations from Voyager

- The Voyager spacecraft have been measuring cosmic rays during their 35-year journey.
- First, V1, in 2005, crossed the termination shock of the solar wind. Then, in 2007, V2 crossed the shock.
- They have greatly increased our knowledge of the effects of the heliosphere on cosmic rays.

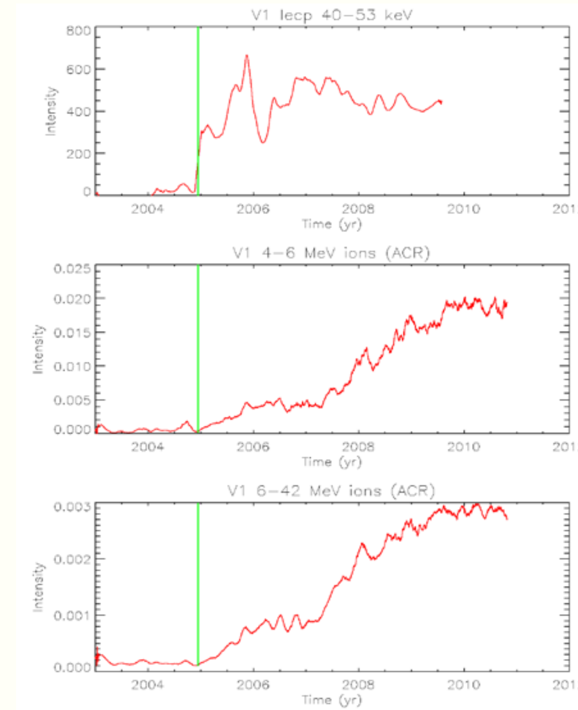


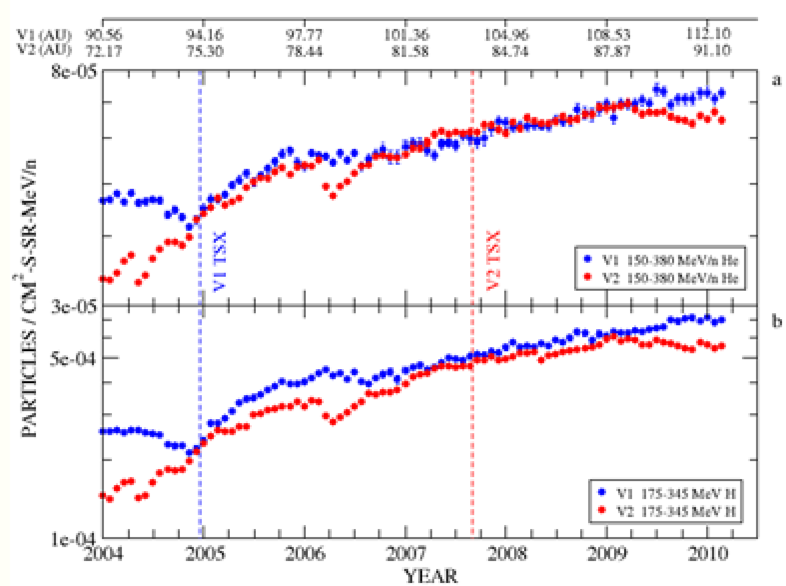
Bow shock
Heliopause
Termination shock
Voyager 1
Voyager 2
Astronomical units
400
200
0
−200
−400
−500
−300
−100
100
300
Astronomical units
7.0E + 03
1.6E + 04
3.8E + 04
8.7E + 04
2.0E + 05
4.7E + 05
1.1E + 06
Temperature (K)

Voyager observations of ACR and GCR in the outer heliosphere present a serious challenge to our understanding. The GCR were not as much of a problem as the ACR.



The expected radial variation prior to the crossing of the termination shock.



