

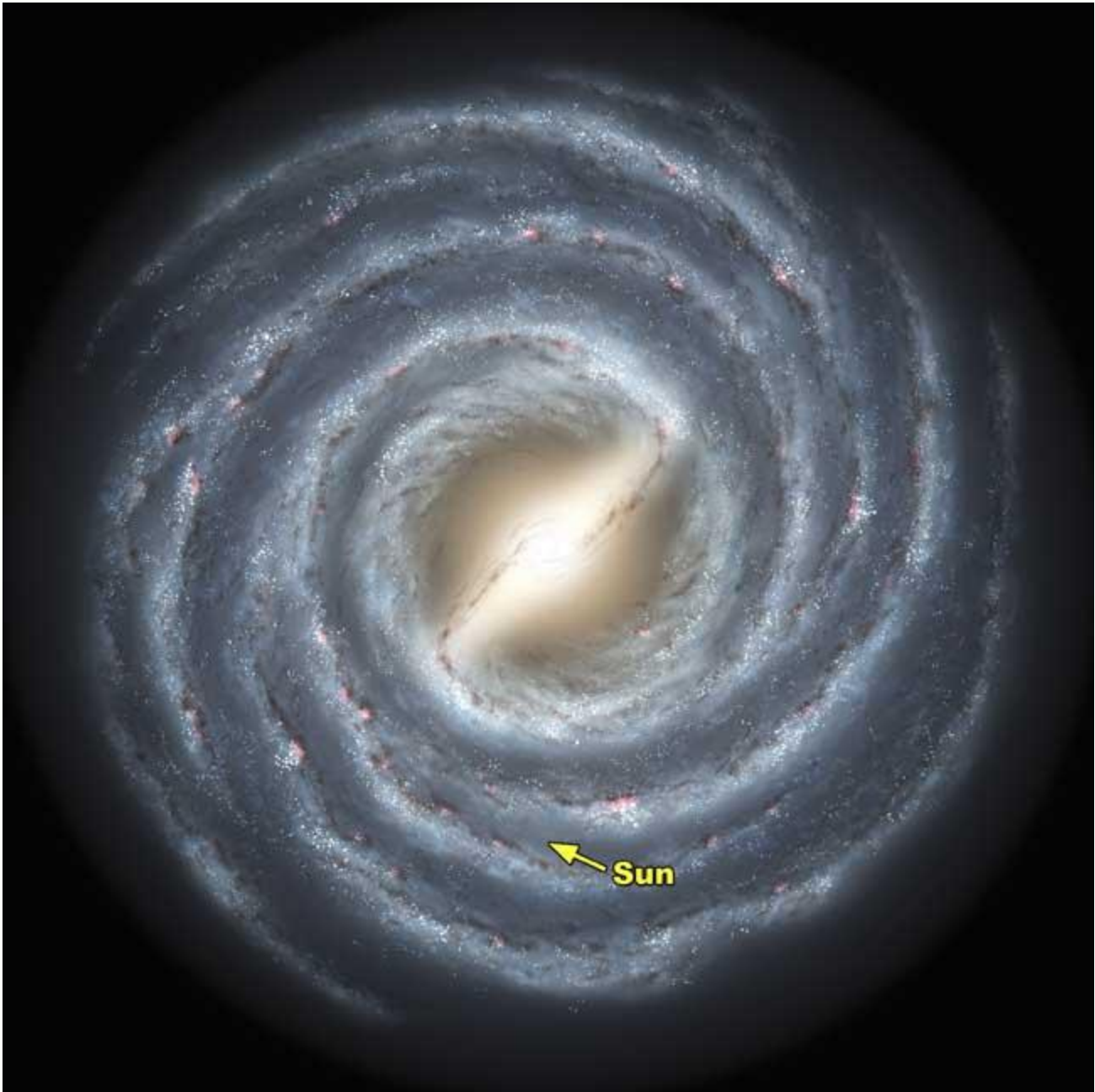
# The Evolving Heliosphere and its Particle Environment

*J. R. Jokipii*  
*University of Arizona*

**Presentation at the 2009 Heliophysics Summer School,  
Boulder, July 25, 2009**

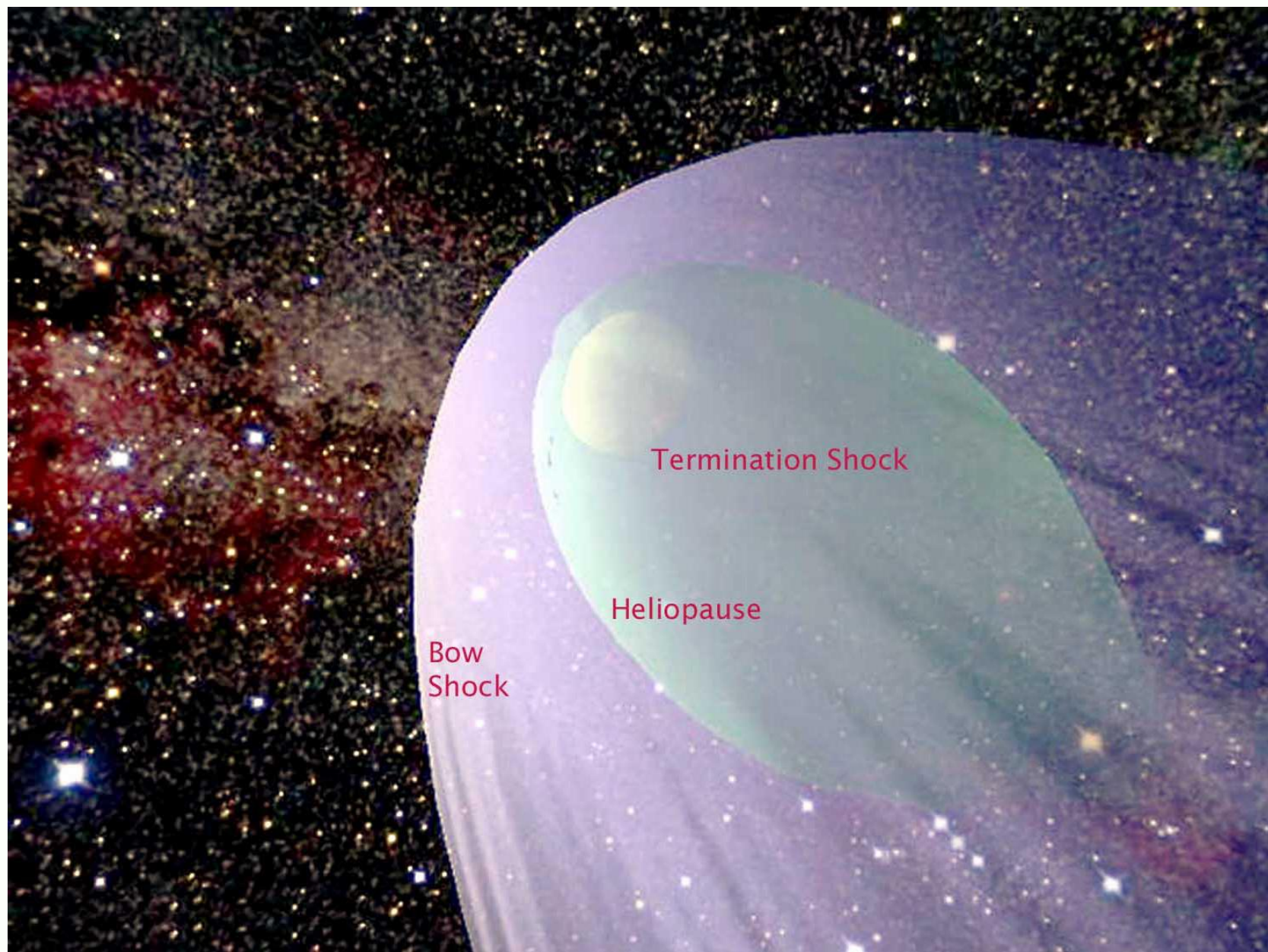
# Outline of Lecture

- Brief introduction to the heliosphere.
- Introduction to cosmic rays/energetic particles.
- Temporal variations of cosmic rays are observed on a continuum of time scales – up to  $10^9$  years.
- These serve as probes of conditions long ago (and also far away).
- To use this tool, we must first unravel the physical processes relating heliospheric conditions to observed cosmic-ray variations.



# SOLAR CORONA – SEEN DURING A TOTAL ECLIPSE



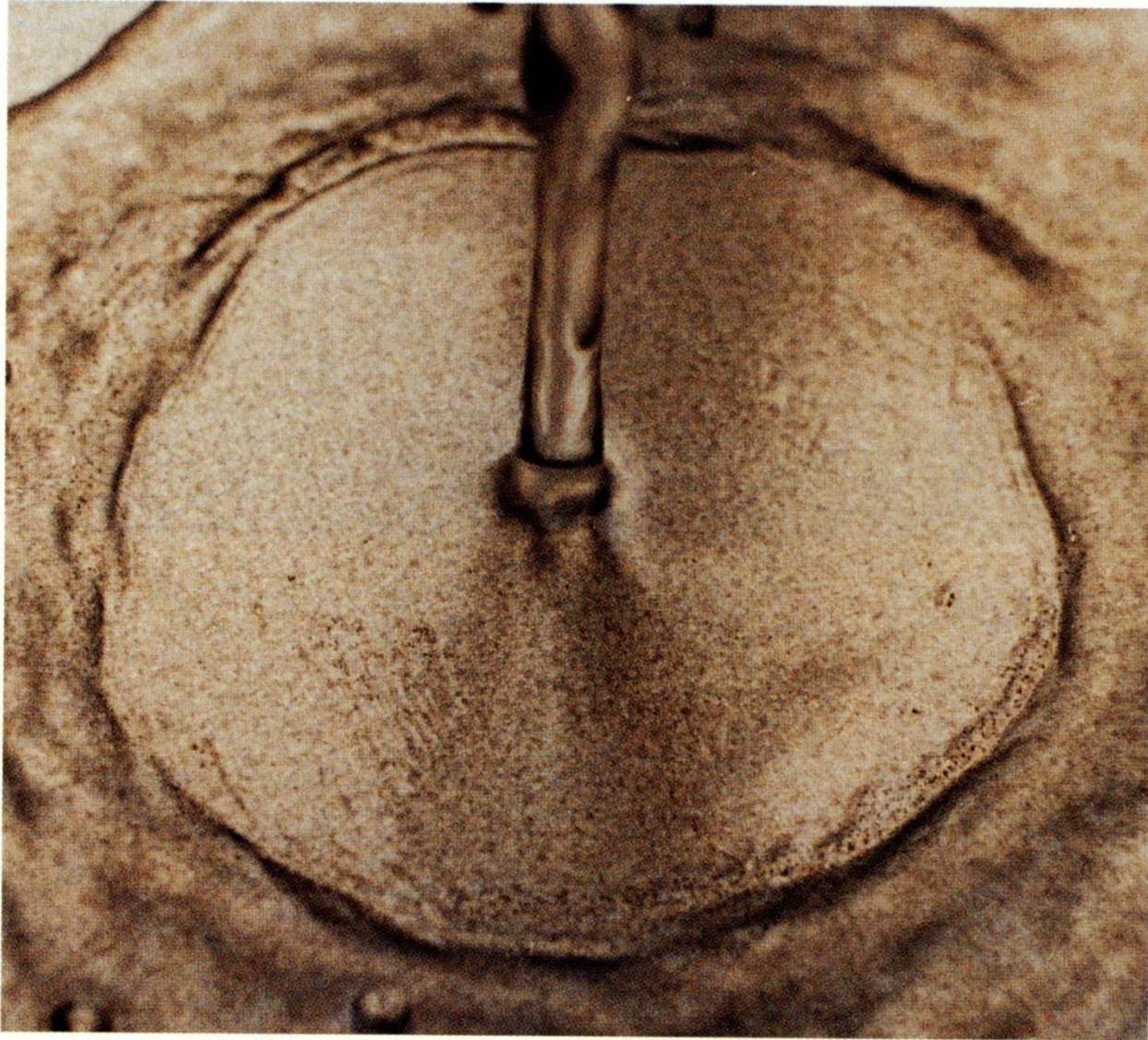


Termination Shock

Heliopause

Bow Shock

An instructive analog may be seen in a kitchen sink.



J. R. JOKIPII

A more-accurate analog model was created by Prof. Hsieh of the University of Arizona physics department.



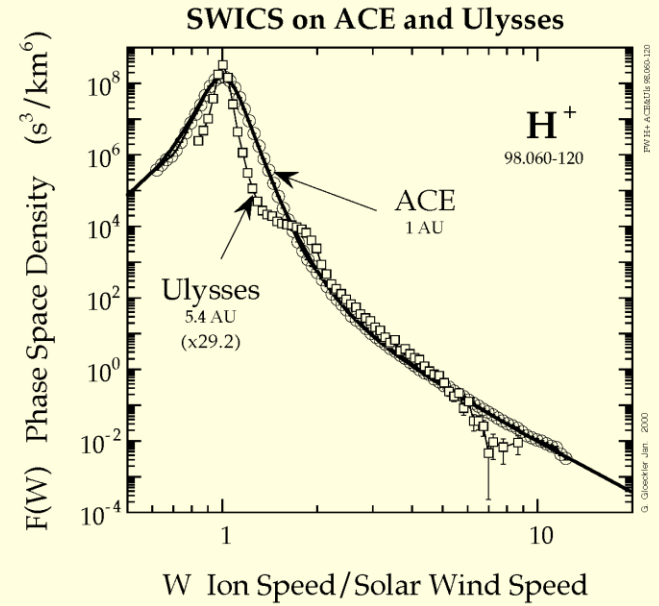
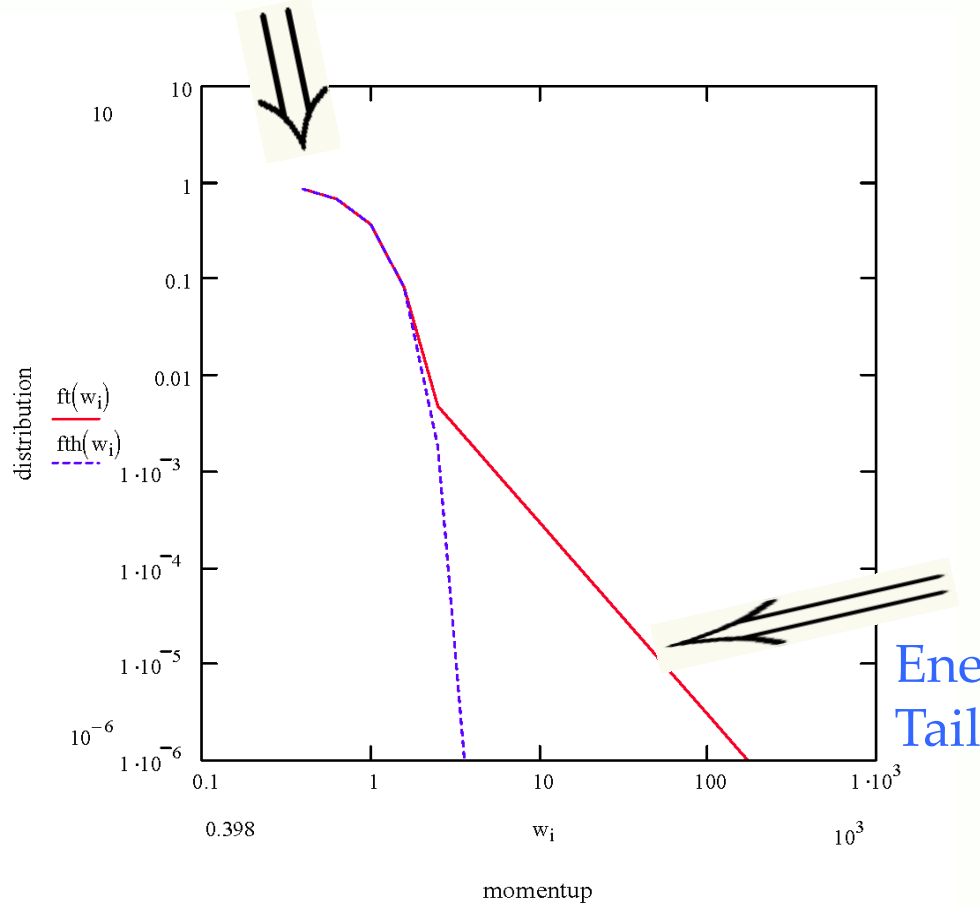
# Cosmic Rays ↔ Energetic Particles

- They are present wherever the ambient density is low enough to permit them to exist.
- They exist from above thermal energies to more than  $10^{20}$  eV, have with few exceptions a normal composition, and are mostly isotropic in direction of arrival.
- They are interesting in their own right, but also serve as probes to determine conditions in space far away or long ago.
- They also pose a significant hazard in space for both instruments and especially humans.



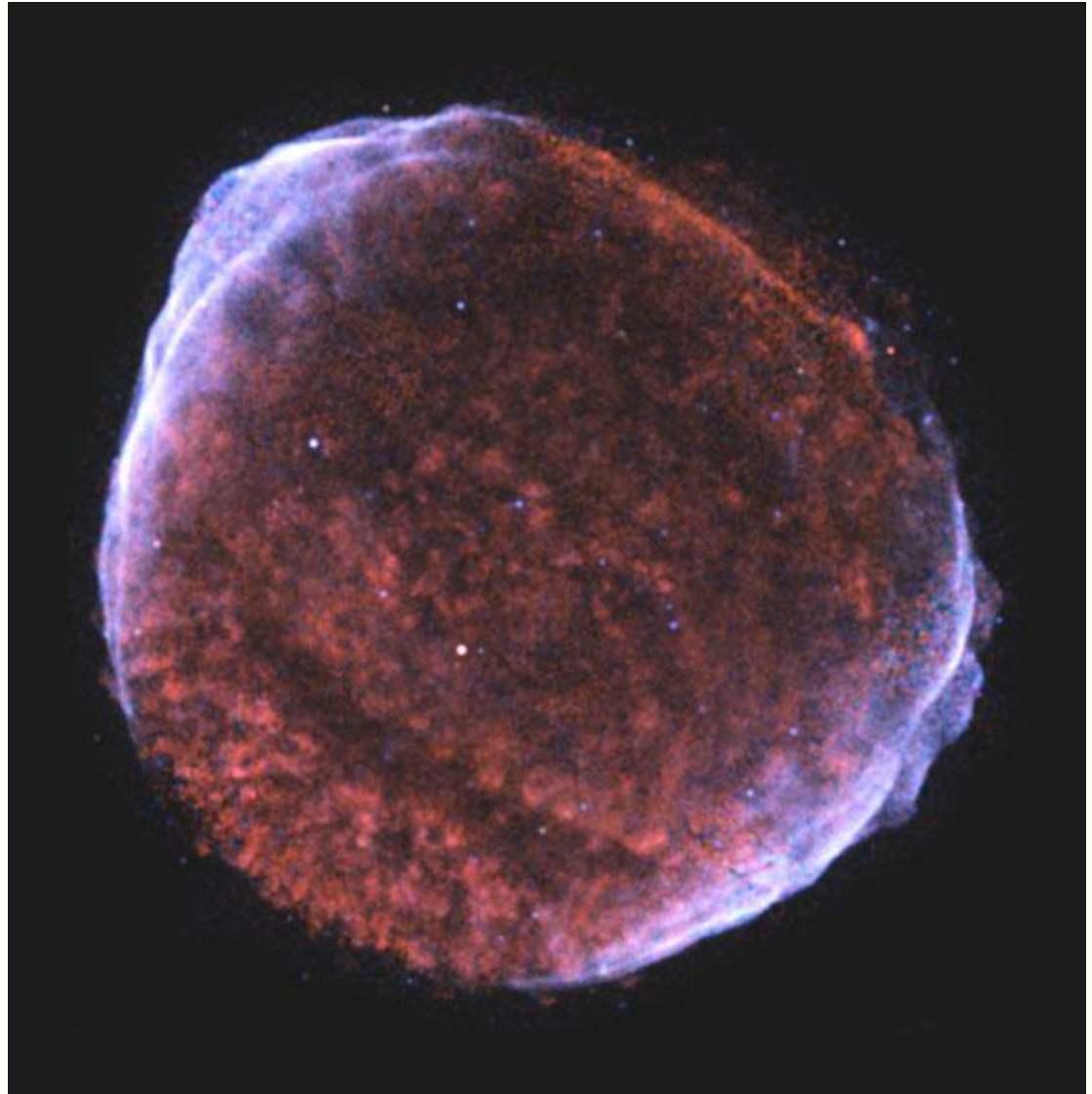
The thermal plasma distribution and the energetic-particles combine to form the full spectrum. The thermal particles contain nearly all of the mass and momentum. Mostly, the energetic particles respond to the plasma.