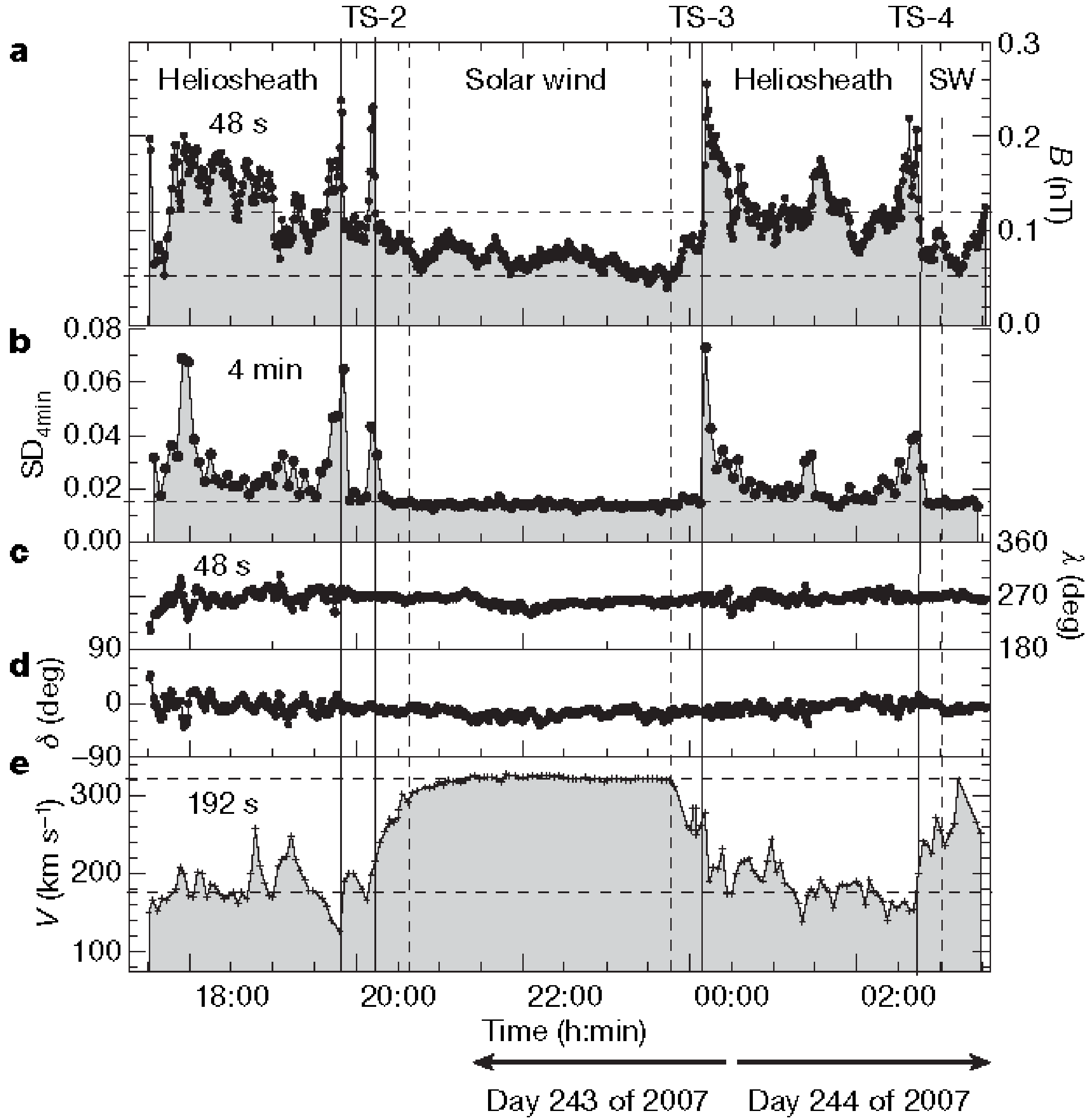


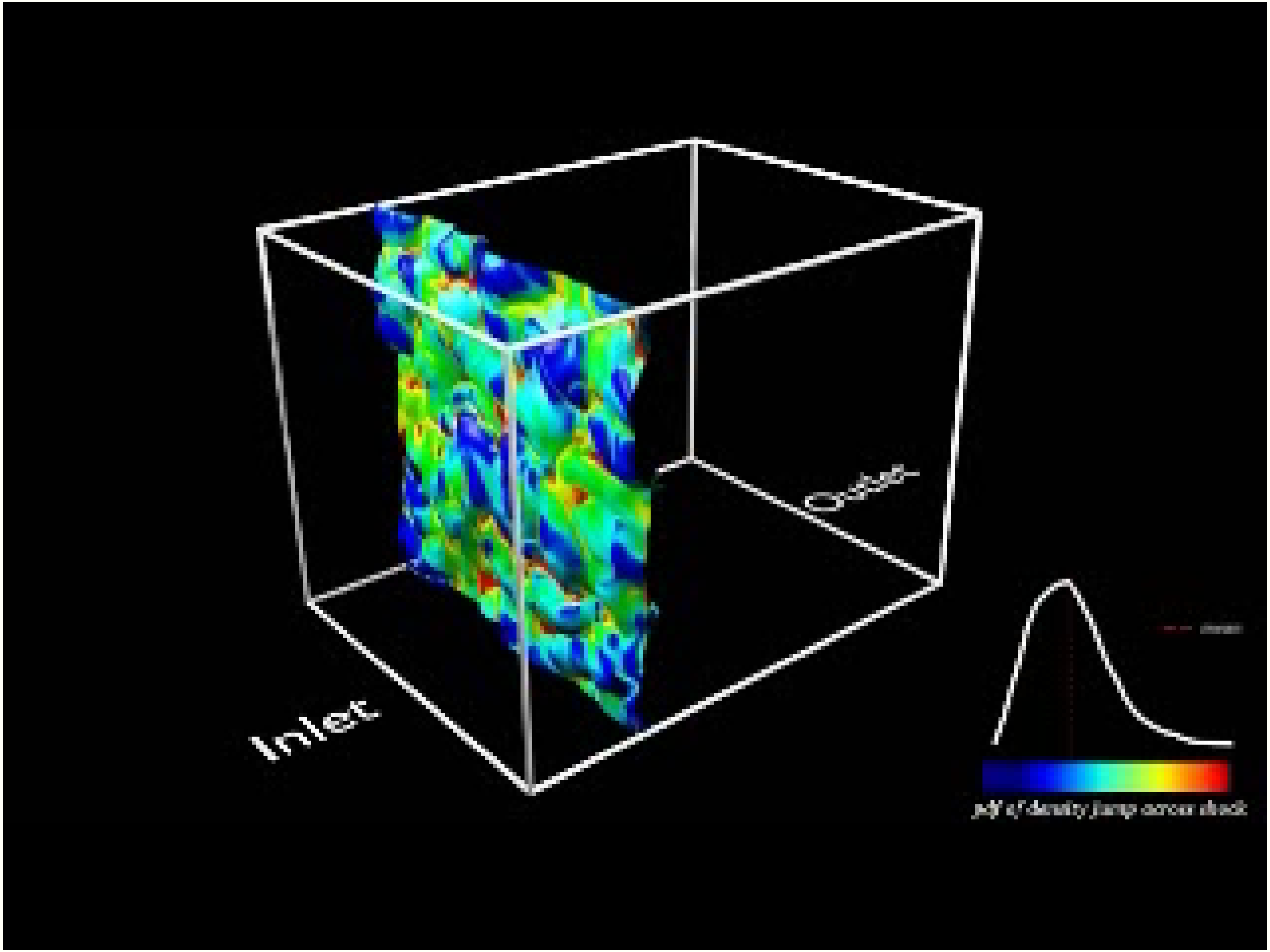
Observations of GCR and AC

The Voyager 2 Termination Shock Crossing Showed that the Shock is Turbulent

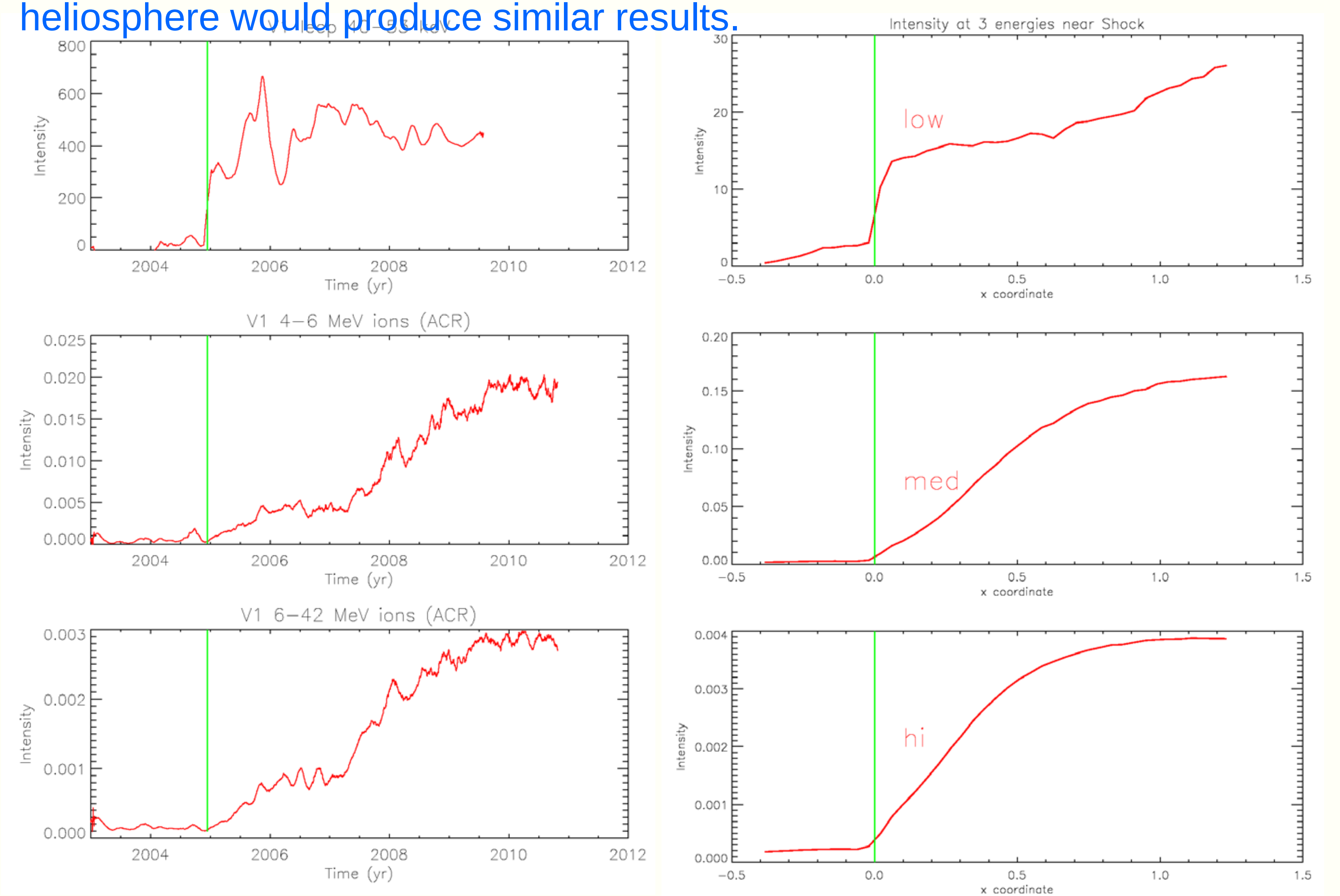
- The functioning plasma detector helped to provide richer data set than from V1.
- Also, the crossing was at a much slower shock speed.

- The shock crossed V2 *several times,* probably because of turbulence caused by the fluctuating upstream solar wind.

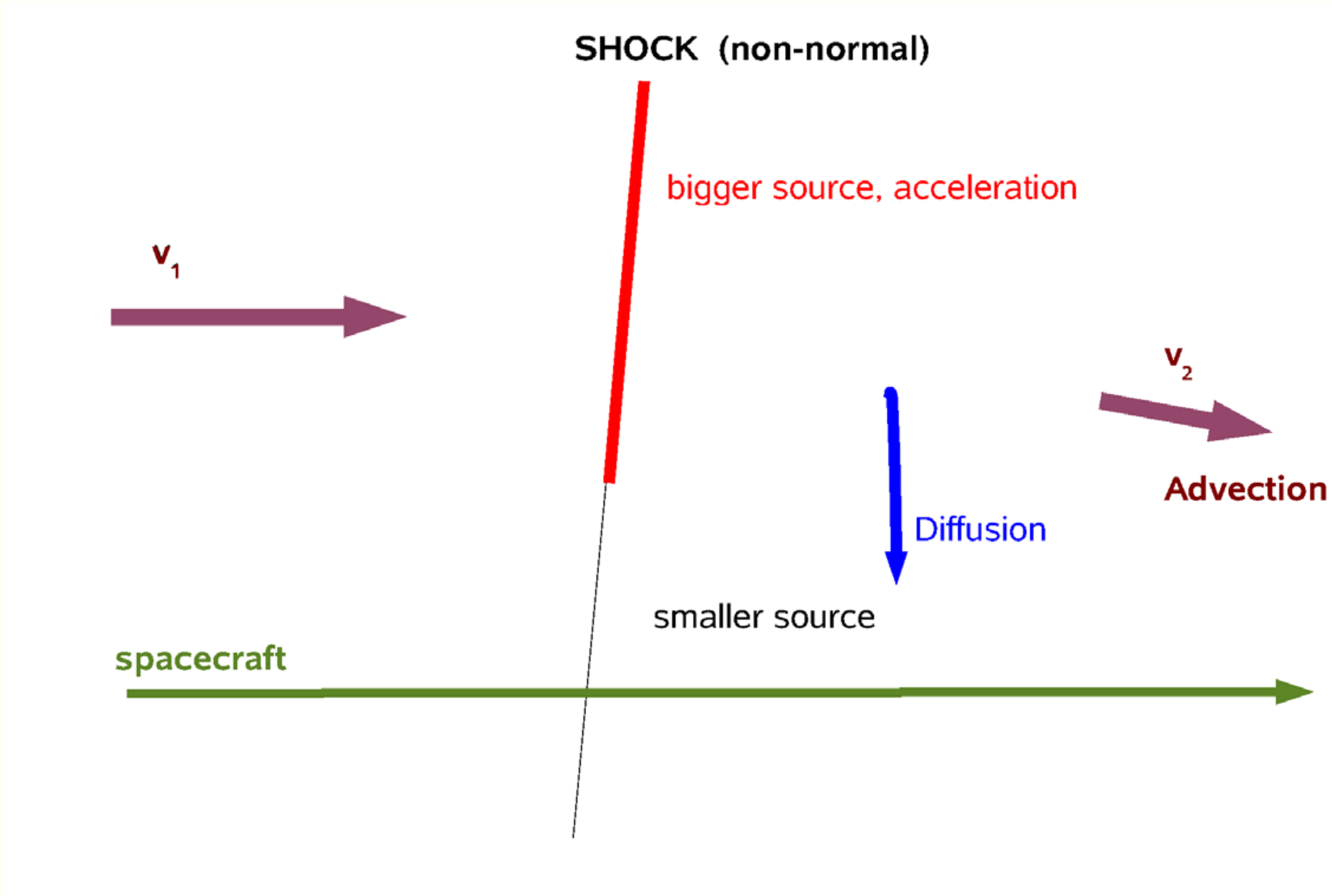

TS-2
TS-3
TS-4
a
Heliosheath
Solar wind
Heliosheath
SW
48 s
0.3
0.2
0.1
0.0
B (nT)
b
0.08
0.06
0.04
0.02
0.00
4 min
SD4min
c
48 s
360
270
180
90
λ (deg)
d
90
0
−90
δ (deg)
e
192 s
300
200
100
V (km s−1)
18:00
20:00
22:00
00:00
02:00
Time (h:min)
Day 243 of 2007
Day 244 of 2007


Inlet
Outlet
pdf of density jump across shock

Guo-Jokipii (2010) considered a varying B. Below is a comparison of their results with LECP data (provided by Rob Decker). A blunt heliosphere would produce similar results.



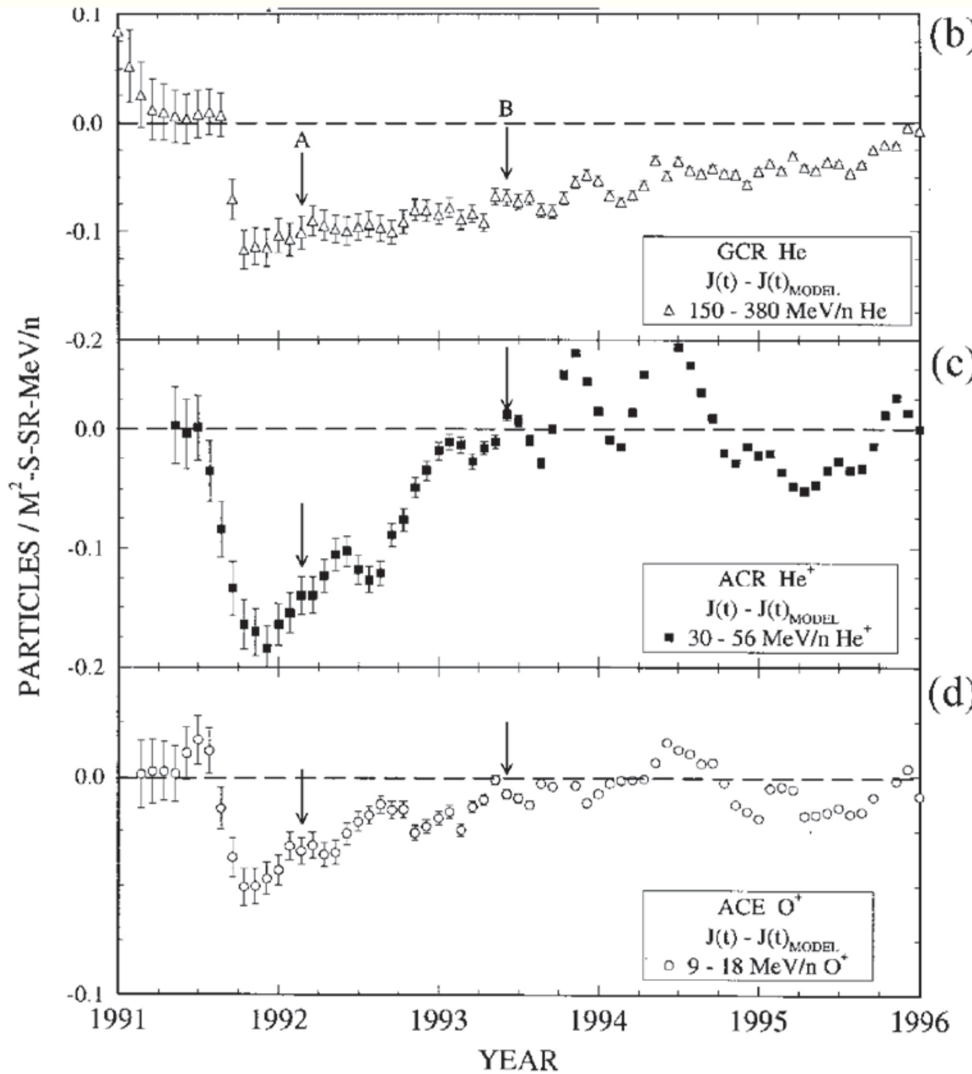
Consider the *general* effect of the spatial variation of acceleration along the face of a shock front.