Thermal



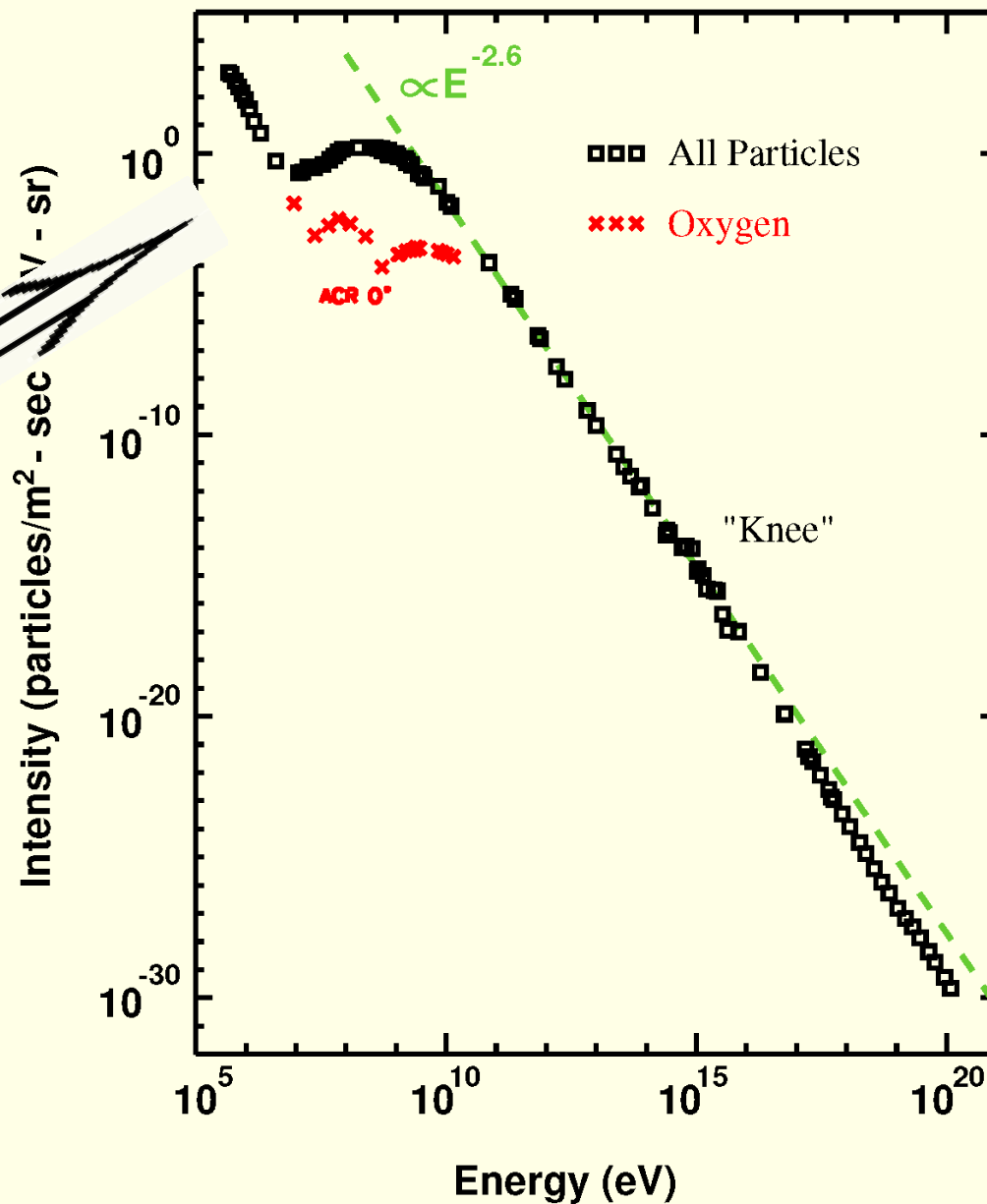
# Galactic Cosmic Rays

- Galactic Cosmic Rays up to about  $10^{15}$  eV kinetic energy are believed to originate from supernovae remnants, where they are accelerated by the expanding shock wave.
- They propagate throughout the galaxy for millions of years before escaping.



Supernova Remnant 1006 – Chandr

# Cosmic-Ray Spectrum



Heliospheric effects

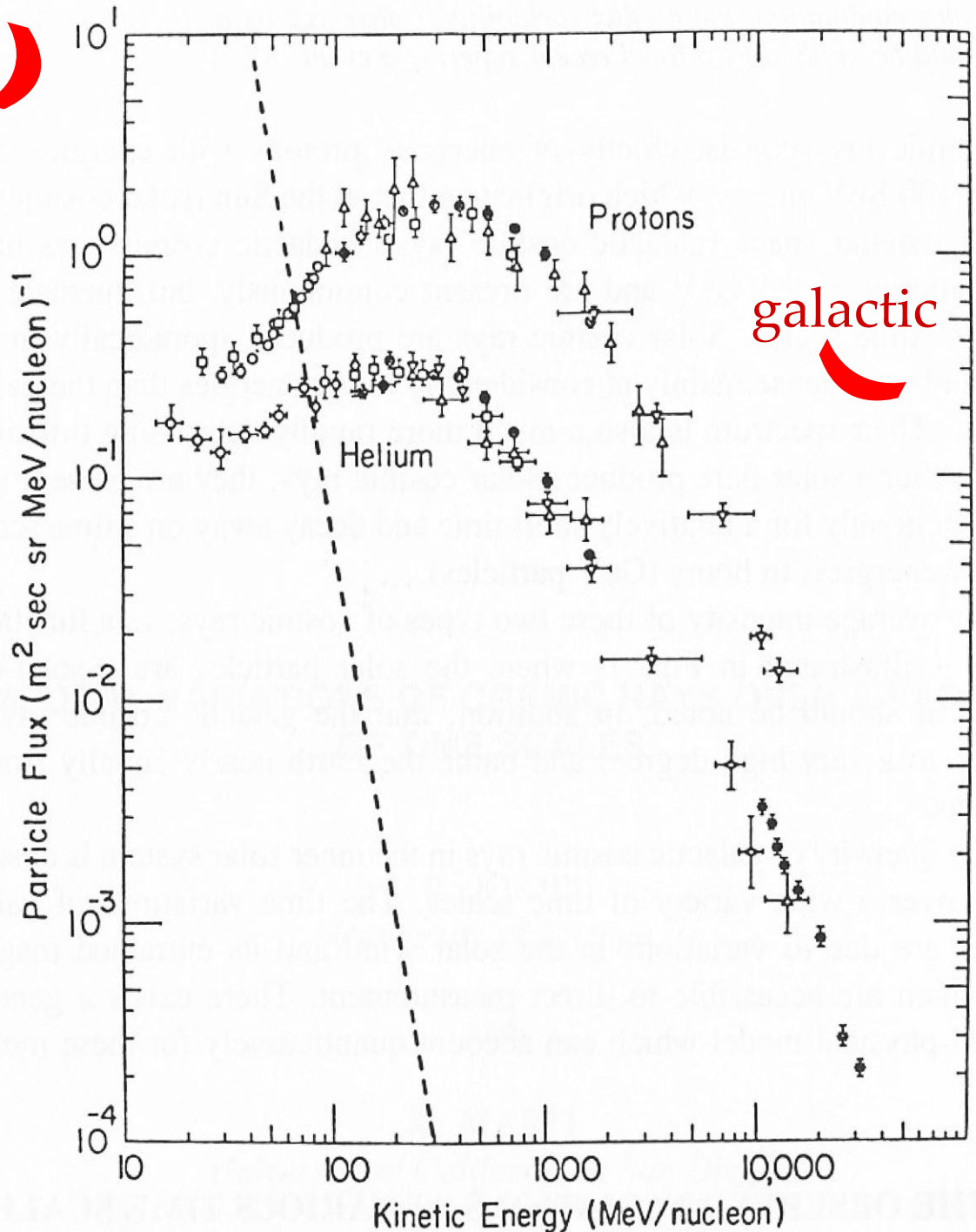
Solar



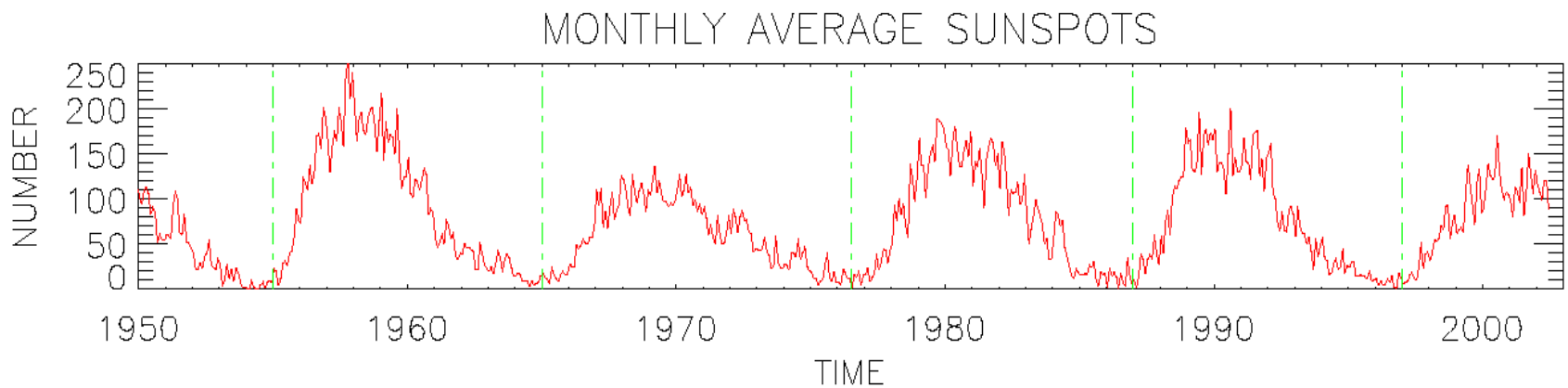
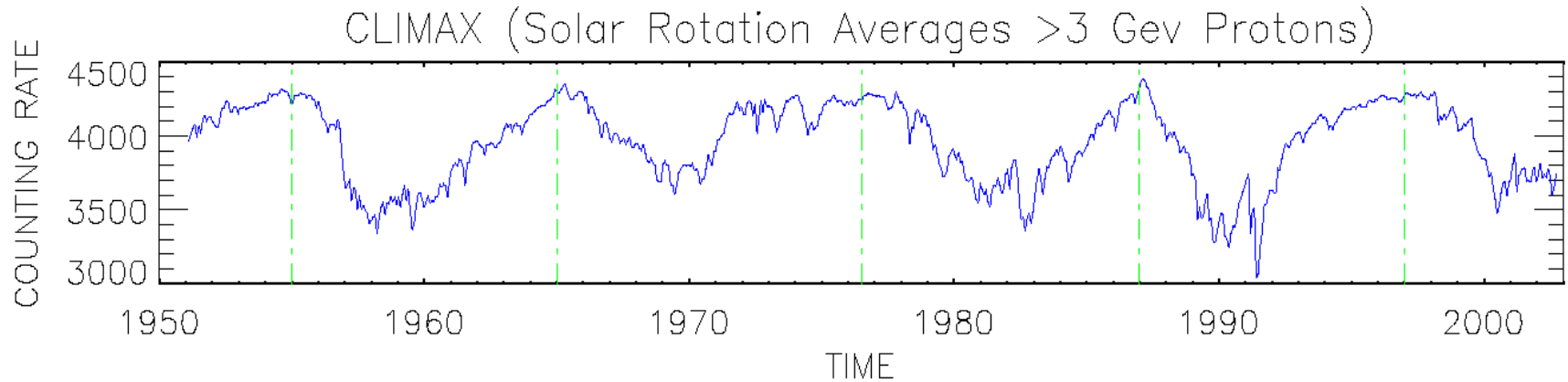
Quiet-time cosmic rays  
with transient solar  
particles  
superimposed.

The solar event lasts  
hours to a day or so.

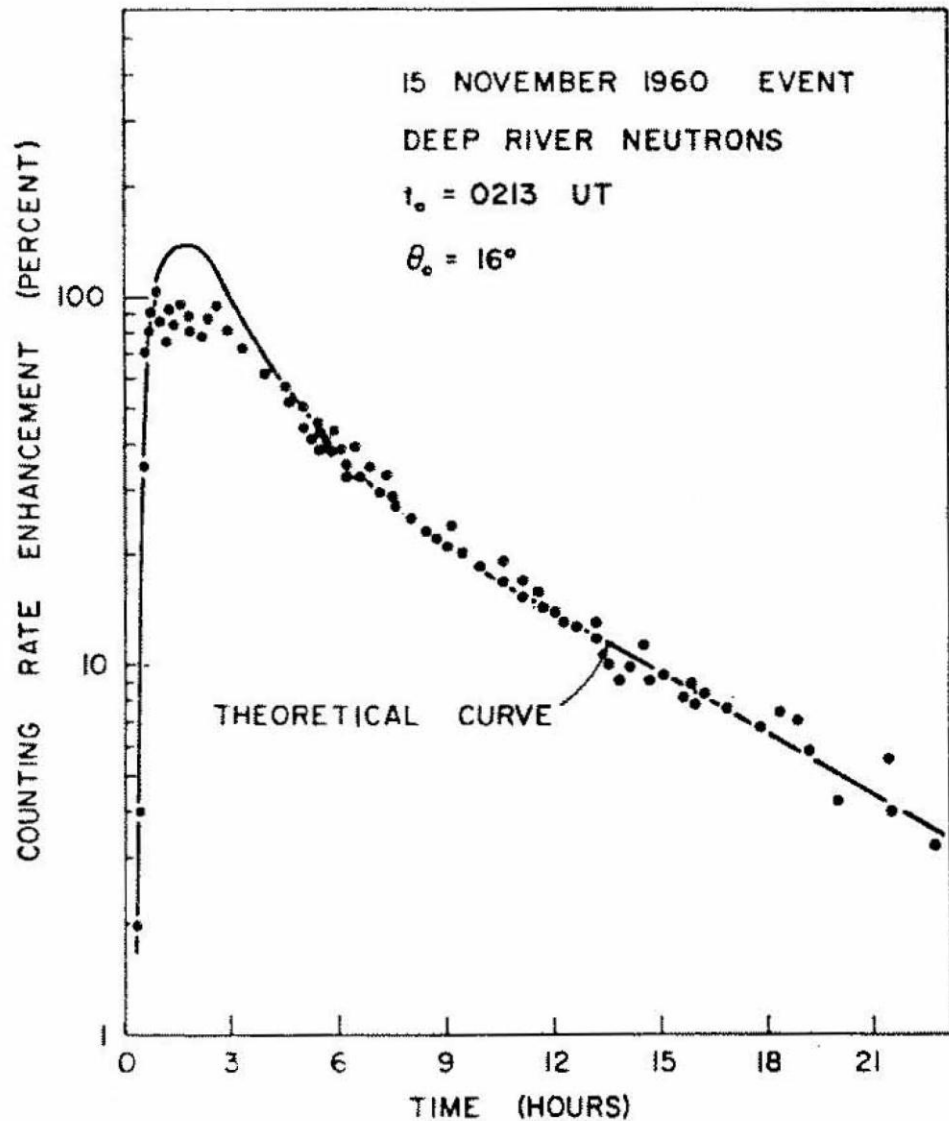
The average intensity  
at energies  $\gtrsim 100$  MeV  
is dominated by  
galactic cosmic rays.



# The variation of $> 3$ Gev protons at Earth and sunspots since 1950.



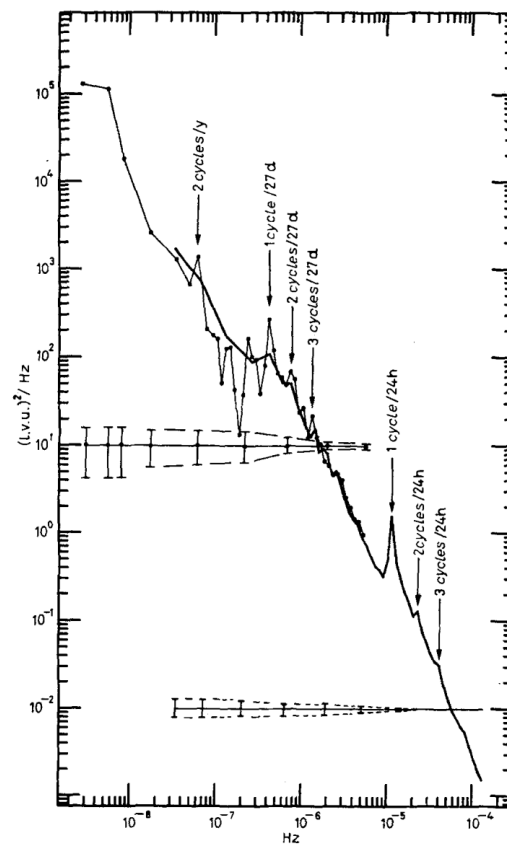
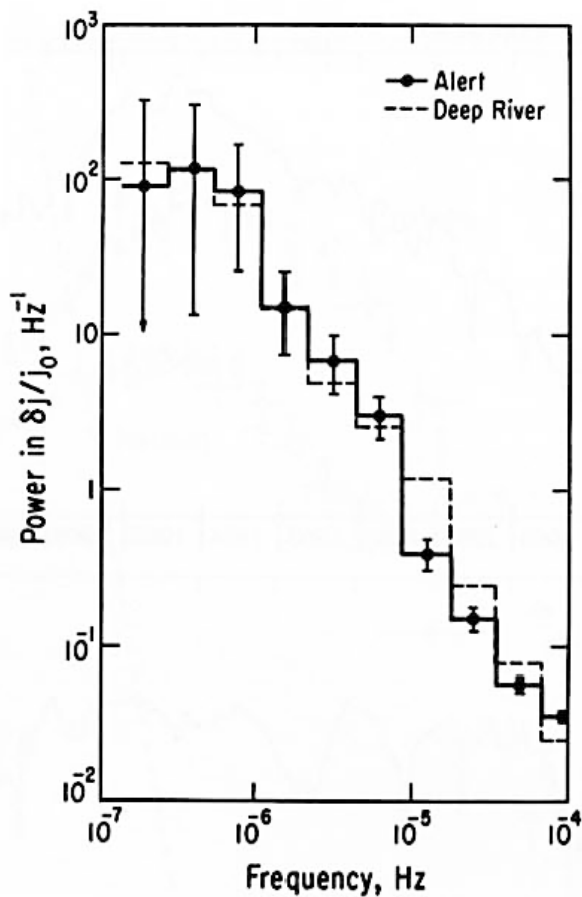
A solar energetic-particle event.



Theoretical fit, using equation 122, to the Deep River neutron monitor data for the November 15, 1960, event.  $\theta_0$  is the angle between the flare and the foot of the average magnetic field line passing through the point of observation [Burlaga, 1967].

Cosmic-Ray variations are seen at all time scales observed.

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.



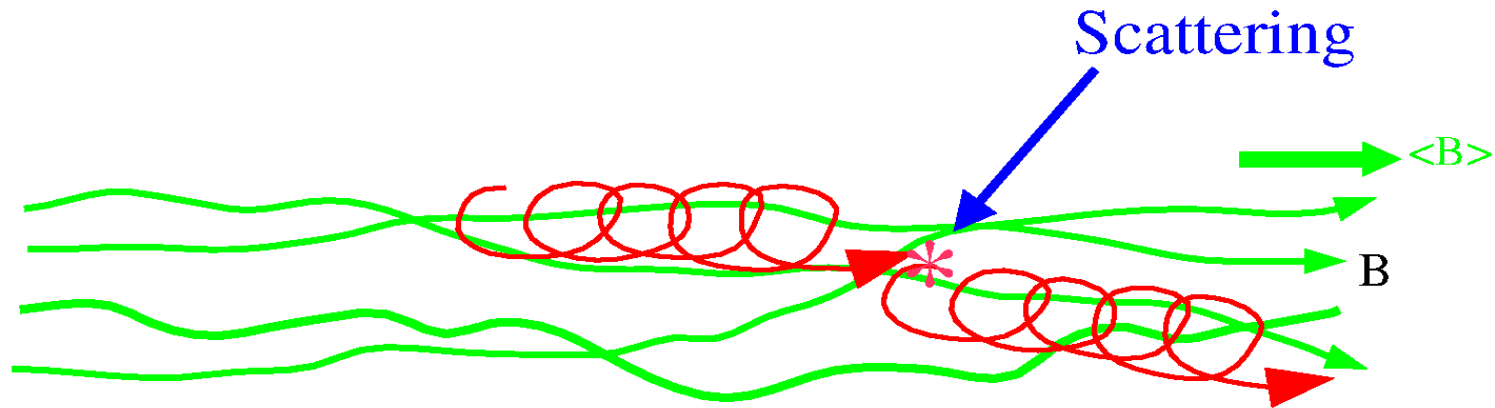
# Brief Summary of Variations

- Short, irregular caused by solar wind variations – irregular and co-rotating with the Sun.
- 11-year and 27-year solar cycle-related variations.
- Longer-term variations – some related to heliospheric phenomena, others of interstellar origin.
- To understand these, we must understand cosmic-ray transport.

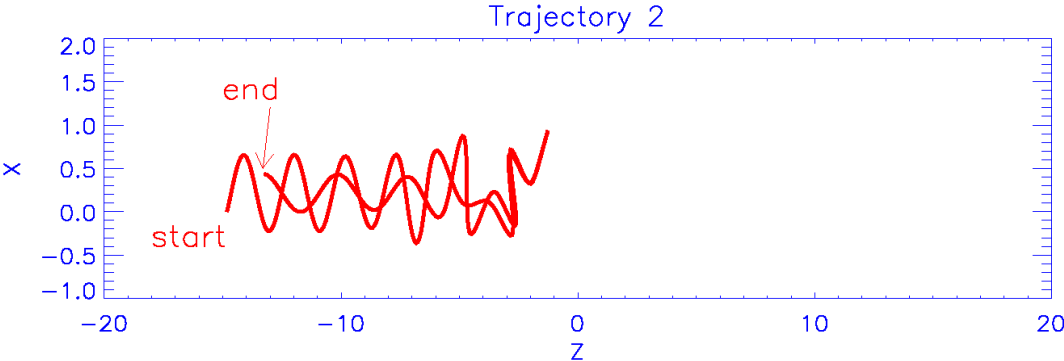
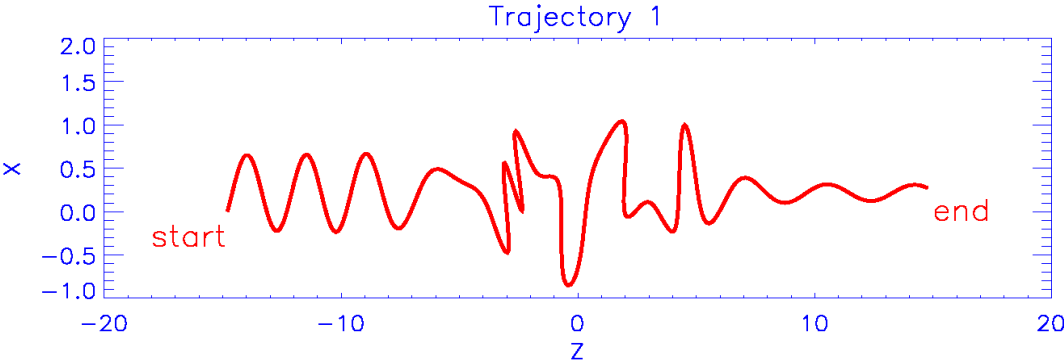
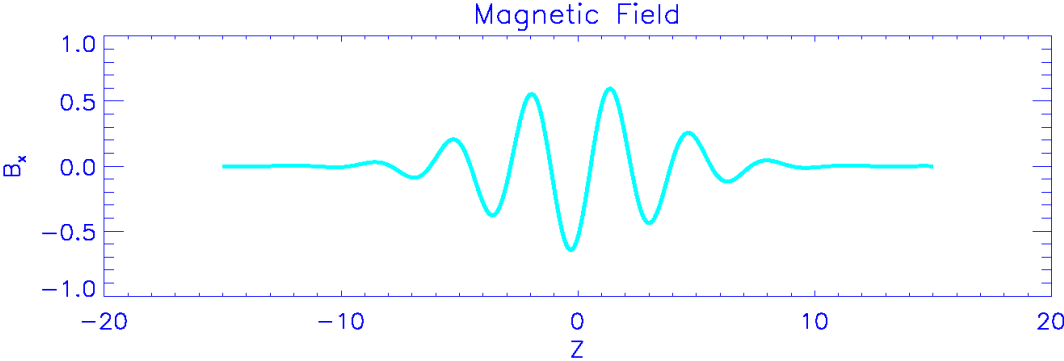


Following Fermi, the transport of cosmic rays is described statistically. The turbulent electromagnetic field is described statistically. In the quasilinear approximation, the scattering rate  $\nu / P_B [1 / (r_c \cos \theta_p)]$ .