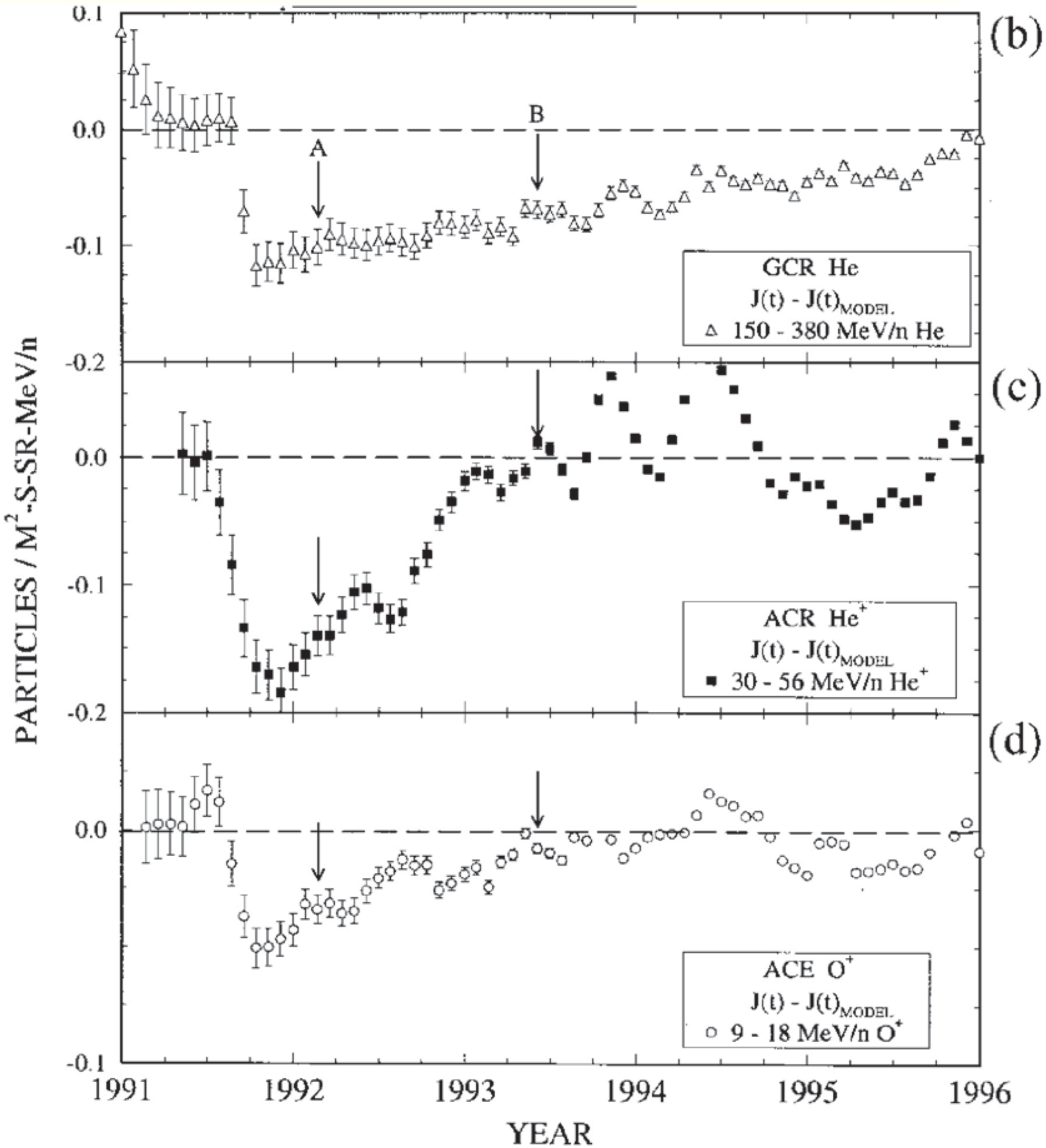


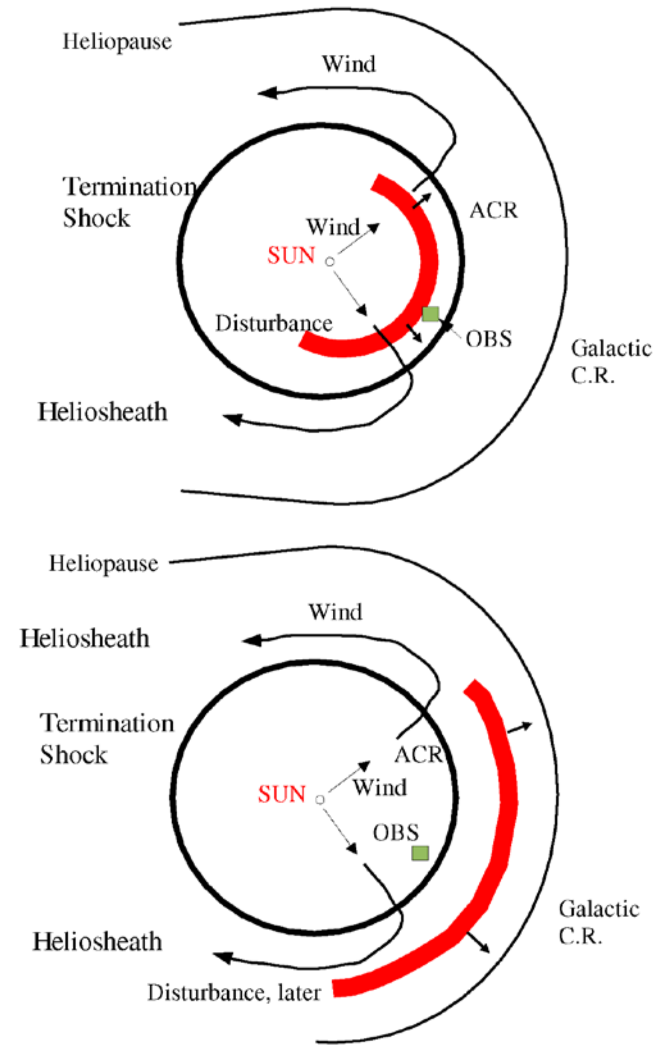
This results in a positive radial gradient along the spacecraft trajectory