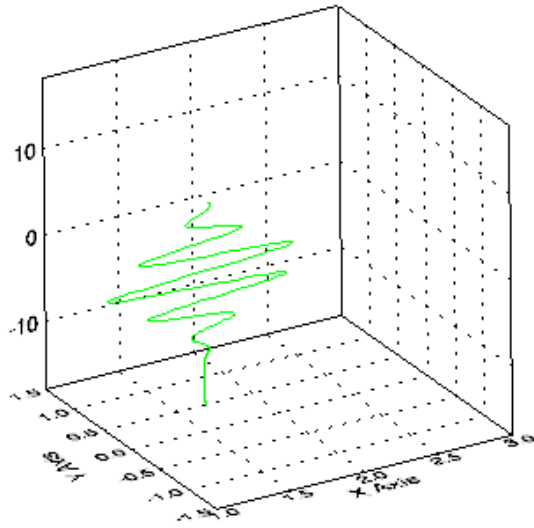
*Particle Trajectory*



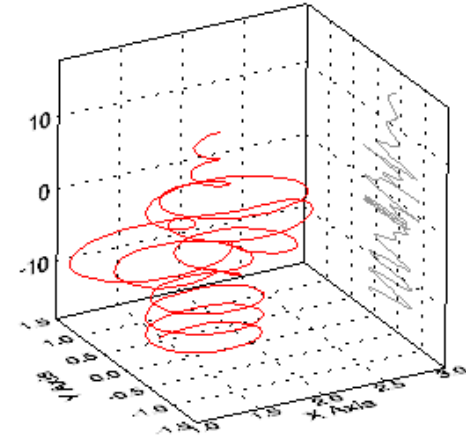
Motion in an irregular magnetic field is sensitive to initial conditions (chaotic).



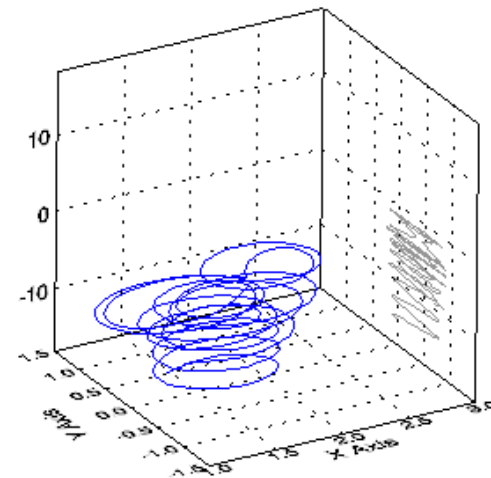
Magnetic Field



Trajectory 1

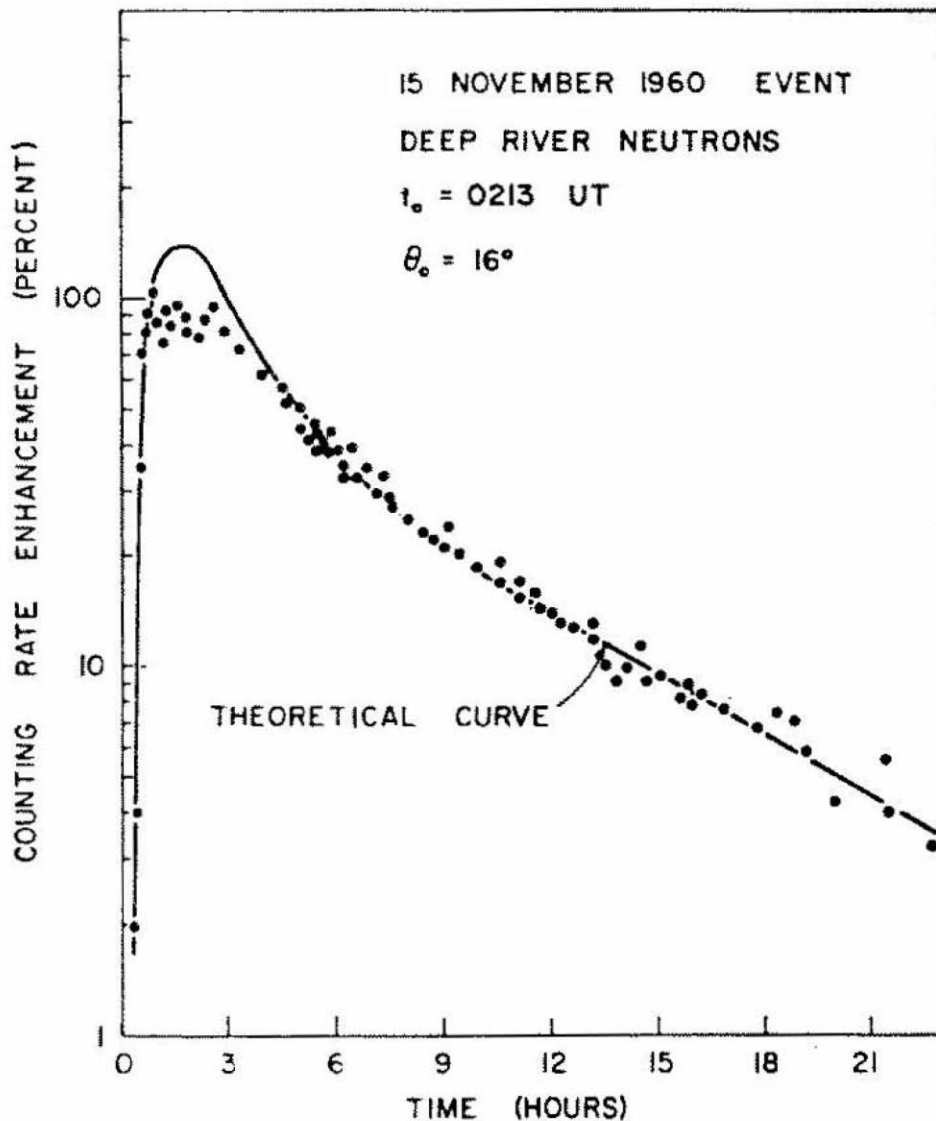


Trajectory2



In this case, we can understand a solar cosmic-ray event using only standard diffusion

$$\frac{\Phi}{\Phi_0} = \frac{\Phi^M}{\Phi_0} \cdot \frac{\Phi^H}{\Phi_0}$$



Theoretical fit, using equation 122, to the Deep River neutron monitor data for the November 15, 1960, event.  $\theta_0$  is the angle between the flare and the foot of the average magnetic field line passing through the point of observation [Burlaga, 1967].

# Particle transport in the heliosphere is the combination of four effects.

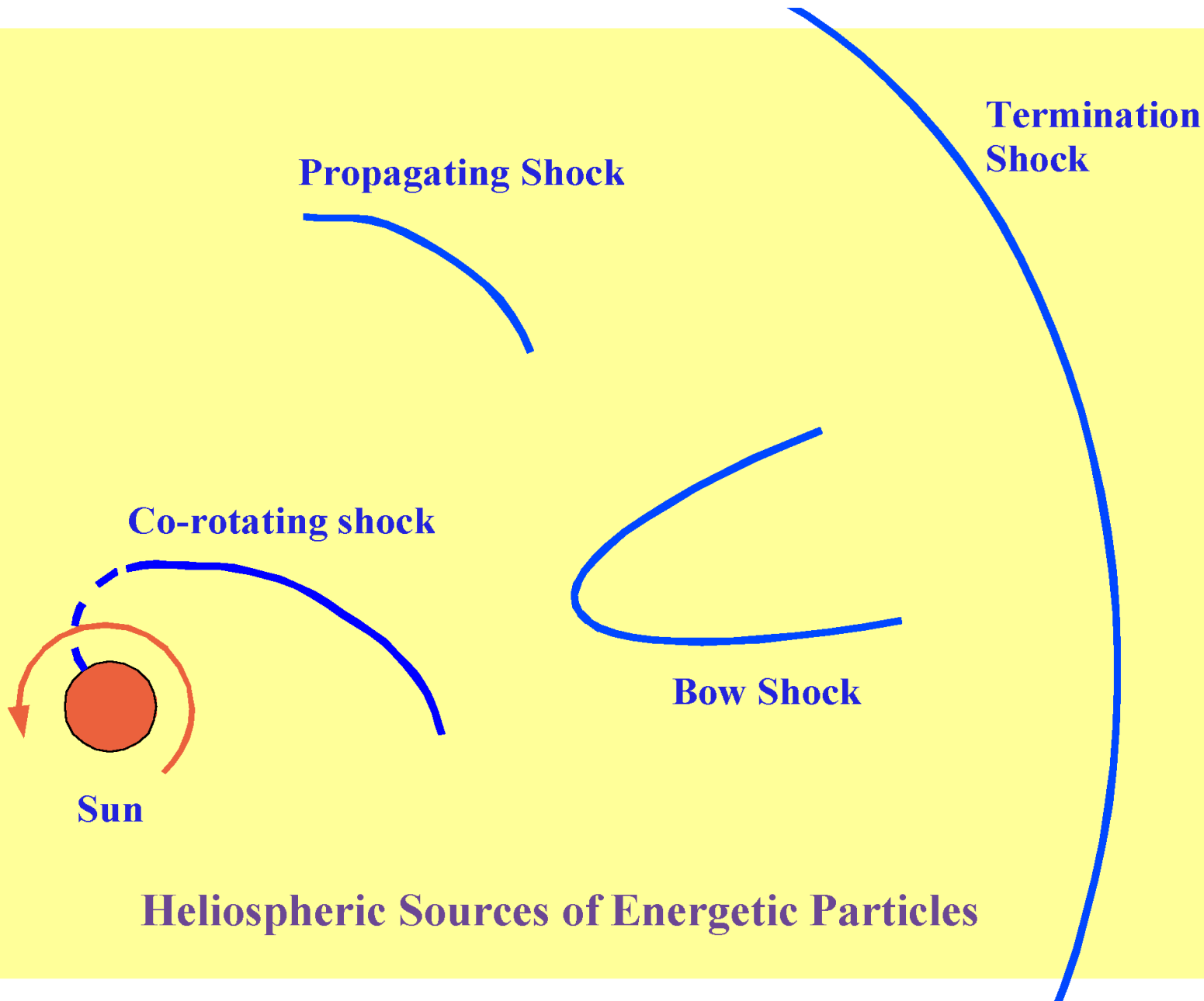
- Diffusion: caused by the scattering of the cosmic rays by the irregularities in the magnetic field. The associated diffusion  $\kappa_{ij}$  is significantly larger along the magnetic field than normal to it.
- Convection: Outward from the Sun at the solar wind velocity  $\mathbf{U}$ .
- Guiding-center drifts: given in terms of the average magnetic field  $B_0$ , the particle charge  $q$  by
$$V_d = pcw/3q) \nabla \times \sim ( \mathbf{B}_0/|B_0|^2)$$
- Energy Change: caused by expansion/compression of the background fluid  $\nabla \cdot \mathbf{U}$

# The Parker Transport Equation:

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

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

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



**Propagating Shock**

**Termination Shock**

**Co-rotating shock**

**Bow Shock**

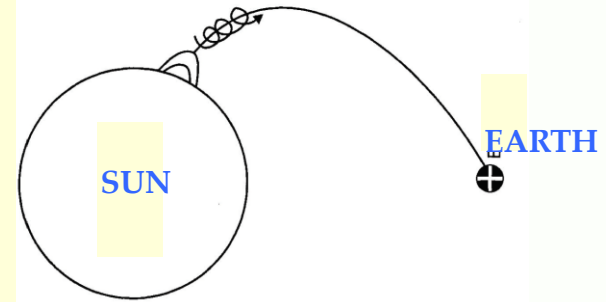
**Sun**

**Heliospheric Sources of Energetic Particles**

# Solar-Energetic Particle (SEP) Paradigms

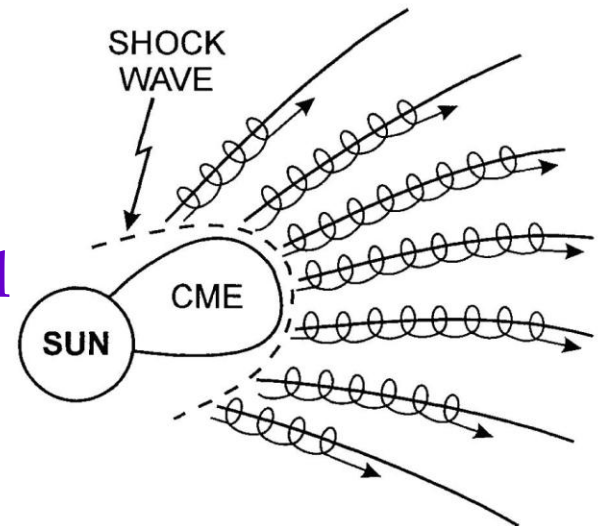
The initial view was that ALL SEPs originated from flares

Impulsive Events



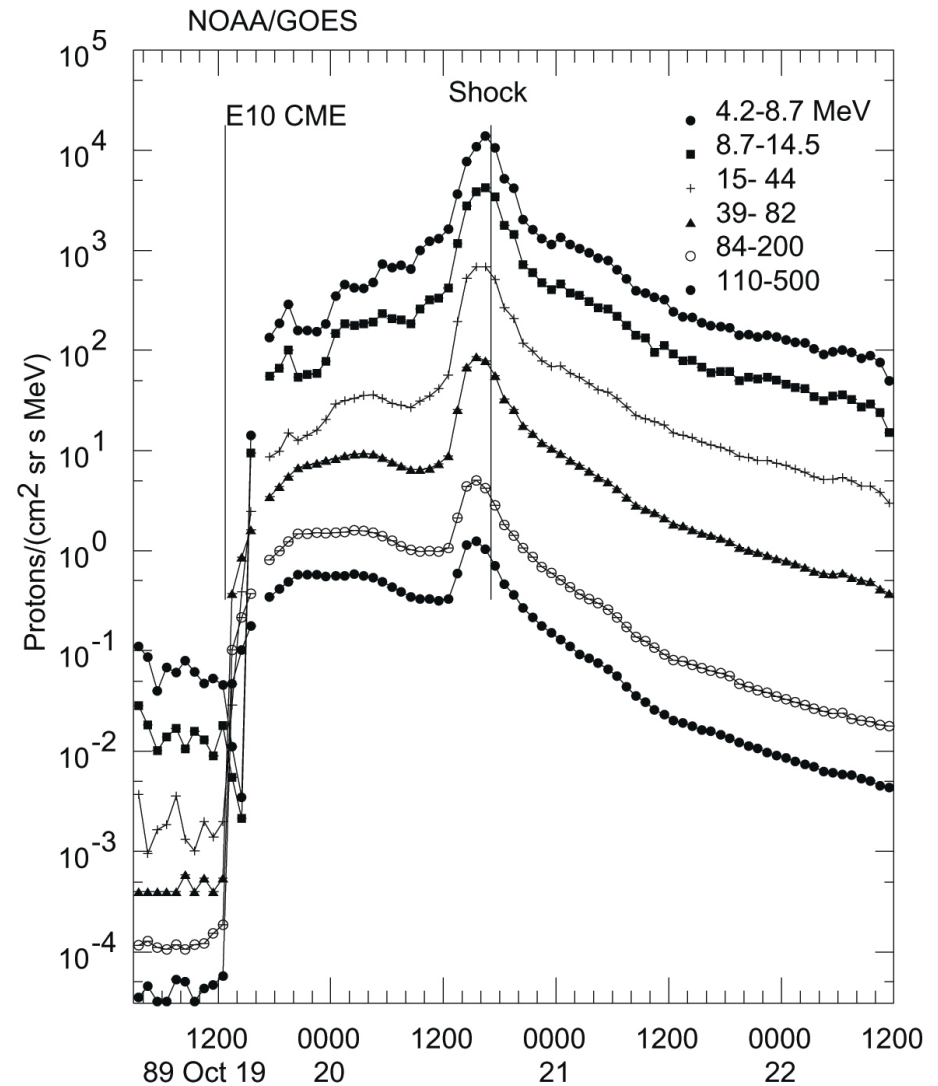
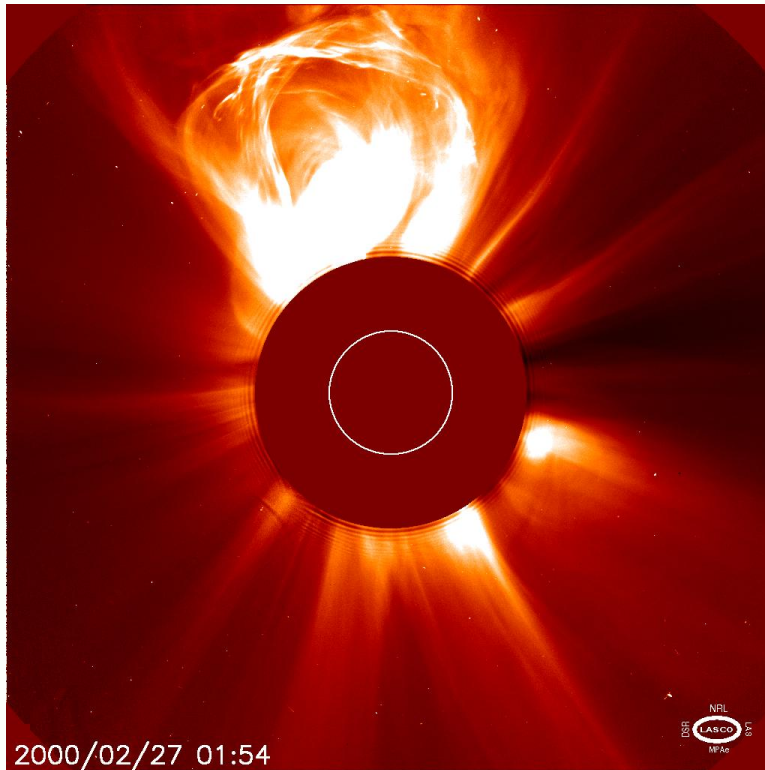
In the early-mid 1990's, the two-class paradigm was suggested

Gradual Events





# Large CME-related SEP events



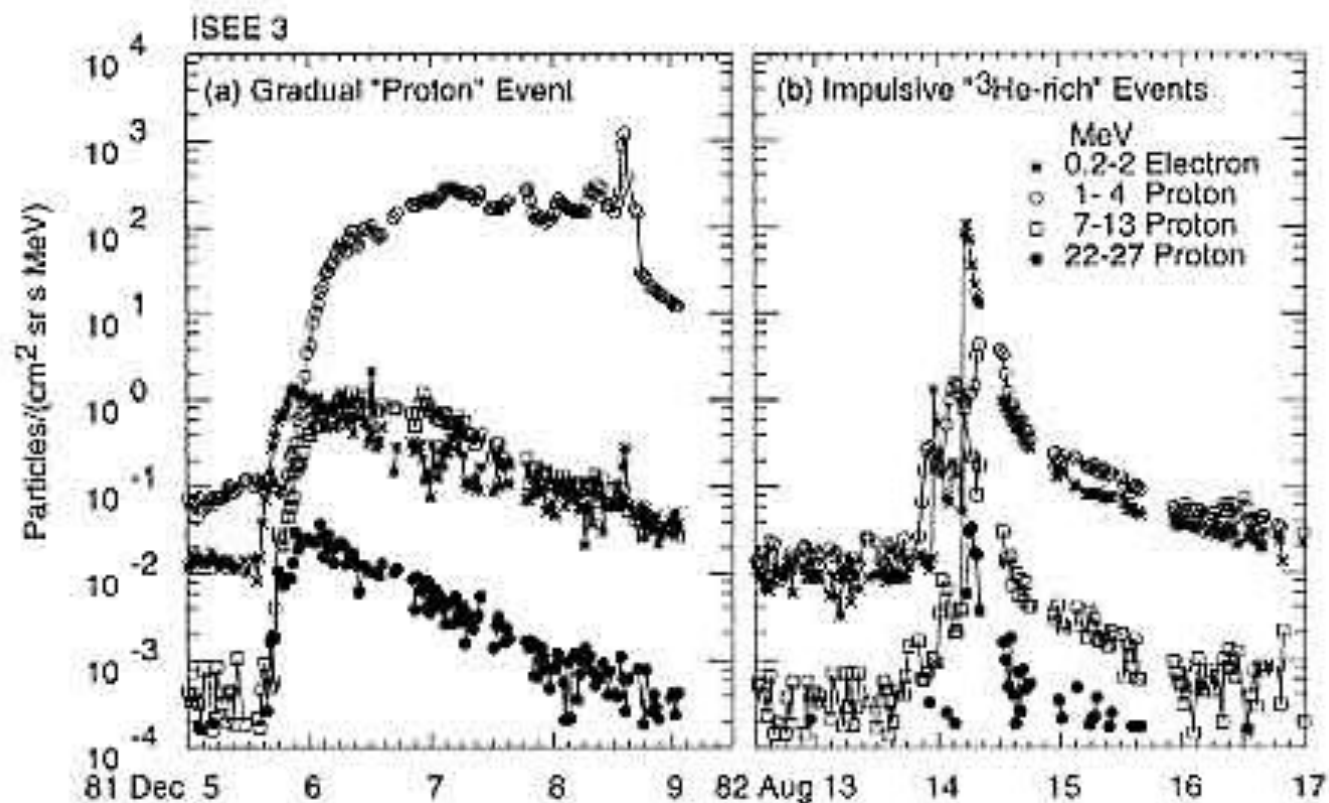
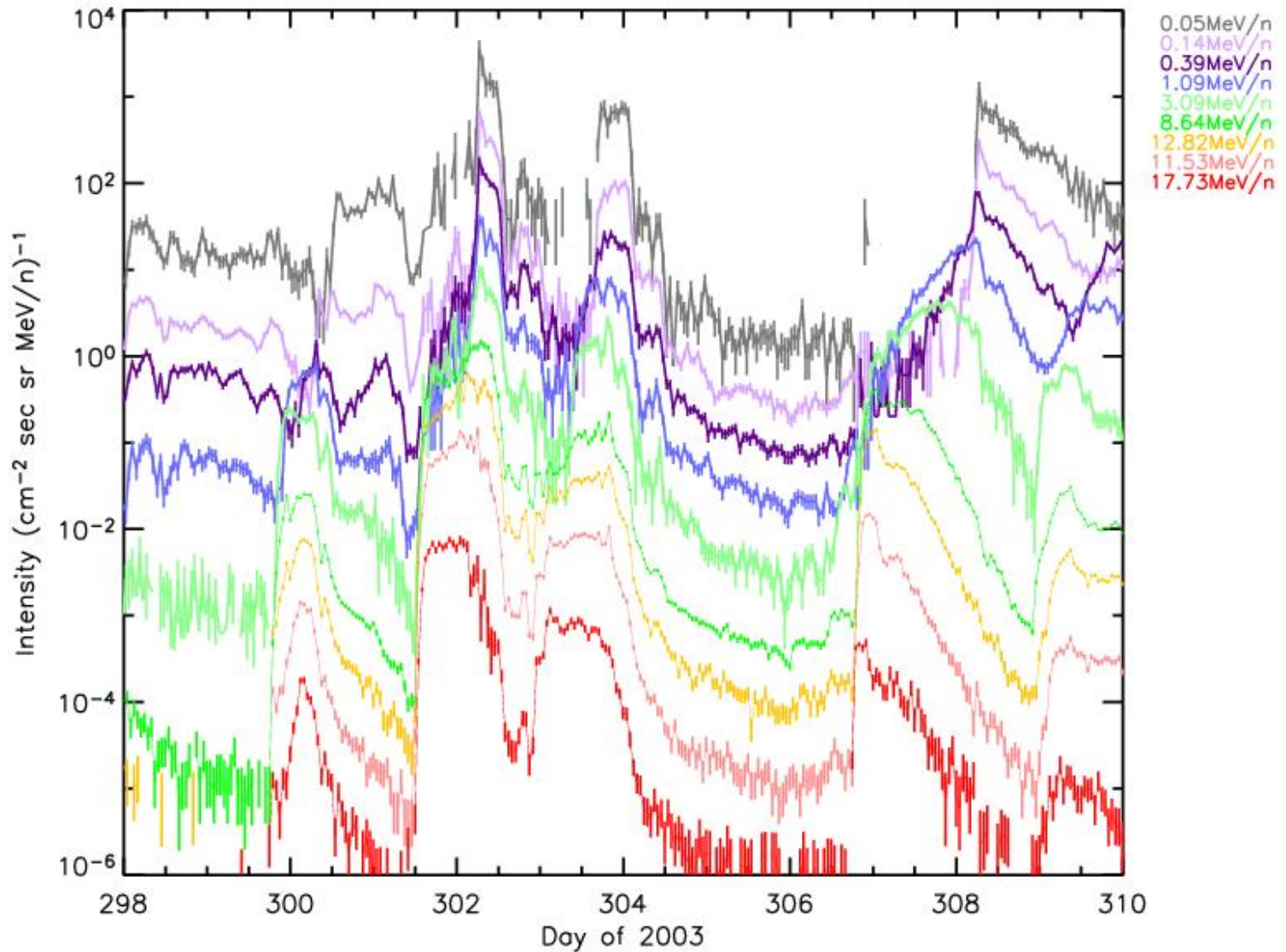
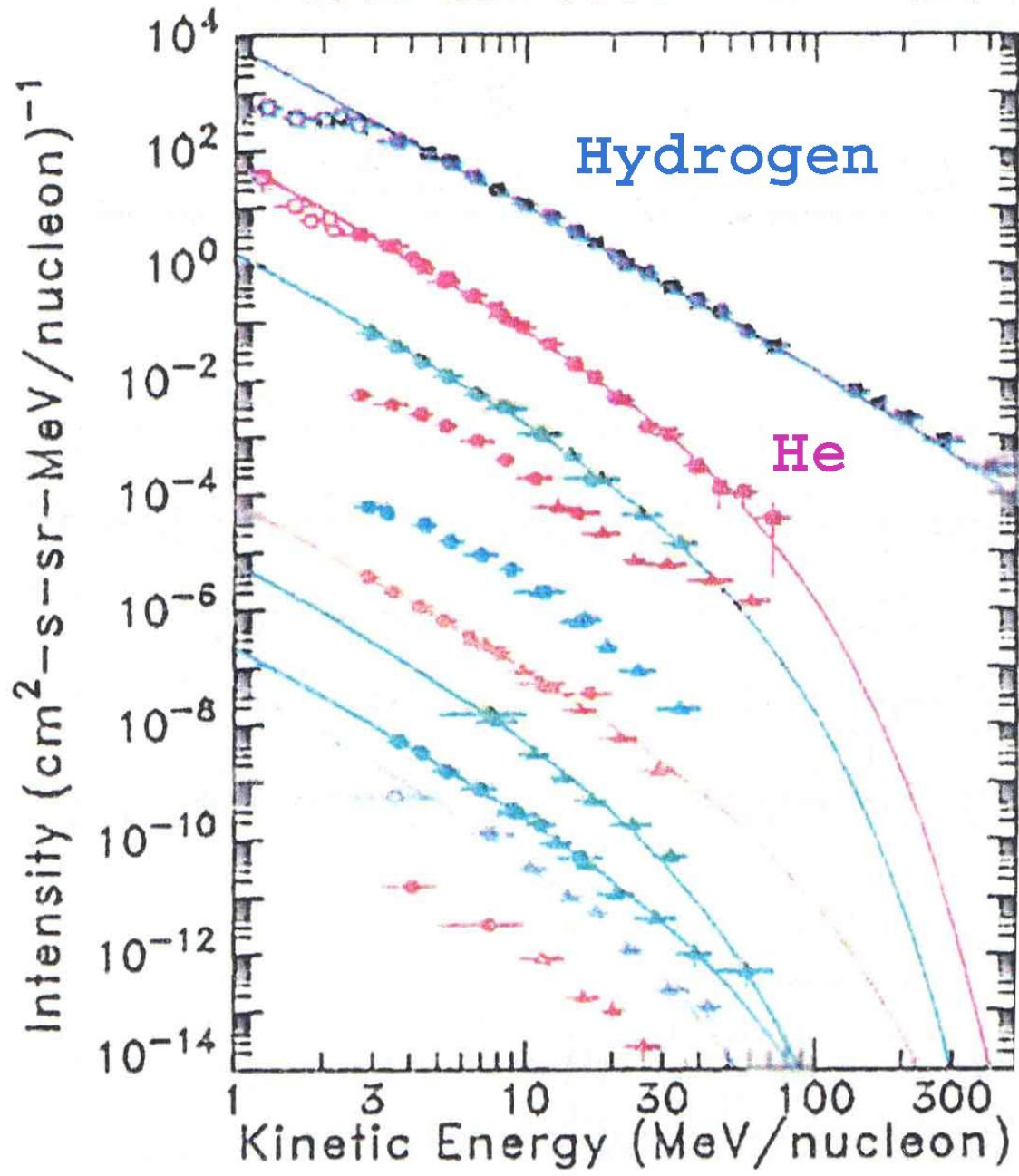


Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.

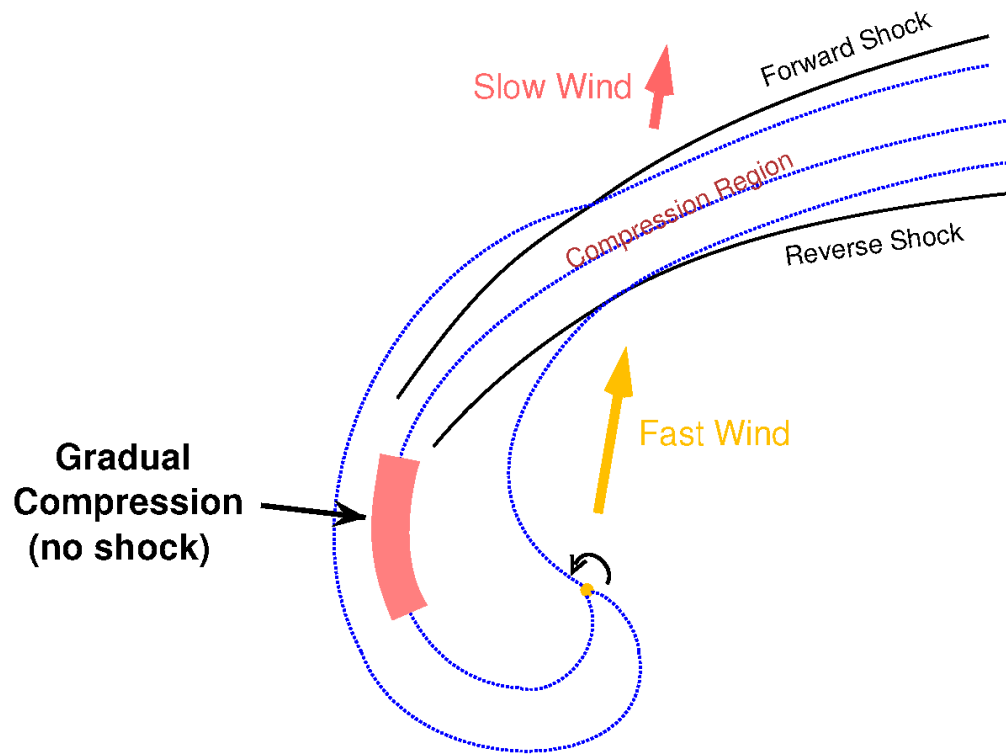
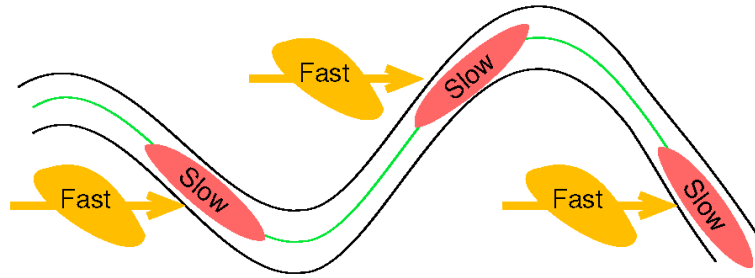
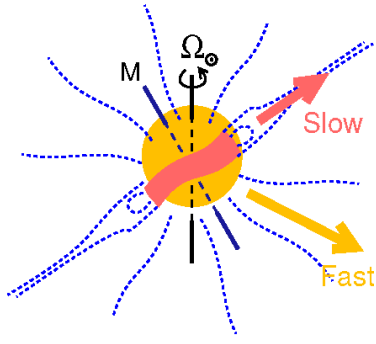
# ACE Observations (1AU)



1998 237 0300 - 237 1059

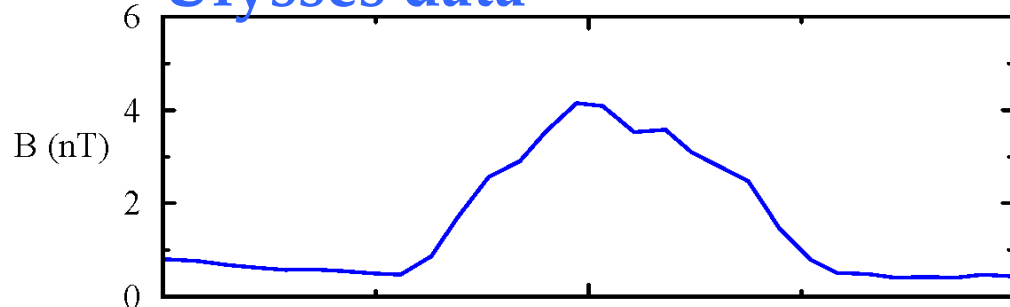


# Co-rotating Interaction Regions

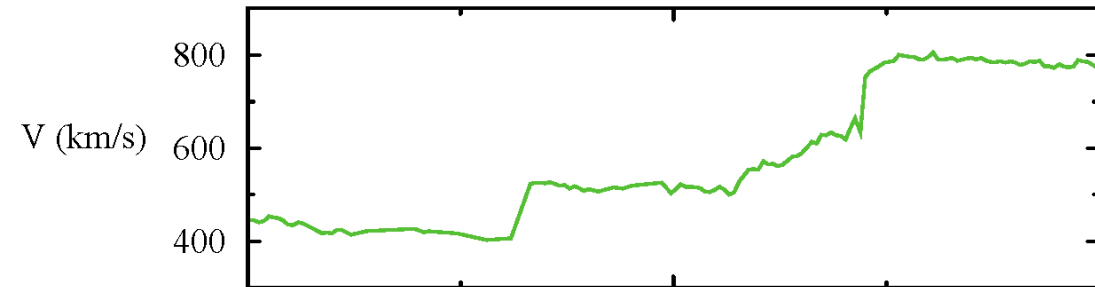


# Corotating Interaction Regions

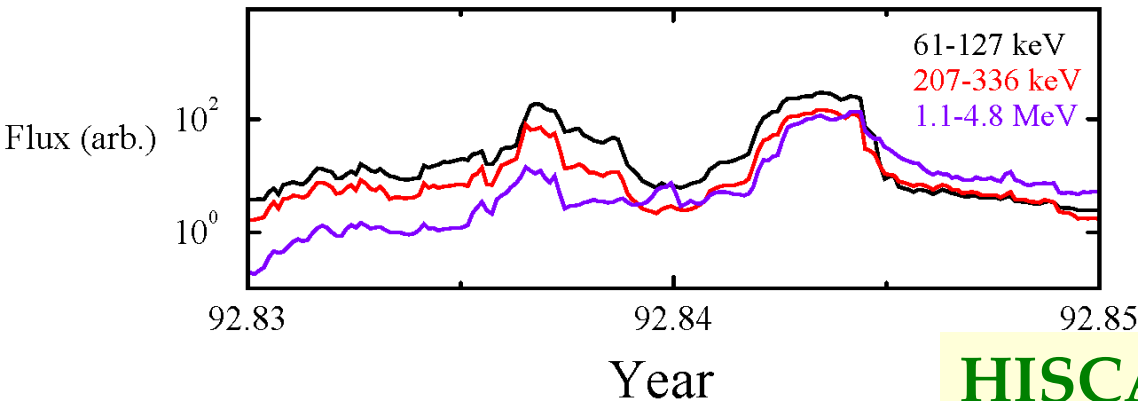
## Ulysses data



Compression of the magnetic field within CIR



Slow, intermediate, and fast wind and both a Forward (F) and Reverse (R) shock.



Energetic Particles peaking at the F/R shocks, with a large increase in intensity at the reverse shock

HISCALE data courtesy Tom Armstrong

- These all contribute to the energetic-particle environment at Earth.
- But important effects comes from energies  $\gtrsim 100$  MeV and higher. These are primarily galactic cosmic rays, coming into the heliosphere from the galaxy.
- Below some  $10^{13}$  eV, they are significantly modified by the heliosphere.
- Galactic cosmic rays  $\approx 100$  MeV-10GeV will be the focus of the rest of this lecture.

# Interstellar Causes of Cosmic-Ray Variations?

- Two Kinds - the Earth could pass through cosmic-ray variations in its motion through the interstellar medium, or dynamical variations in the interstellar gas could cross the solar system.
- Such 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  $\kappa$  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  $L^2 / \kappa \gg L / V_E$ .
- Setting  $V_E \approx 20$  km/sec and  $\kappa = (1/3) \lambda c$ , where  $\lambda$ , the diffusion mean free path  $\gg$  cosmic-ray gyro-radii, we find that  $L \gg 3 \times 10^{17}$  cm, which would be crossed by Earth in  $\gg 10^5$  yrs.



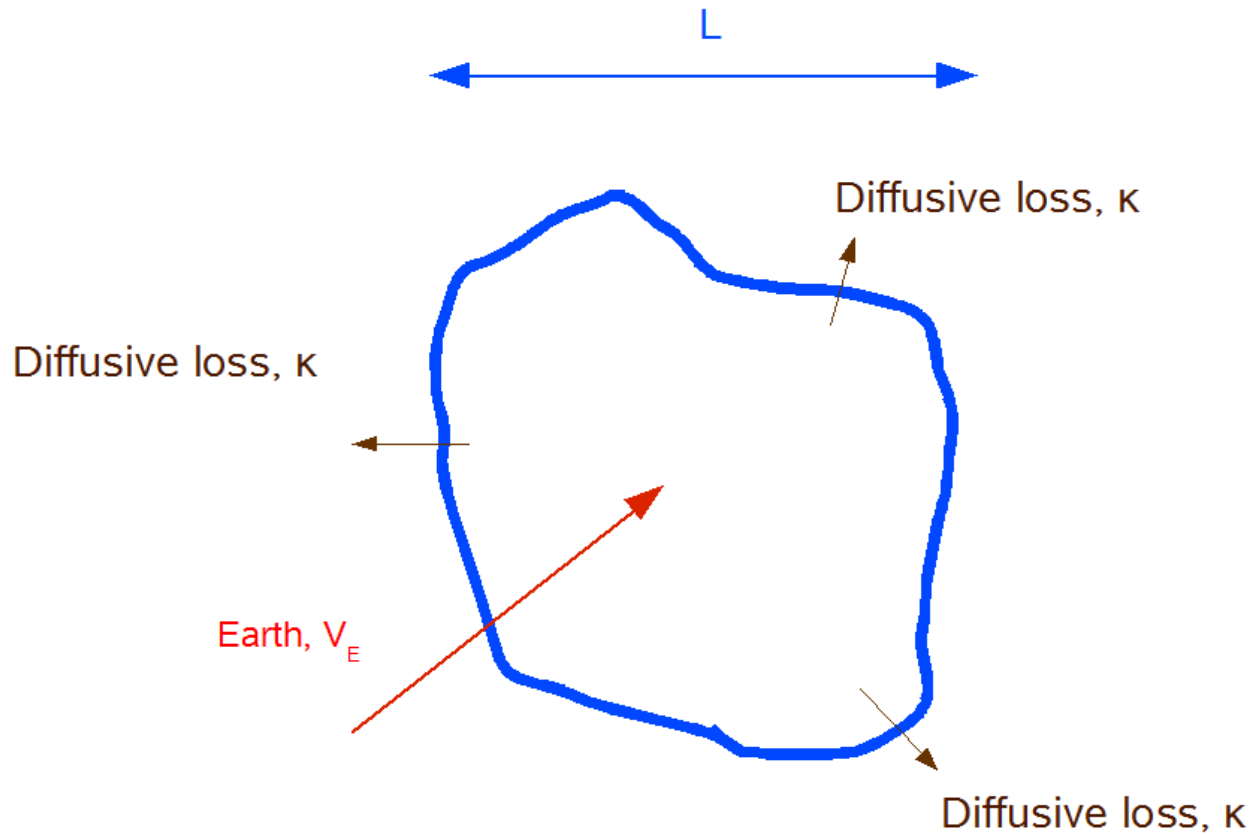


Illustration of the Earth passing through a quasi-static region of spatial scale  $L$ . The diffusive loss time is  $\approx L^2/\kappa$ . The Earth passes through the region in  $\approx L/V_E$ .

# Effects of the Heliosphere on the Local Interstellar medium?

- It is likely that the heliosphere affects the environment in the local interstellar medium, to several hundreds of AU.
- The effects depend on the poorly determined transport parameters in the LISM. These effects have not been much addressed in the published literature.
- This effect has not been studied to any significant degree.