Evidence Regarding the Location of the ACR Source

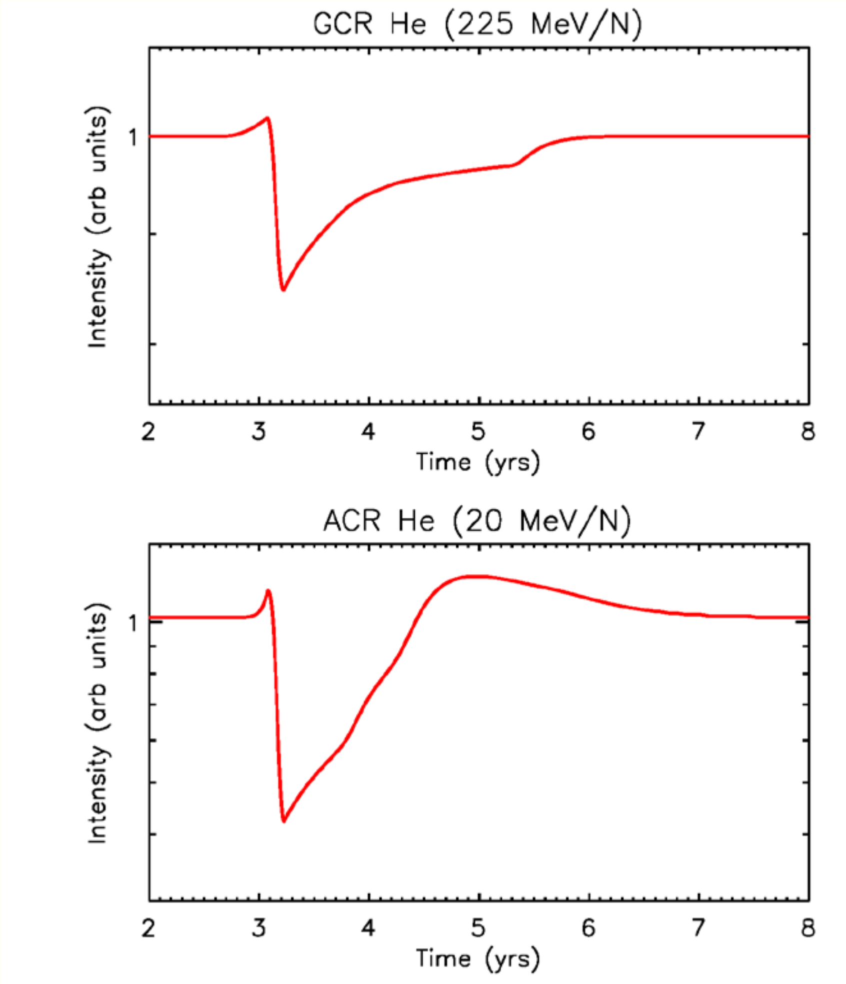
- In 2000, McDonald et al published V1 data concerning the recovery of GCR and ACR from the passage of a disturbance (MIR?) at ~ 42 AU.
- The recovery of the GCR took much longer than that of the ACR.
- This shows that the source of the ACR is well within the source of the GCR.

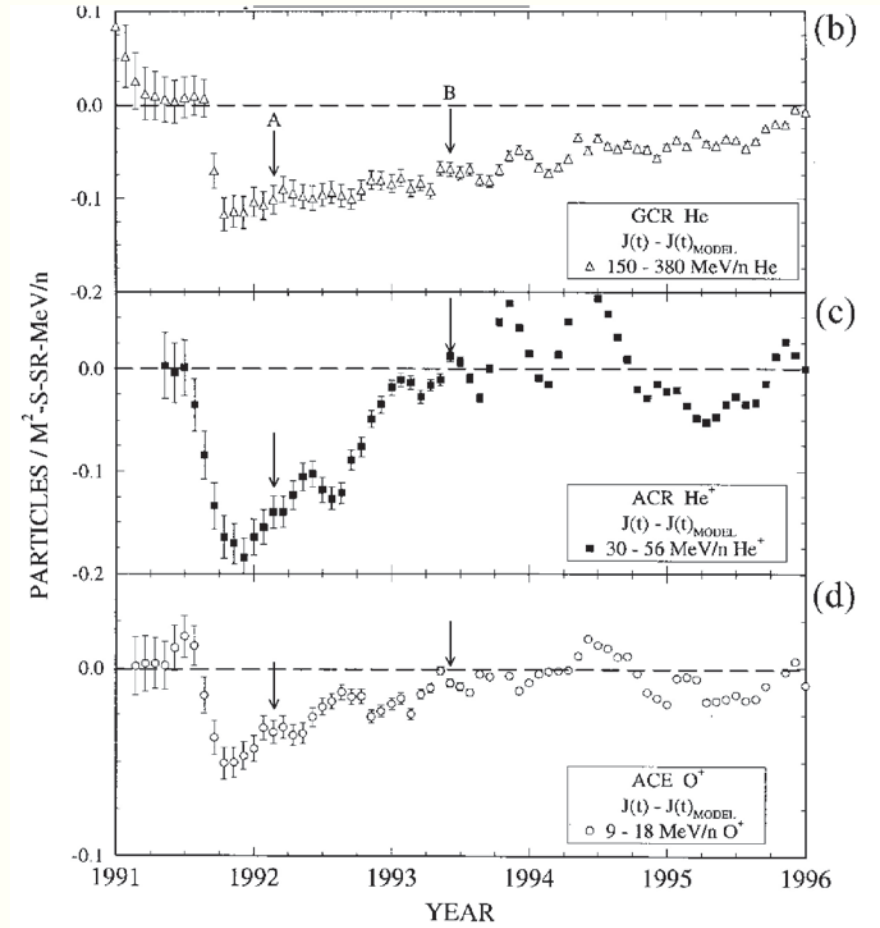






The cartoon at right illustrates the effects of a disturbance on the ACR and GCR.