An important parameter in this is  $\nu_{ism}$  the diffusion coefficient in the local ISM. There are two important dimensionless parameters which will determine the nature of the boundary condition. They are

$$\tau(T) = \frac{R_{\alpha} V_{ISM}}{\nu_{ISM}} \quad (1)$$

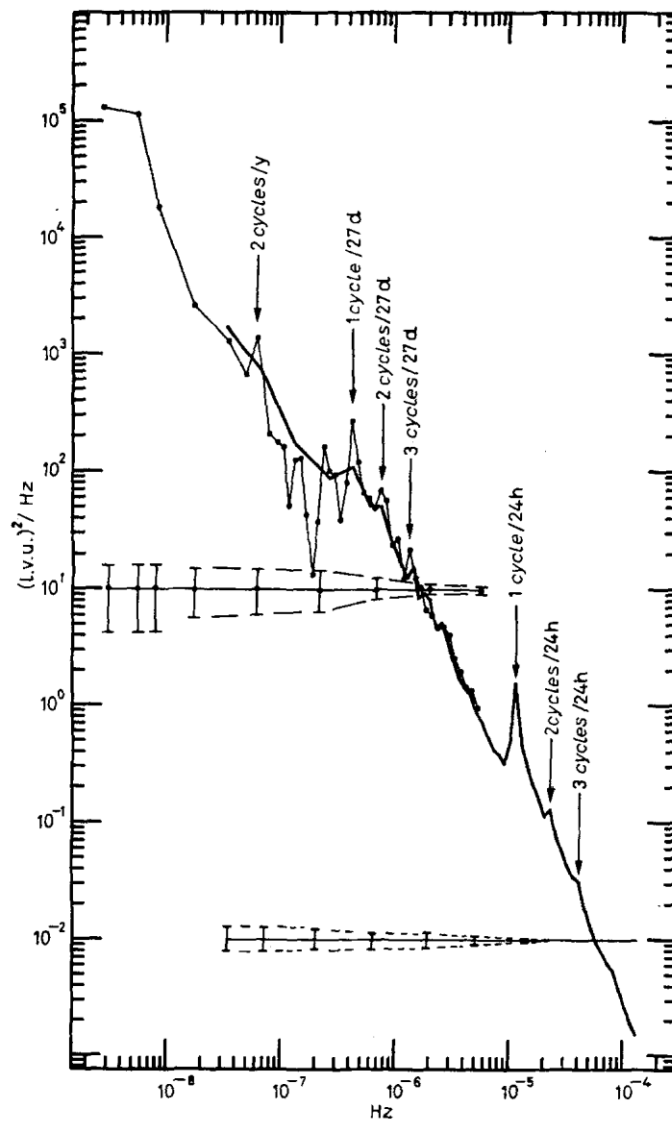
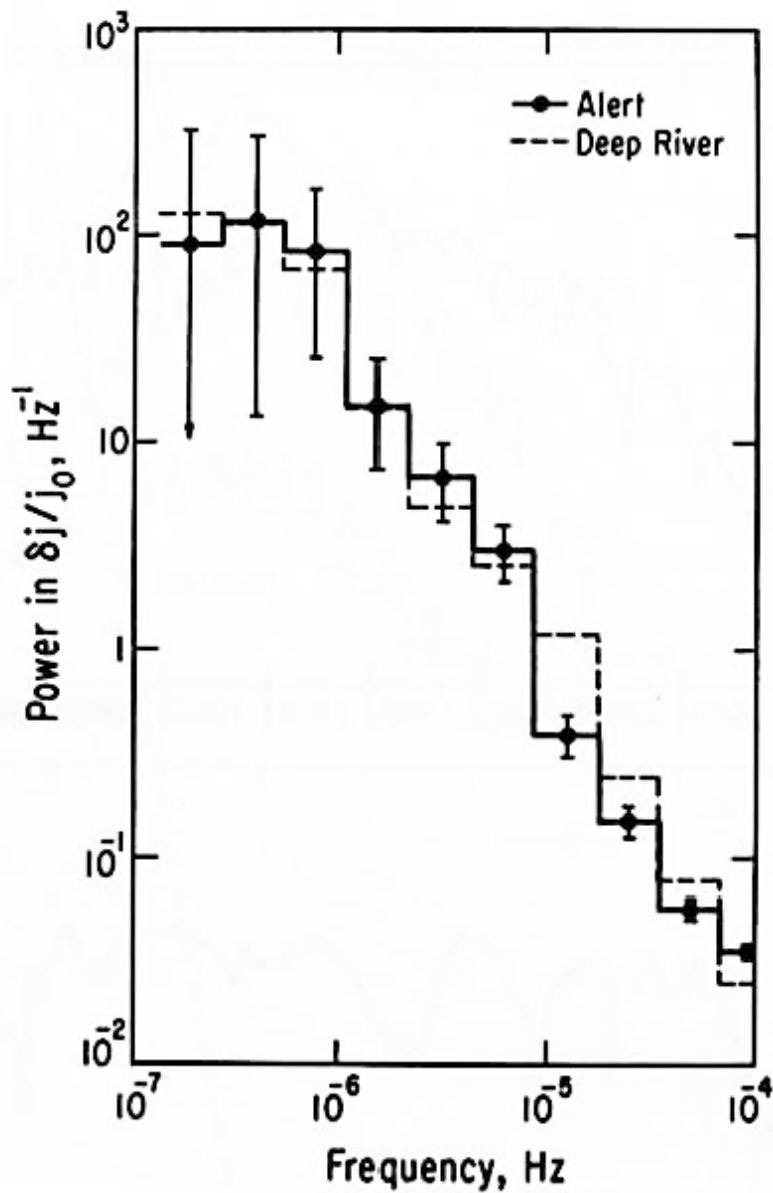
and

$$r(T) = \frac{\nu_{HS}}{\nu_{ISM}} \quad (2)$$

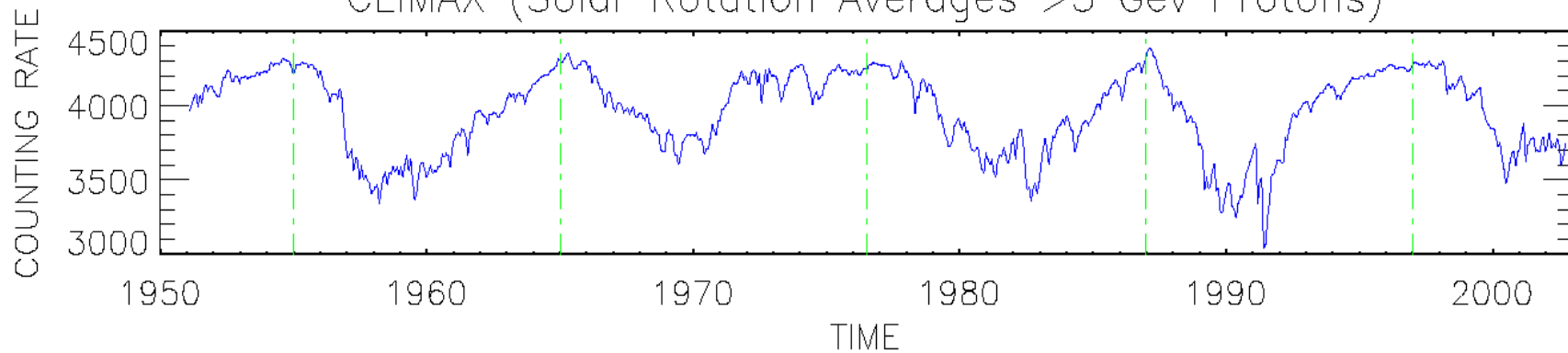
It is readily seen that if  $\nu_{ISM}$  is large enough that both  $\tau(T)$  and  $r(T)$  are much less than unity, the diffusion in the local ISM is very rapid, and the boundary may be taken to be the standard "free escape" boundary at the heliopause.

# Heliospheric Causes of Galactic Cosmic-Ray Variations

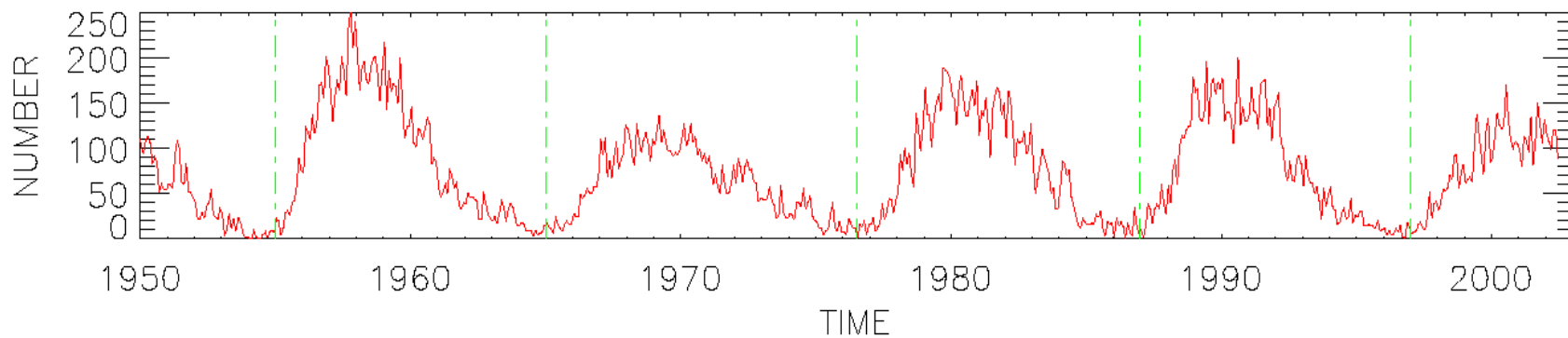
- Variations with scales less than about  $10^5$  years are probably heliospheric in origin.
- These are caused by solar-wind fluctuations and changes in the heliosphere.

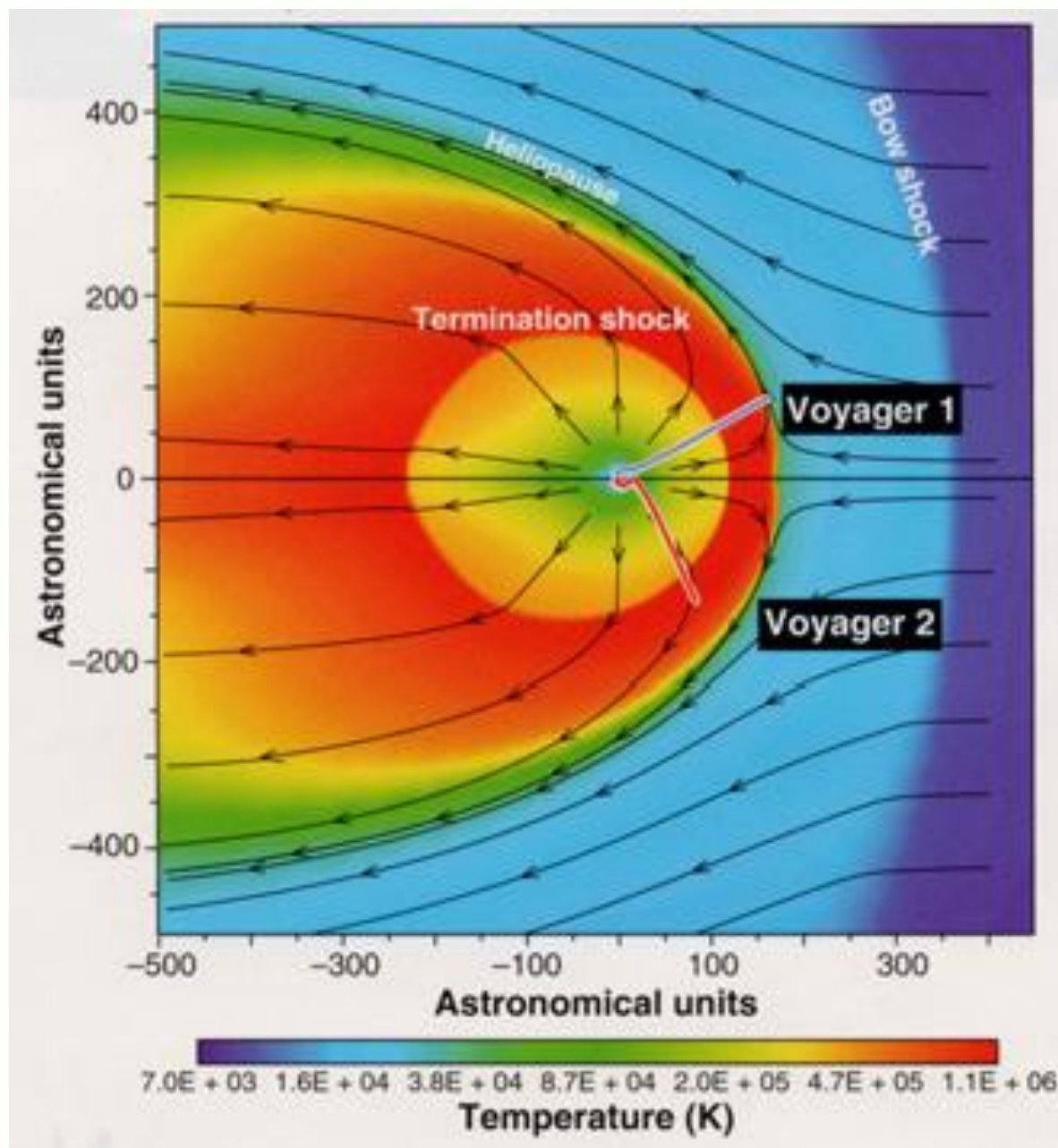


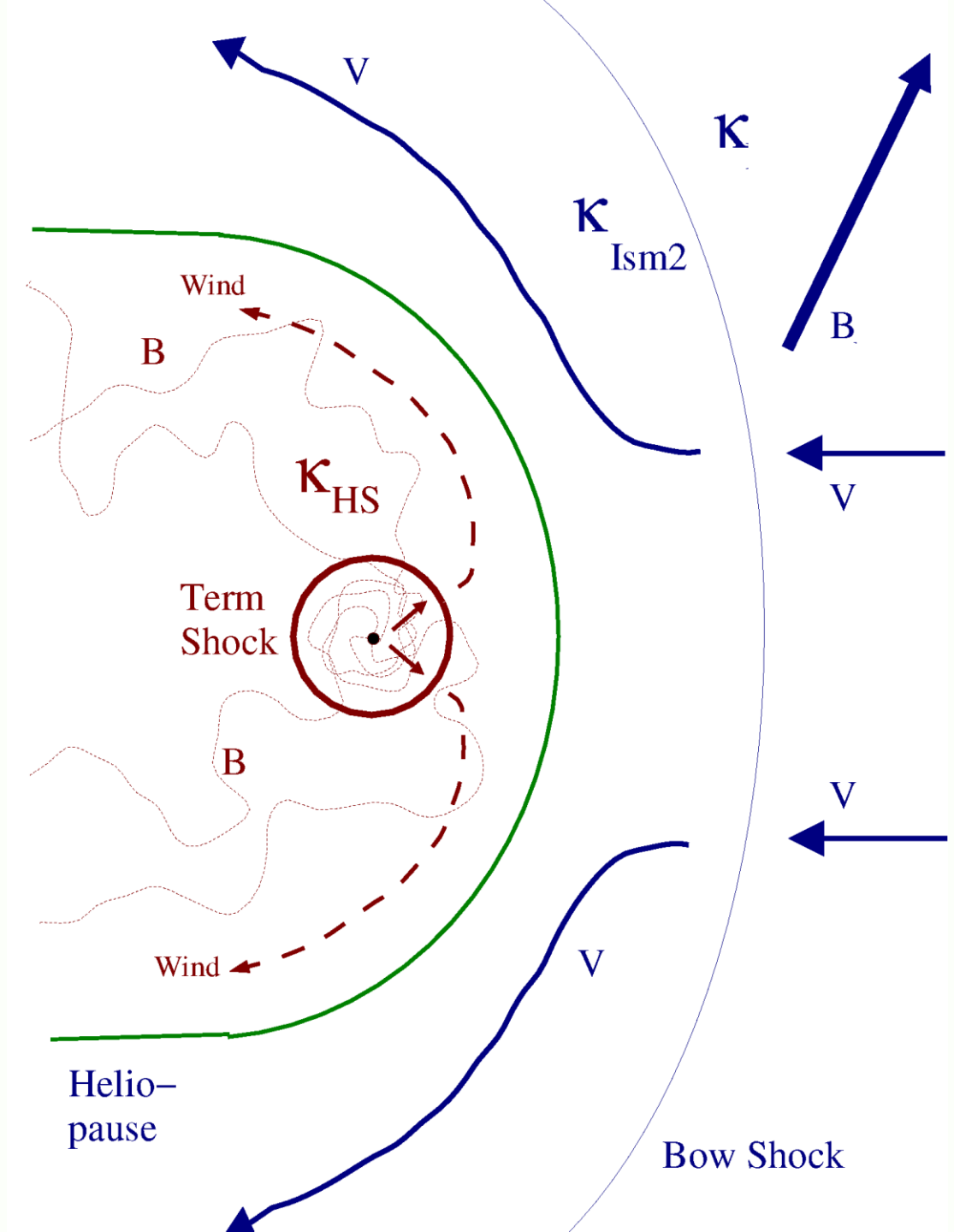
CLIMAX (Solar Rotation Averages  $>3$  Gev Protons)



MONTHLY AVERAGE SUNSPOTS

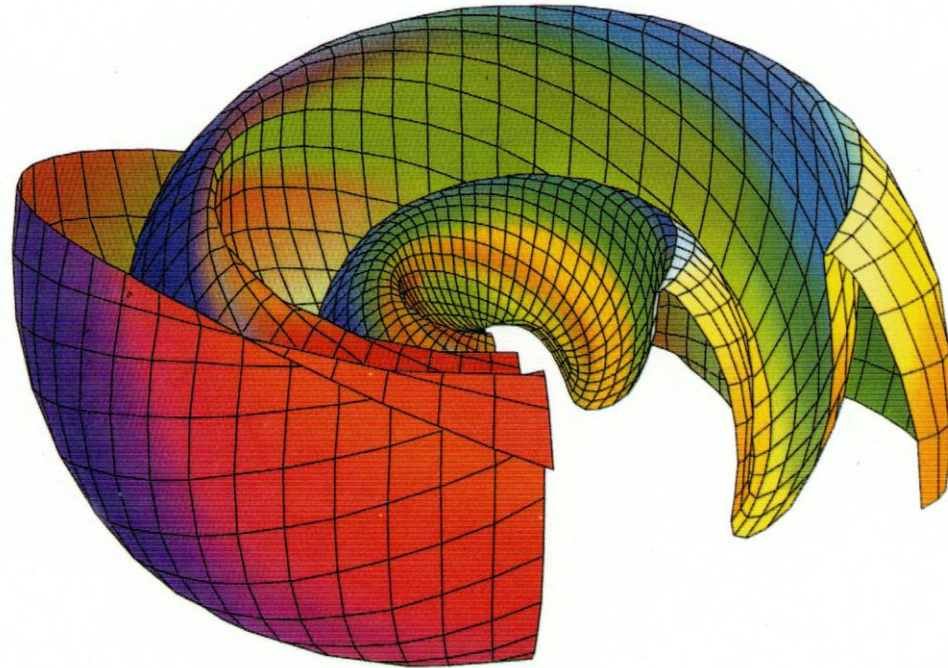




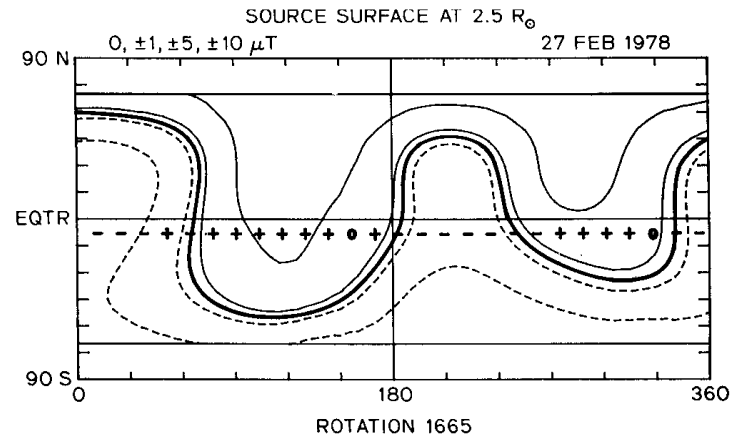
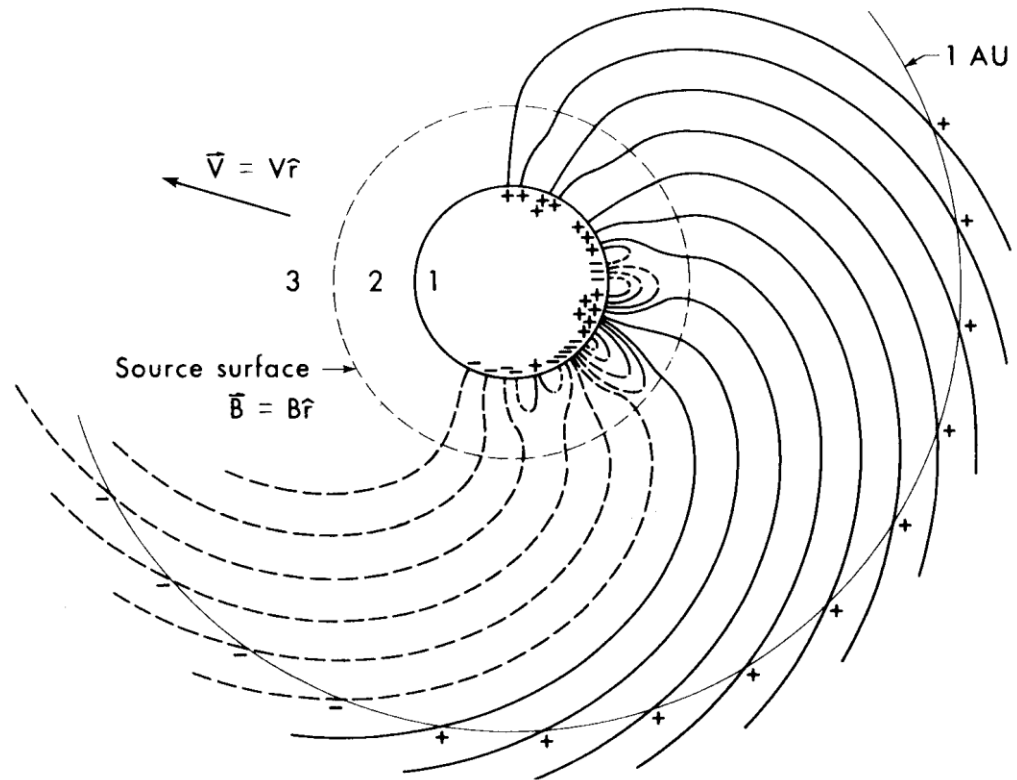




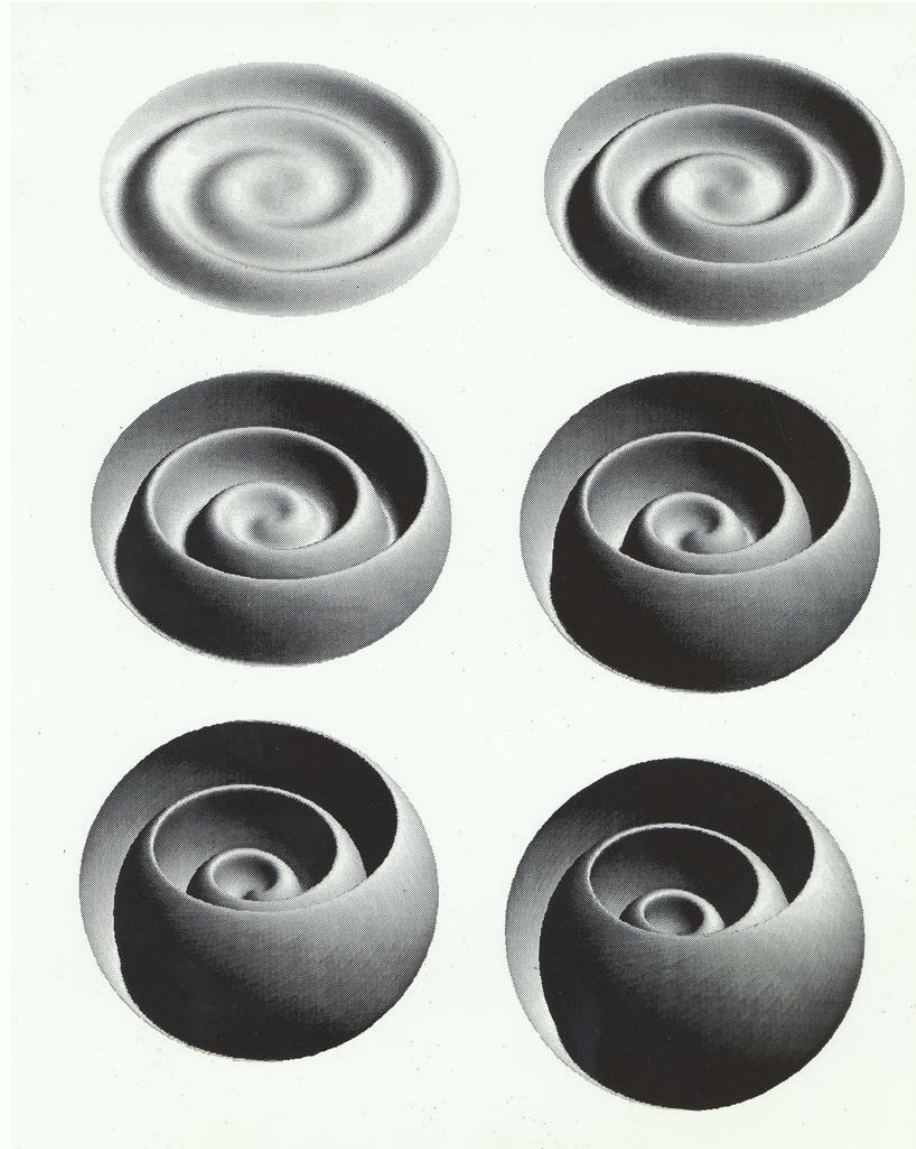
The heliospheric magnetic field for much of a sunspot cycle is organized by the heliospheric current sheet, which separates the northern and southern heliospheric magnetic field.



Magnetic sector structure.



The current sheet changes from sunspot minimum to sunspot maximum



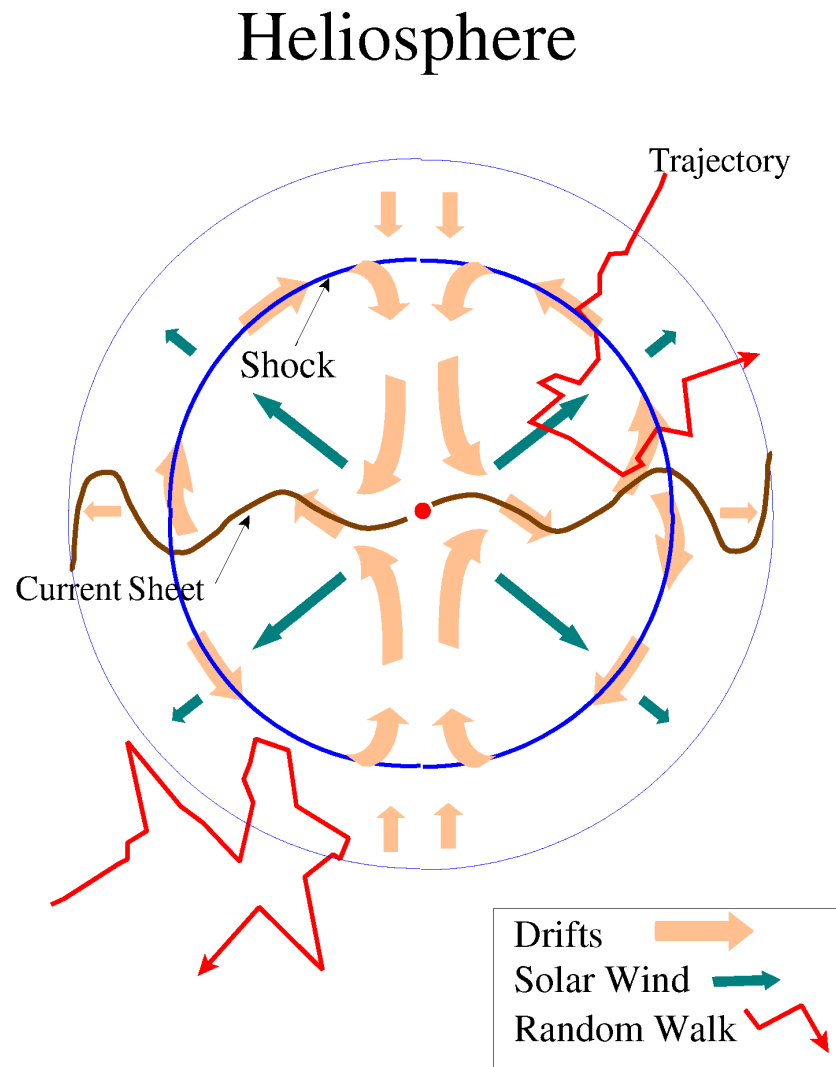
# The Physical Picture of Galactic Cosmic Rays in the Heliosphere

- Because the sense of the particle drift changes from one sunspot cycle to the next, one expects changes in the cosmic-ray intensity and its spatial distribution from one cycle to the next.
- For  $A < 0$ , come inward along current sheet, out toward the poles.
- For  $A > 0$ , inward over the poles and out along the current sheet.
- This leads to differing latitudinal gradients.

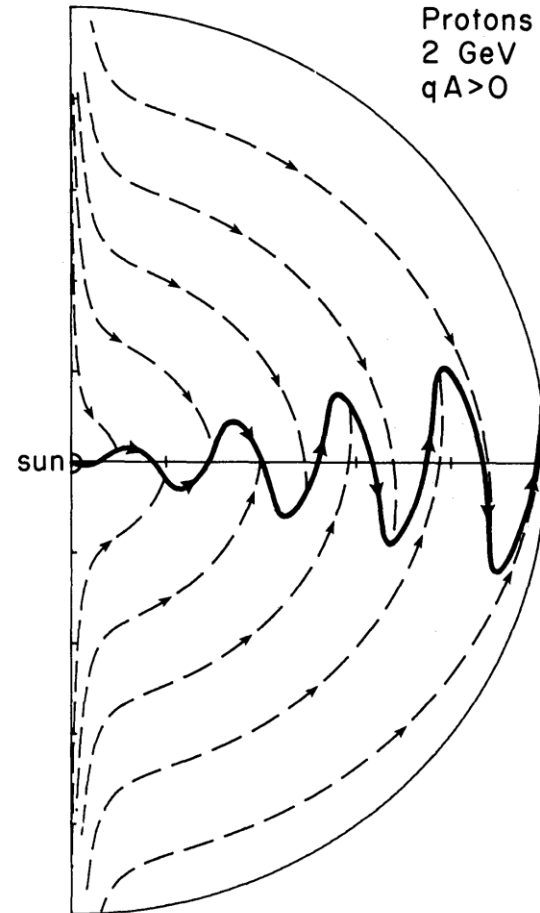
The galactic cosmic rays enter the heliosphere through a combination of diffusion (random walk) and drift.

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

The drift motions are very significant.

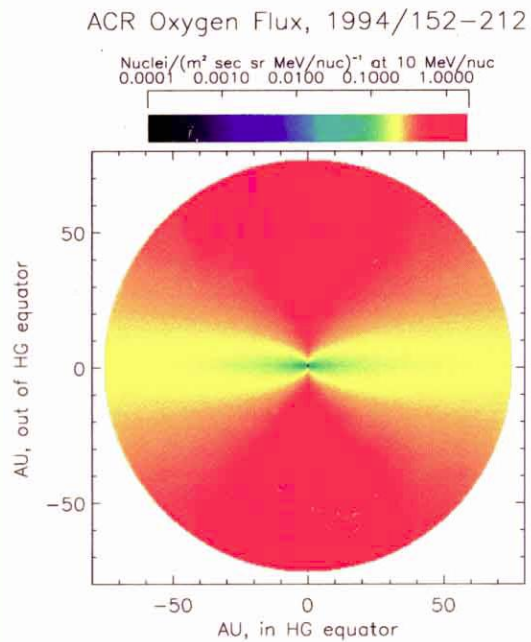


The figure illustrates the gradient and curvature drifts for  $qA > 0$  (northern heliospheric field outward), near sunspot minimum. The direction changes sign for  $qA < 0$ . The result is a 22-year solar magnetic and cosmic-ray cycle.



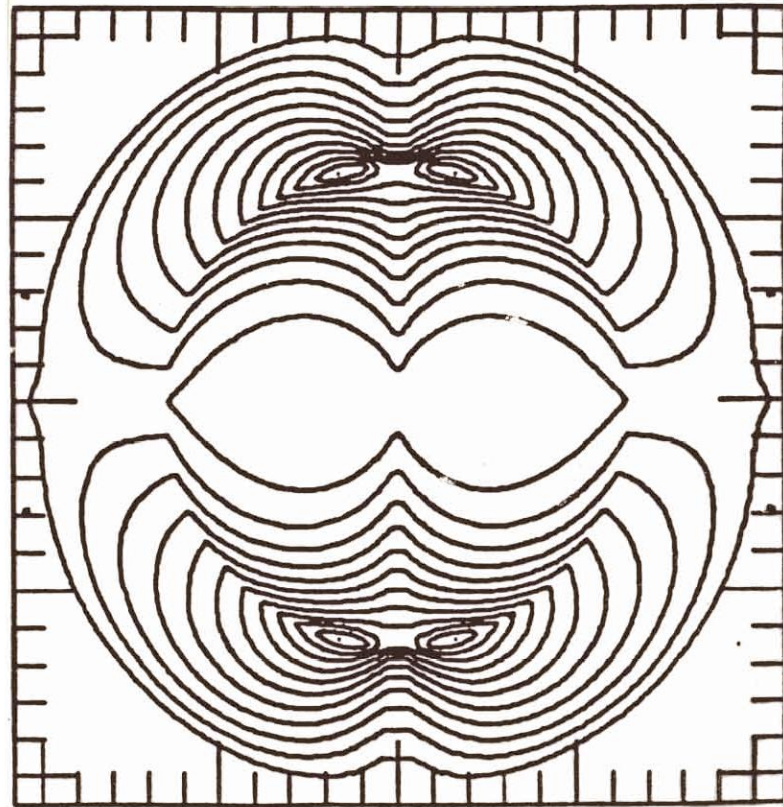
# Illustration of the latitudinal gradients for 1994 ( $A < 0$ )

## Multi-spacecraft observations



## Model Calculation

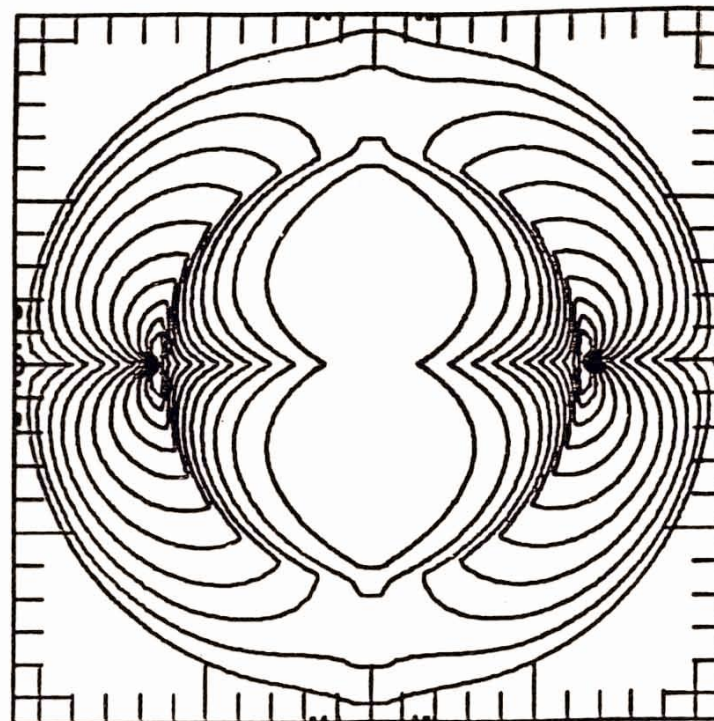
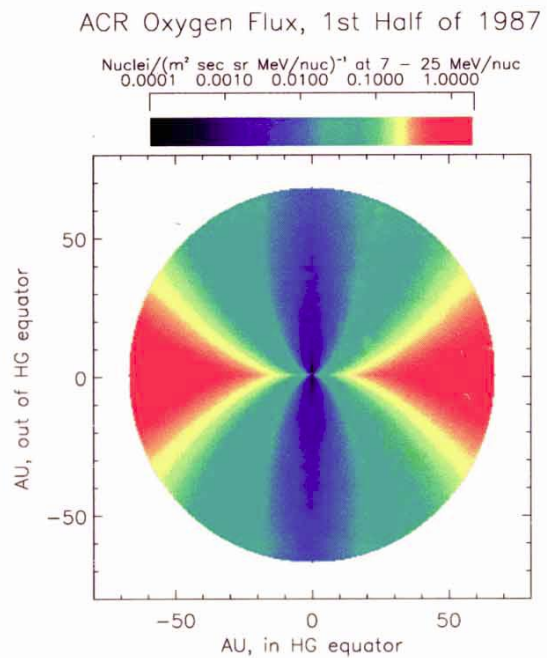
$A > 0$



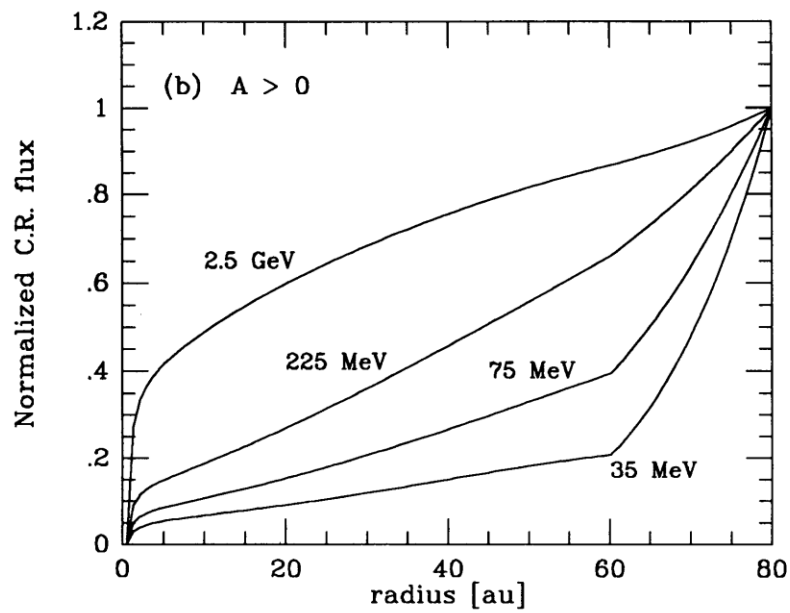
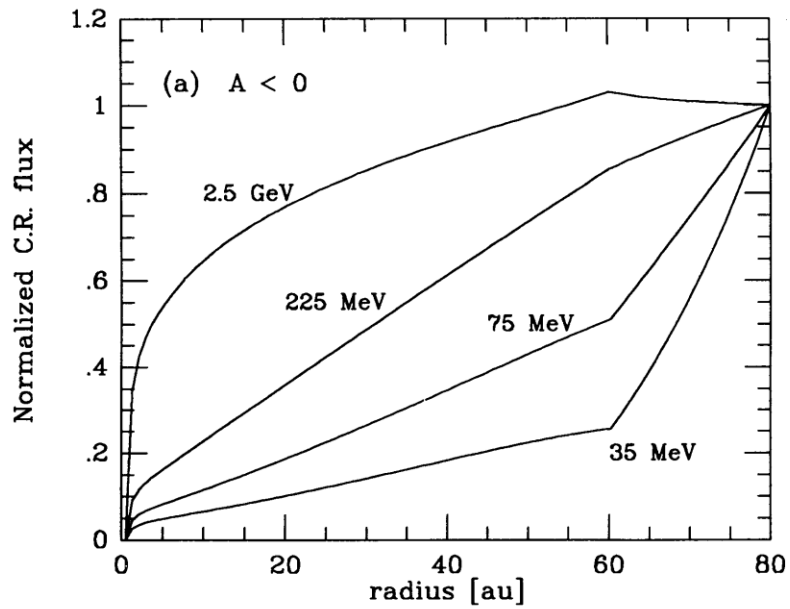
# The latitudinal distribution for $A > 0$

Model Calculation

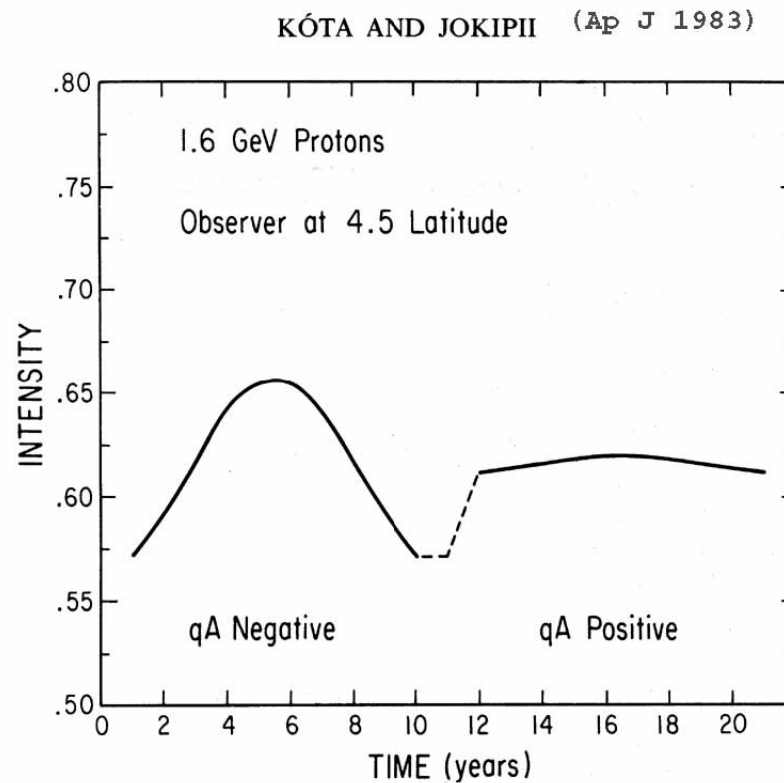
$A < 0$



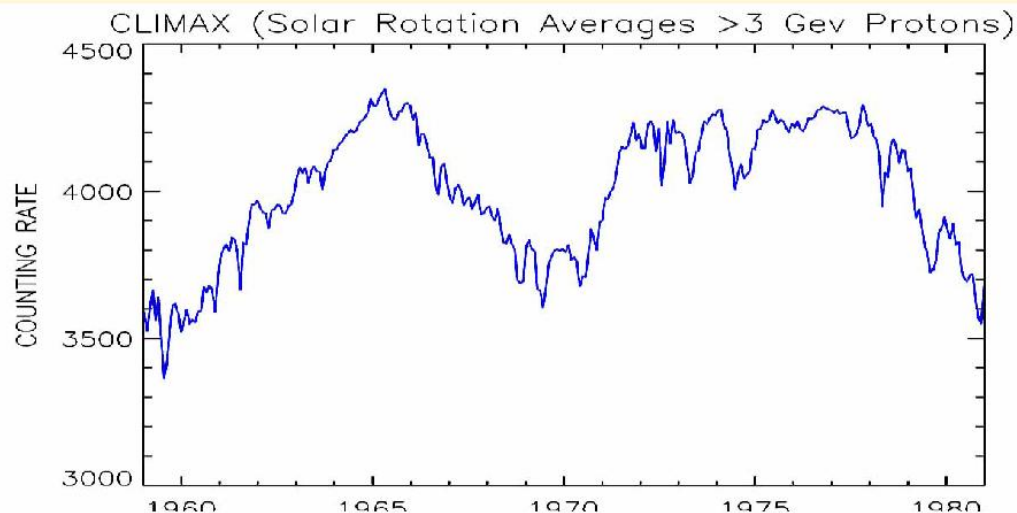




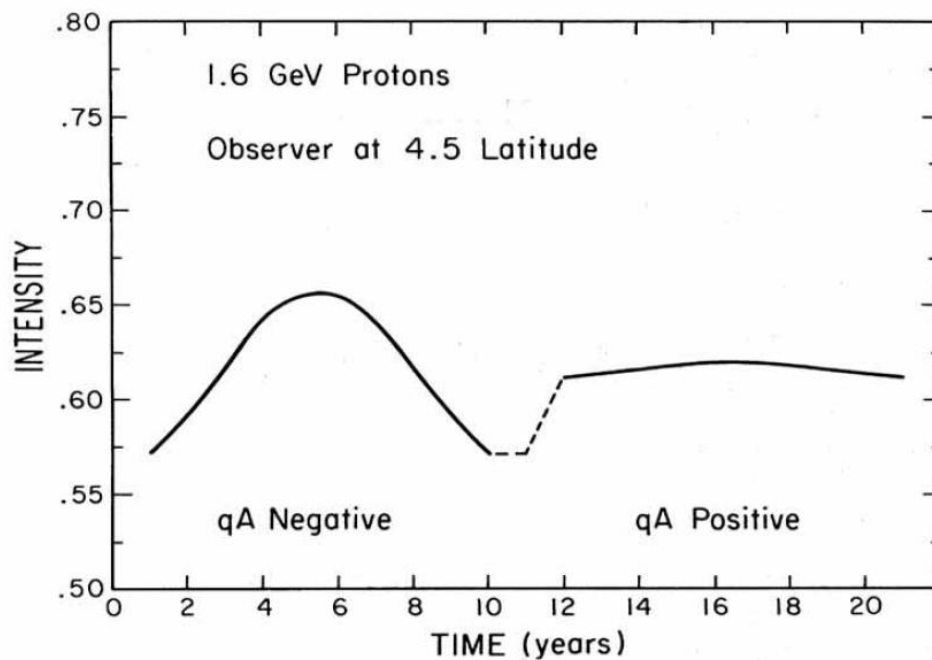
The predicted time variation is also different for the two signs of the magnetic field and associated drift motions.