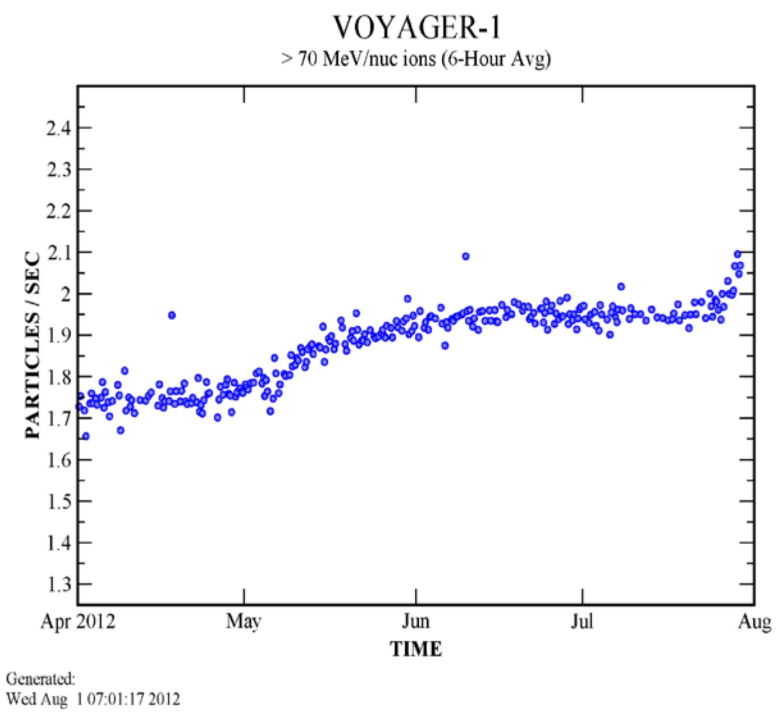




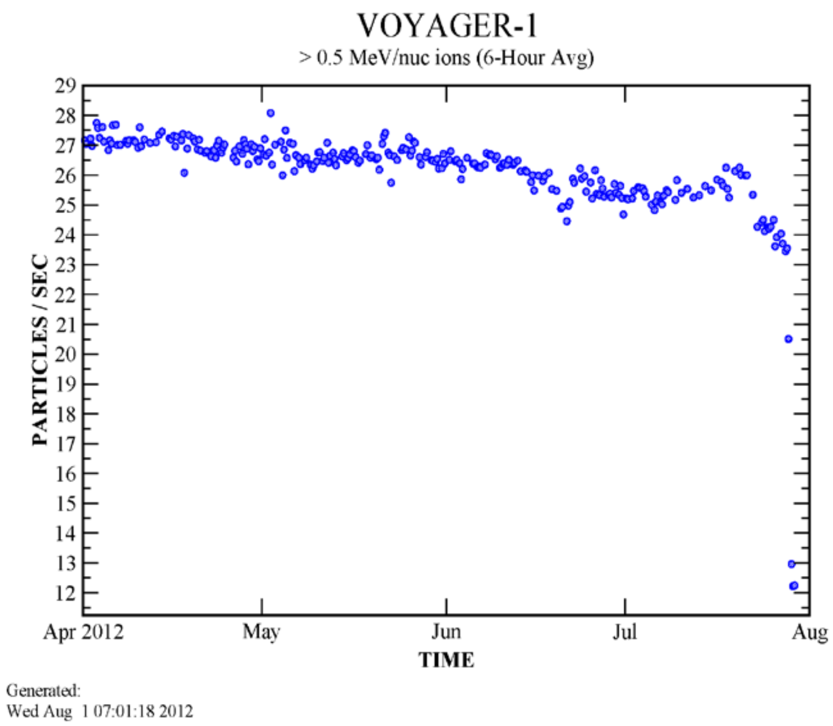
Left, the result of a computer simulation of a simple *2-dimensional blunt* model heliosphere, with a propagating disturbance, including ACR acceleration at the termination shock. Note the similarities with the observations at right. These were not optimized.