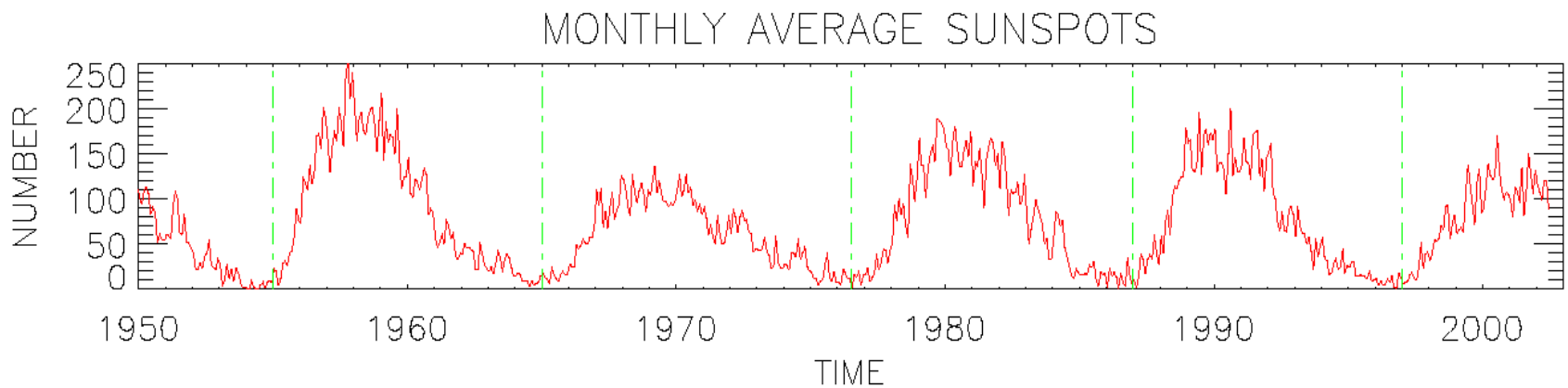
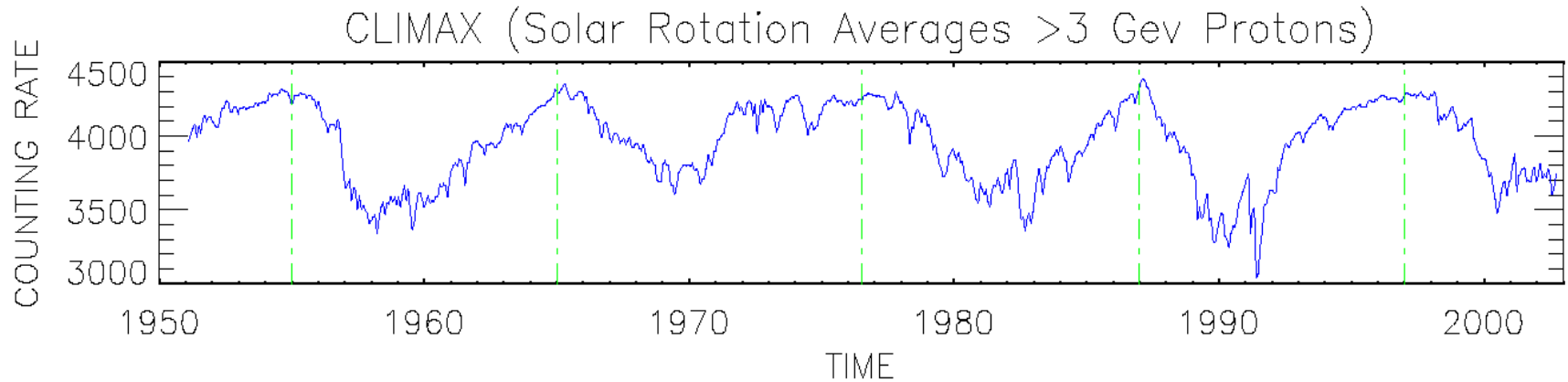
This basic picture provides a robust interpretation of many observations.



KÓTA AND JOKIPII (Ap J 1983)



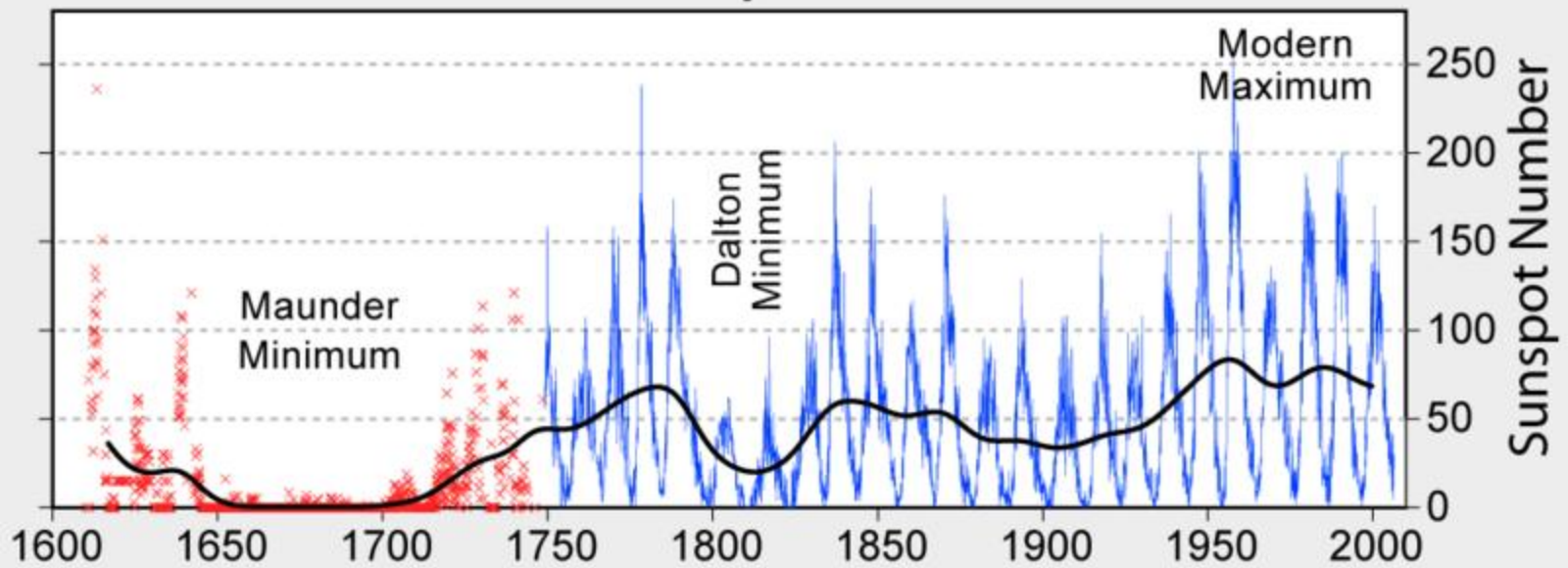
# The variation of $> 3$ Gev protons at Earth and sunspots since 1950.



# Further Back: The Maunder Minimum

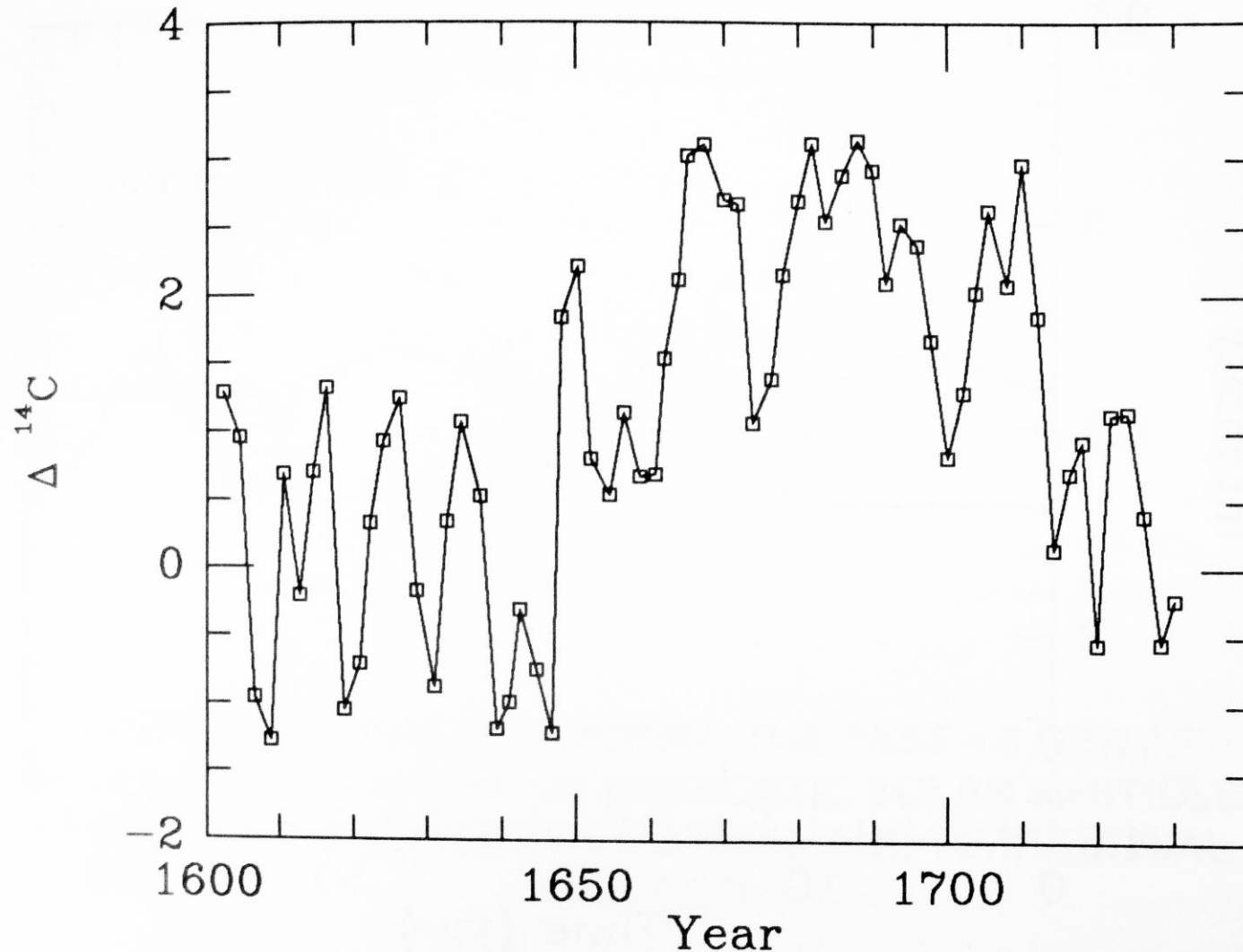
- The Maunder Minimum is the name given to the period spanning roughly the years 1645 to 1715, when sunspots were exceedingly rare.
- It was possibly associated with a period of cold.
- The cosmic rays could only be measured by proxy.

# 400 Years of Sunspot Observations



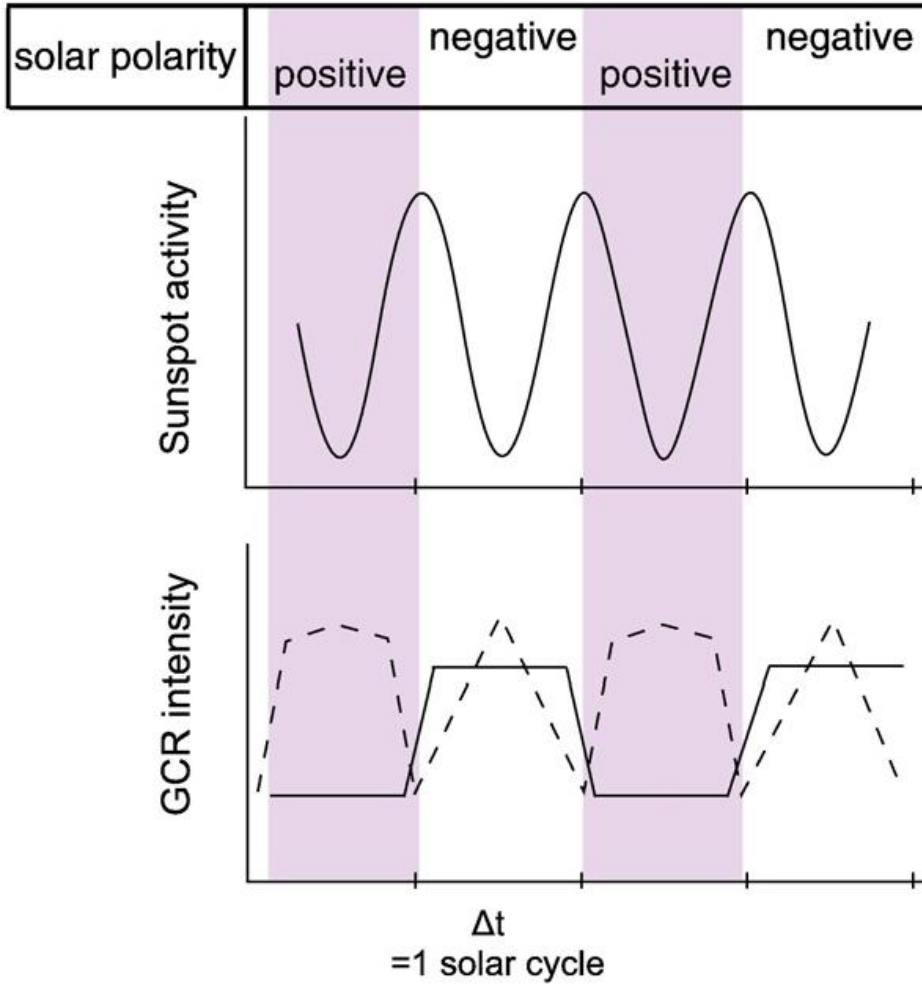
Data from Kocharov (1987) during the Maunder Minimum.  
Note the longer period during the Maunder minimum.

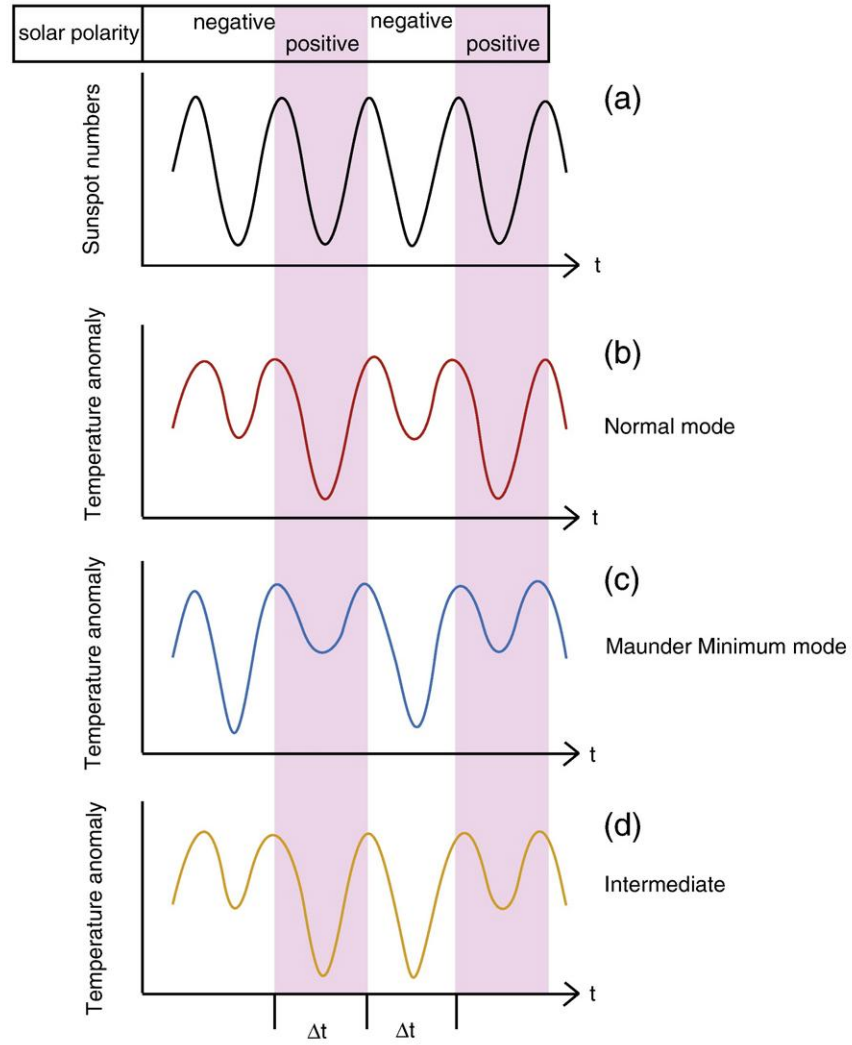
VARIATIONS OF THE COSMIC-RAY FLUX







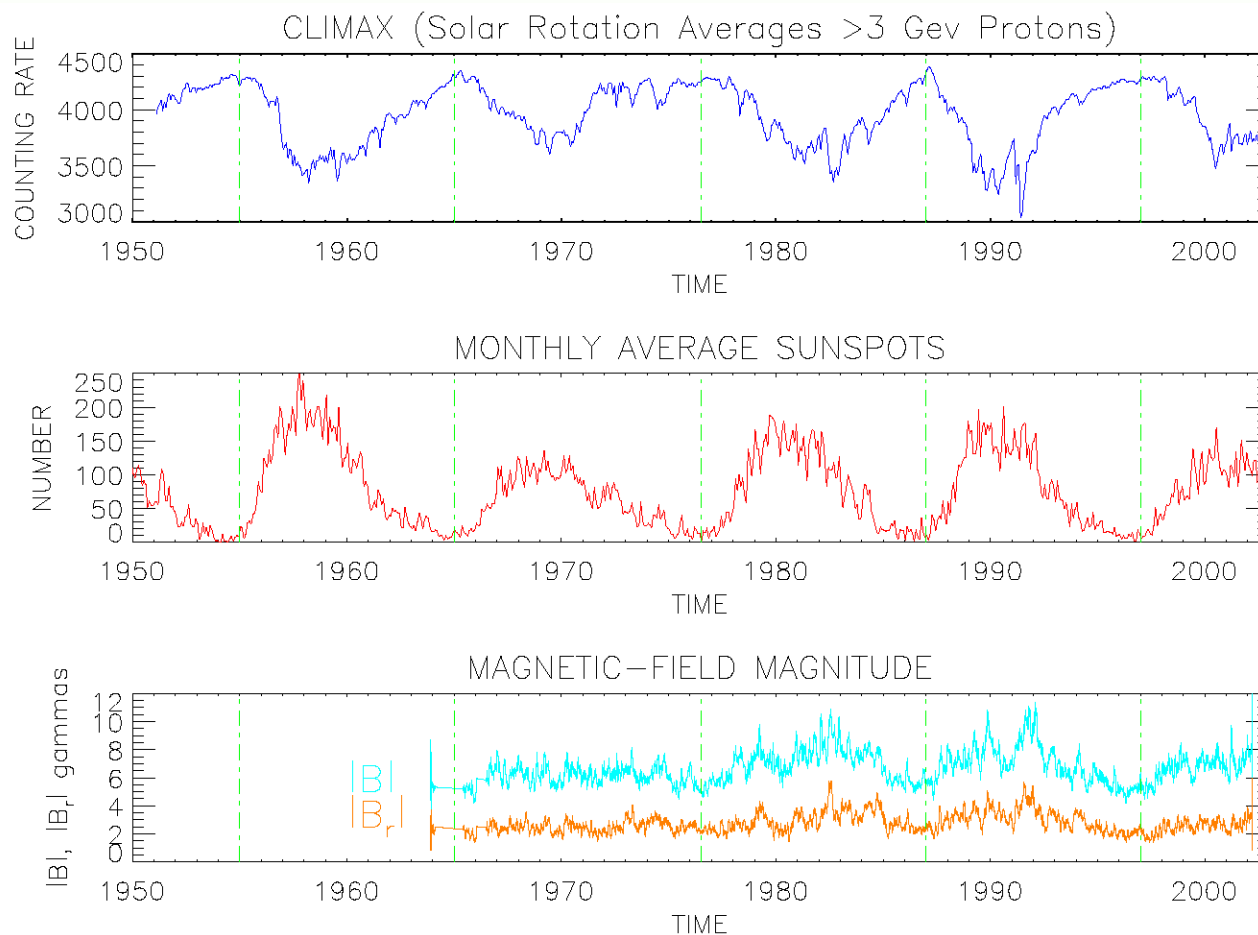




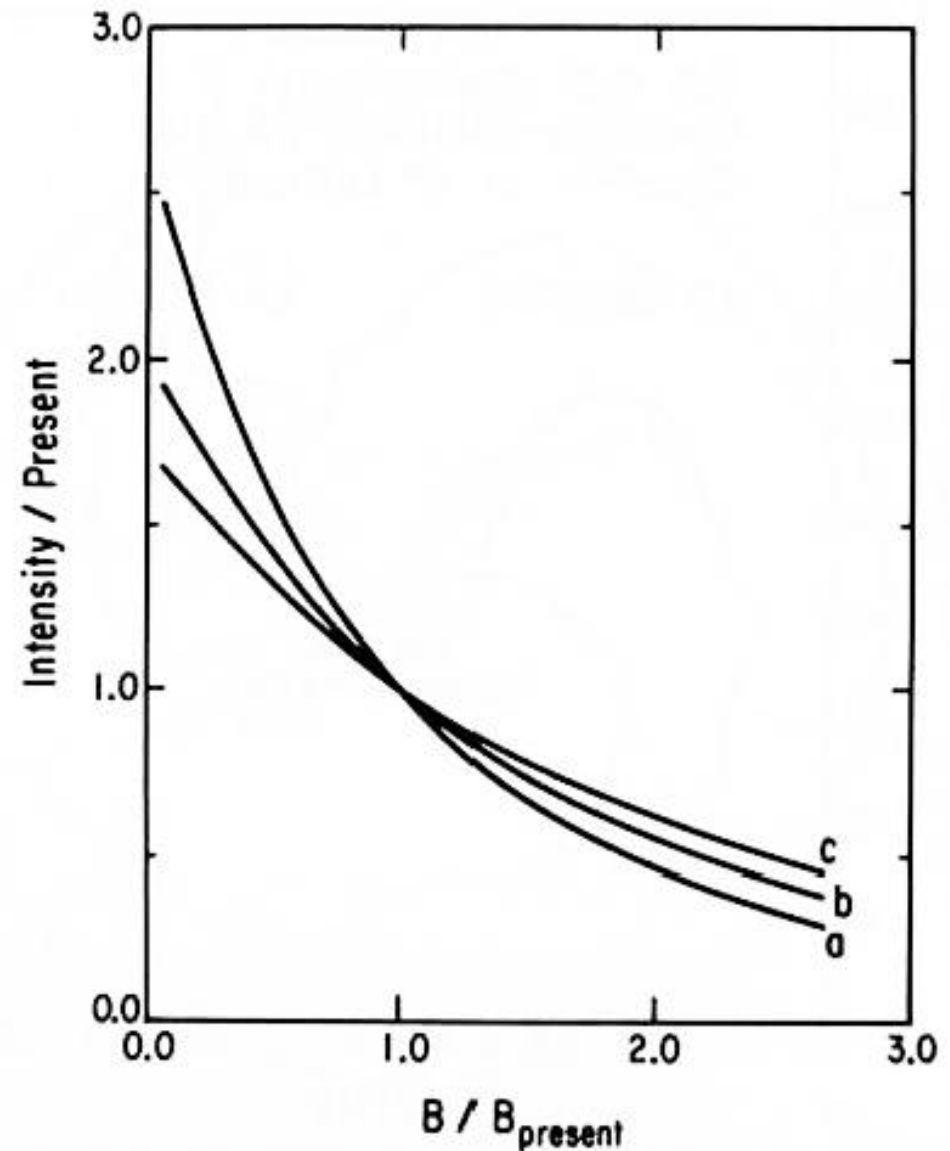
# Causes of Longer-Term Variations

- Relating the longer-term variations to detailed physical processes is more difficult.
- It is clear that variations in the solar wind and its fluctuations are a likely cause. But variations in the interplanetary magnetic field are also likely to be very important.
- Beyond some 50,000 years, interstellar causes remain likely.
- Interstellar clouds and supernova blast waves undoubtedly contributed to the variations seen at these time scales.

The recent record shows a clear relationship between the interplanetary magnetic-field magnitude and the cosmic-ray intensity.



An illustration of the effect of varying the magnitude of the interplanetary magnetic field keeping everything else constant.



# Radiation Hazards to Humans

- The “**health threat from cosmic rays**” is much discussed.
- It is the danger posed by cosmic rays to astronauts, primarily for long-duration missions.
- They are one of the most important barriers standing in the way of plans for interplanetary travel by humans.

Several strategies are being studied for ameliorating the effects of this radiation hazard for planned human interplanetary spaceflight:

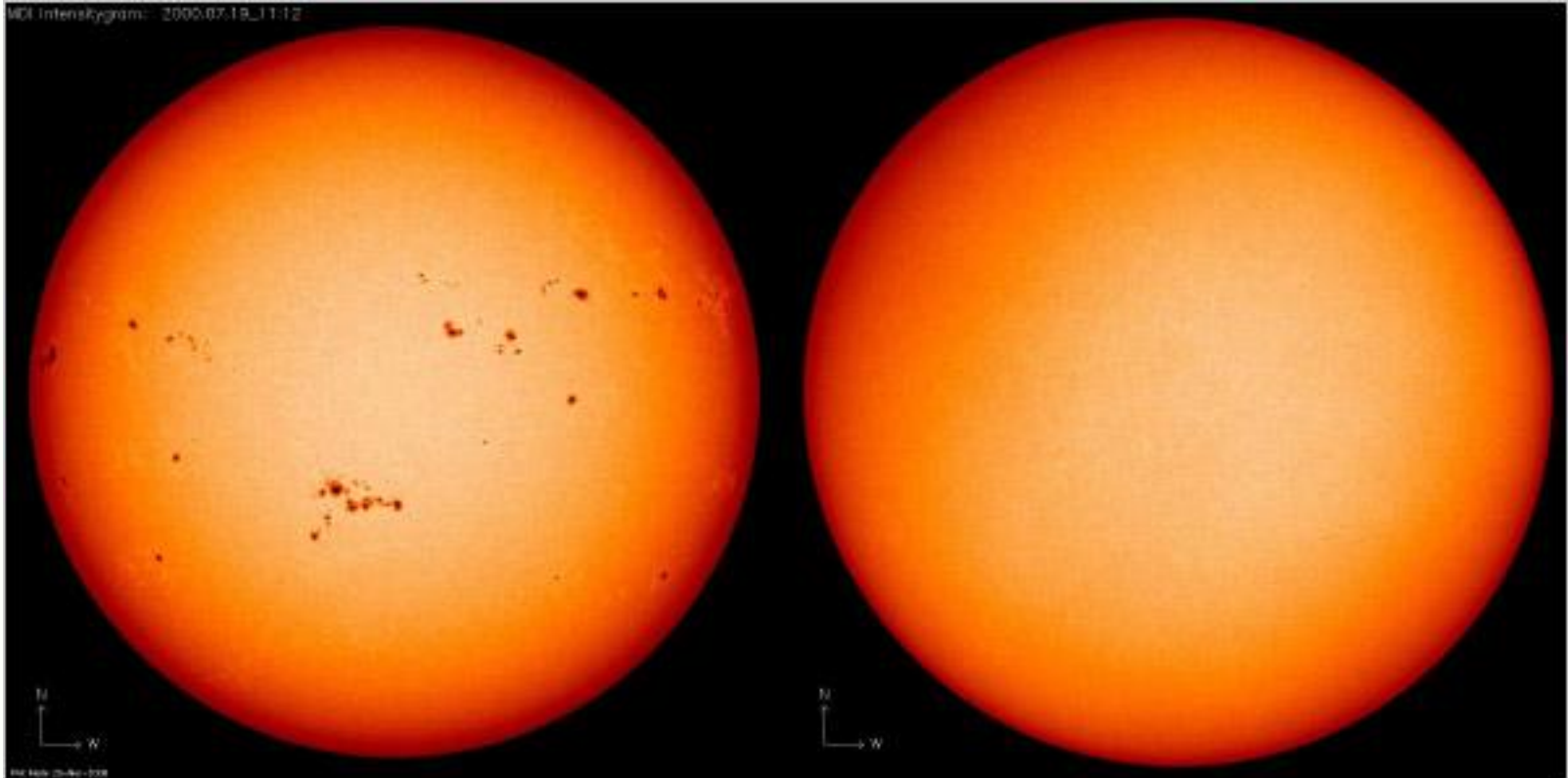
Spacecraft can be constructed out of hydrogen-rich plastics, rather than aluminum.

Material shielding has been considered. Liquid hydrogen, which would be brought along as fuel in any case, tends to give relatively good shielding, while producing relatively low levels of secondary radiation. Therefore, the fuel could be placed so as to act as a form of shielding around the crew. Water, which is necessary to sustain life, could also contribute to shielding.

Electromagnetic fields may also be a possibility.

None of these strategies currently provides a method of protection that is close to being sufficient, while using known engineering principles and conforming to likely limitations on the mass of the payload.

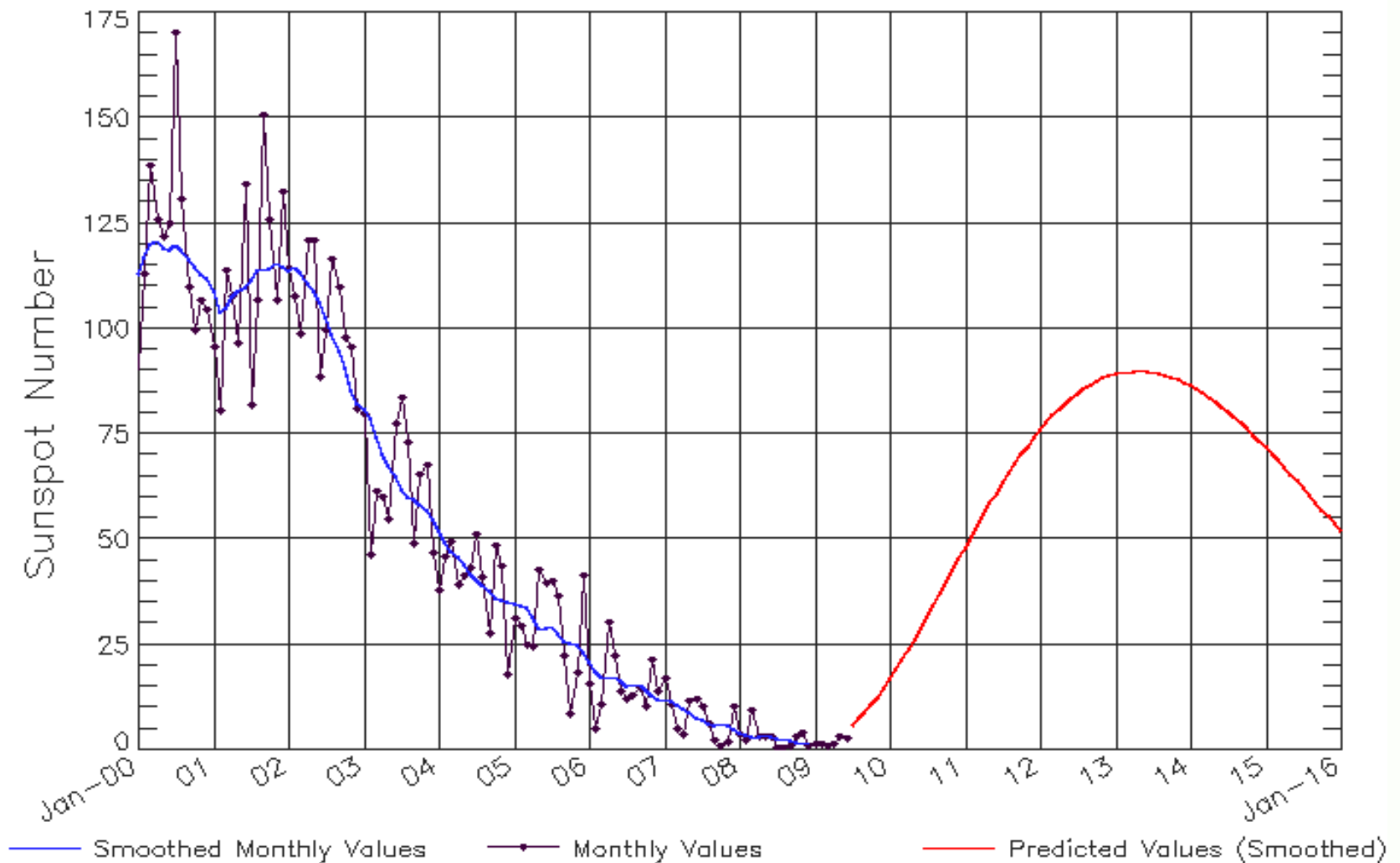
The current solar minimum is anomalously long-lived.





# The current sunspot minimum

ISES Solar Cycle Sunspot Number Progression  
Data Through Jun 09





- + NASA Home
- + Search NASA Web
- + Pagina en Español
- + Contact NASA



- HEADLINE NEWS
- + SATELLITE TRACKING
- + ABOUT
- + MAILING LISTS
- + STORY ARCHIVES
- + OTHER

FEATURE

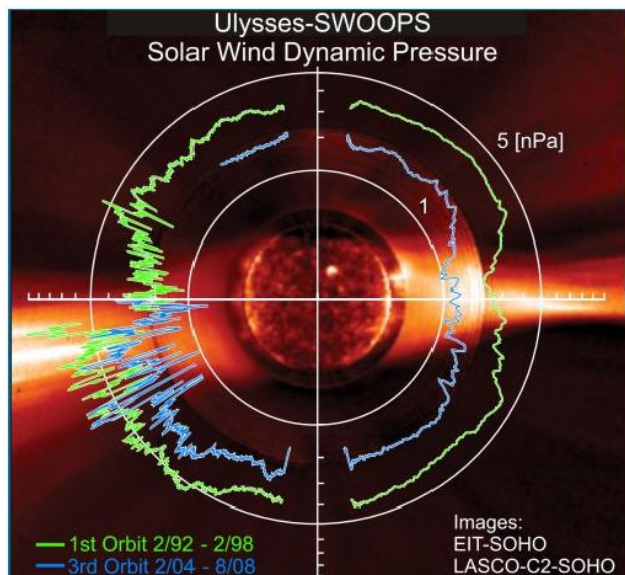
## Solar Wind Loses Power, Hits 50-year Low 09.23.2

[+ Play Audio](#) | [+ Download Audio](#) | [+ Email to a friend](#) | [+ Join mailing list](#)

**Sept. 23, 2008:** In a briefing today at NASA headquarters, solar physicists announce that the solar wind is losing power.

"The average pressure of the solar wind has dropped more than 20% since the mid-1990s," says Dave McComas of the Southwest Research Institute in San Antonio, Texas. "This is the weakest it's been since we began monitoring solar wind almost 50 years ago."

McComas is principal investigator for the SWOOPS solar wind sensor onboard the Ulysses spacecraft, which measured the decrease. Ulysses, launched in 1990, circles the sun in a unique orbit that carries it over both the sun's poles and equator, giving Ulysses a global view of solar wind activity:



**Above:** Global measurements of solar wind pressure by Ulysses. Green curves trace solar wind in 1992-1998, while blue curves denote lower pressure winds in 2004-2011. [Larger image]

Curiously, the *speed* of the million mph solar wind hasn't decreased much—only 3%.

The change in pressure comes mainly from reductions in temperature and density. The solar wind is 13% cooler and 20% less dense.

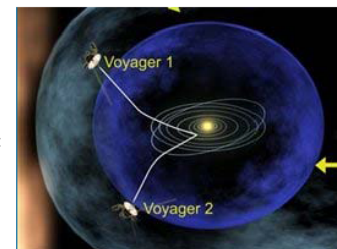
"What we're seeing is a long term trend, a steady decrease in pressure that began sometime in the mid-1990s," explains Arik Posner, NASA's Ulysses Program Scientist in Washington DC.

How unusual is this event?

"It's hard to say. We've only been monitoring solar wind since the early years of the Space Age—from the early 60s to the present," says Posner. "Over that period of time, it's unique. How the event stands out over centuries or millennia, however, is anybody's guess. We don't have data going back that far."

Flagging solar wind has repercussions across the entire solar system—beginning with the heliosphere.

The heliosphere is a bubble of magnetism springing from the sun and inflated to colossal proportions by the solar wind. Every planet from Mercury to Pluto and beyond is inside it. The heliosphere is our solar system's first line of defense against galactic cosmic rays. High-energy particles from black holes and supernovas try to enter the solar system, but most are deflected by the heliosphere's magnetic fields.



**Right:** The heliosphere. [Click](#) to view a larger image showing the rest of the bubble.

"The solar wind isn't inflating the heliosphere as much as it used to," says McComas. "That means less shielding against cosmic rays."

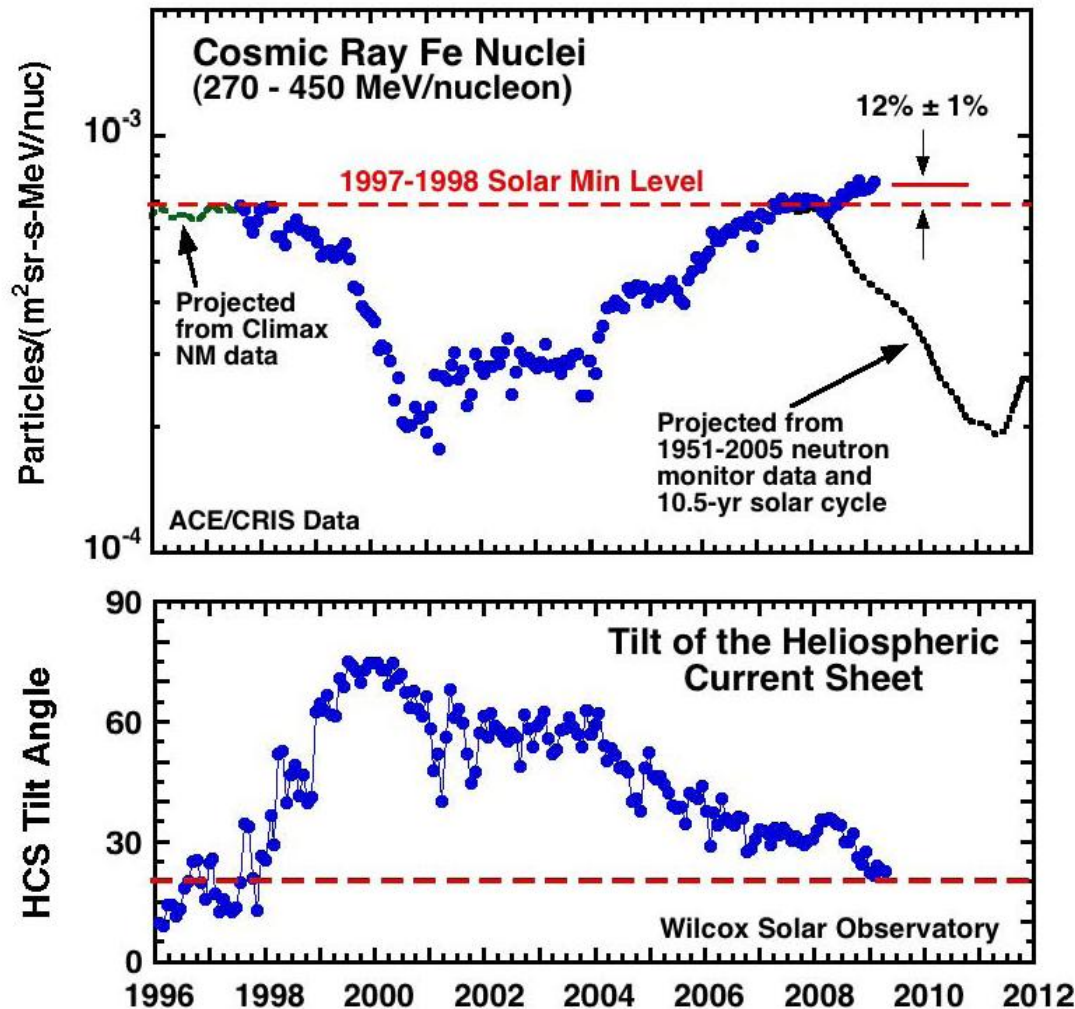
In addition to weakened solar wind, "Ulysses also finds that the sun's underlying magnetic field has weakened by more than 30% since the mid-1990s," says Posner. "This reduces natural shielding even more."

Unpublished Ulysses cosmic ray data show that, indeed, high energy (GeV) electrons, a minor but telltale component of cosmic rays around Earth, have jumped in number by about 20%.

These extra particles pose no threat to people on Earth's surface. Our thick atmosphere and planetary magnetic field provide additional layers of protection that keep us safe.

But any extra cosmic rays can have consequences. If the trend continues, astronauts on the Moon or en route to Mars would get a higher dose of space radiation. Robotic space probes and satellites in high Earth orbit face an increased risk of instrument malfunctions and reboots due to cosmic ray strikes. Also, there are controversial studies linking cosmic ray fluxes to cloudiness and climate change on Earth. That link may be tested in the years ahead.

# Cosmic-Ray Fe Intensity Reaches Record Levels in 2008-2009



Spacecraft data show that in the current solar minimum the interplanetary magnetic field strength and solar wind speed are at the lowest levels of the space era. Since the solar wind and its magnetic field play key roles in the modulation of galactic cosmic rays, one expects that the GCR intensity at Earth would reach record levels.

# Conclusions

- Galactic cosmic rays dominate the average (over scales of weeks) energetic-particle intensity at energies  $>\approx 100$  MeV.
- They vary on a continuum of time scales.
- The physics of the variation is understood, but the parameters are more-poorly understood.
- The cosmic-ray variations on long time scales serve as a proxy of solar variations on these time scales.
- The current anomalous solar minimum will provide, at a minimum, a further calibration of our understanding.