The Most-Recent Voyager 1 Data From a Distance of 121 AU

Galactic Cosmic Rays

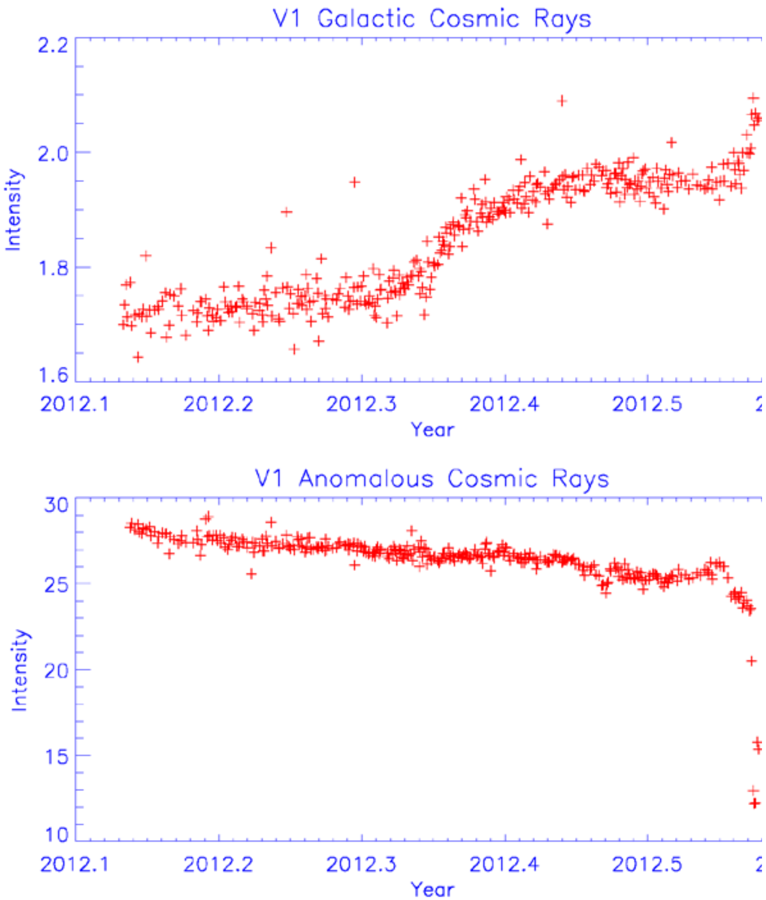


Anomalous Cosmic Rays

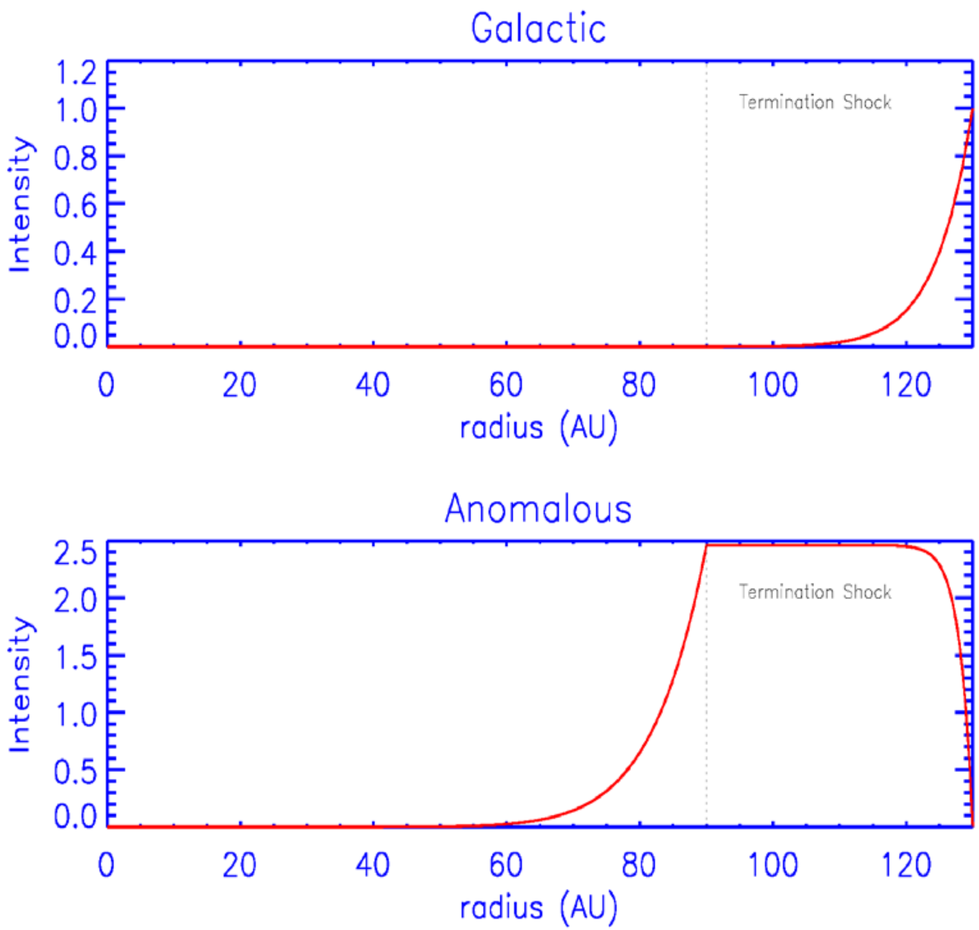


Compare V1 Observations with a Simple Model Calculation

Observations

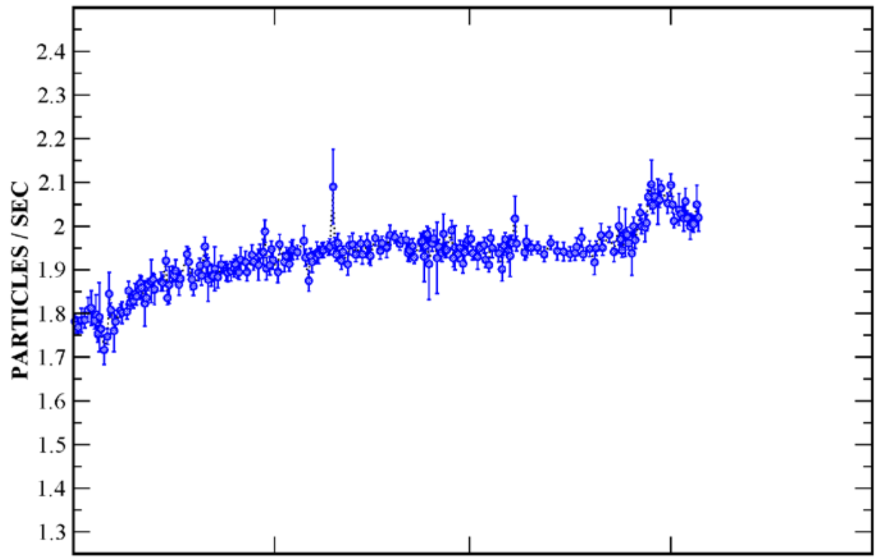


Model



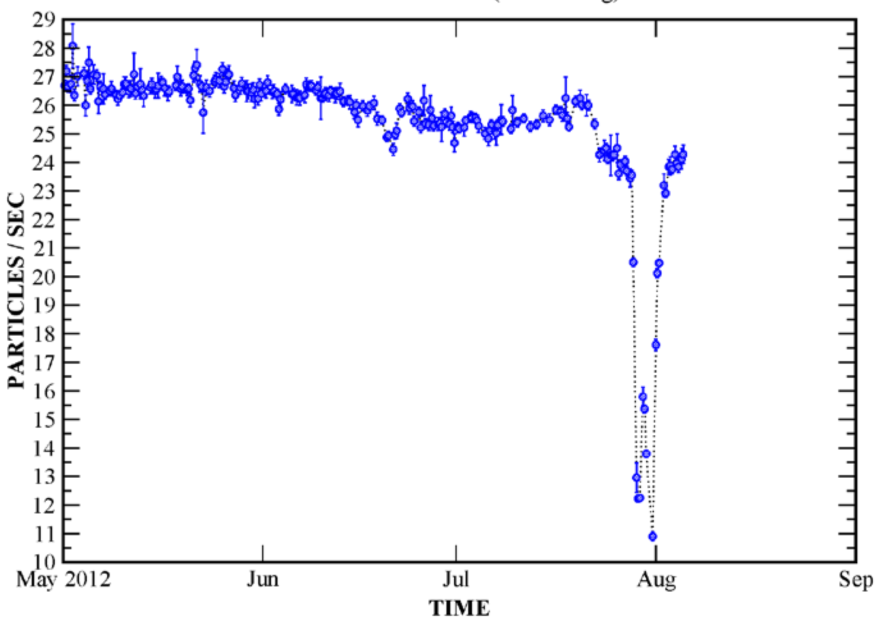
VOYAGER-1

> 70 MeV/nuc ions (6-Hour Avg)



VOYAGER-1

> 0.5 MeV/nuc ions (6-Hour Avg)



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Tue Aug 7 07:01:18 2012

Conclusions

- The effects of the heliosphere on cosmic rays has had two effects:
  - They have greatly increased our knowledge of the transport of cosmic rays.
  - They have enabled the use of cosmic rays as remote probes of the heliosphere.
- We are fortunate at present to have the Voyager spacecraft to carry out in situ observations in the very outer reaches.