Cosmic Rays in the Heliosphere

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**Presentation at the 2011 Heliophysics Summer School,
Boulder, July 29, 2011**

Outline of Lecture

- Brief introduction to the heliosphere.
- Introduction to cosmic rays/energetic particles.
- Various sources of cosmic rays – Sun, Interplanetary Medium, Galaxy.

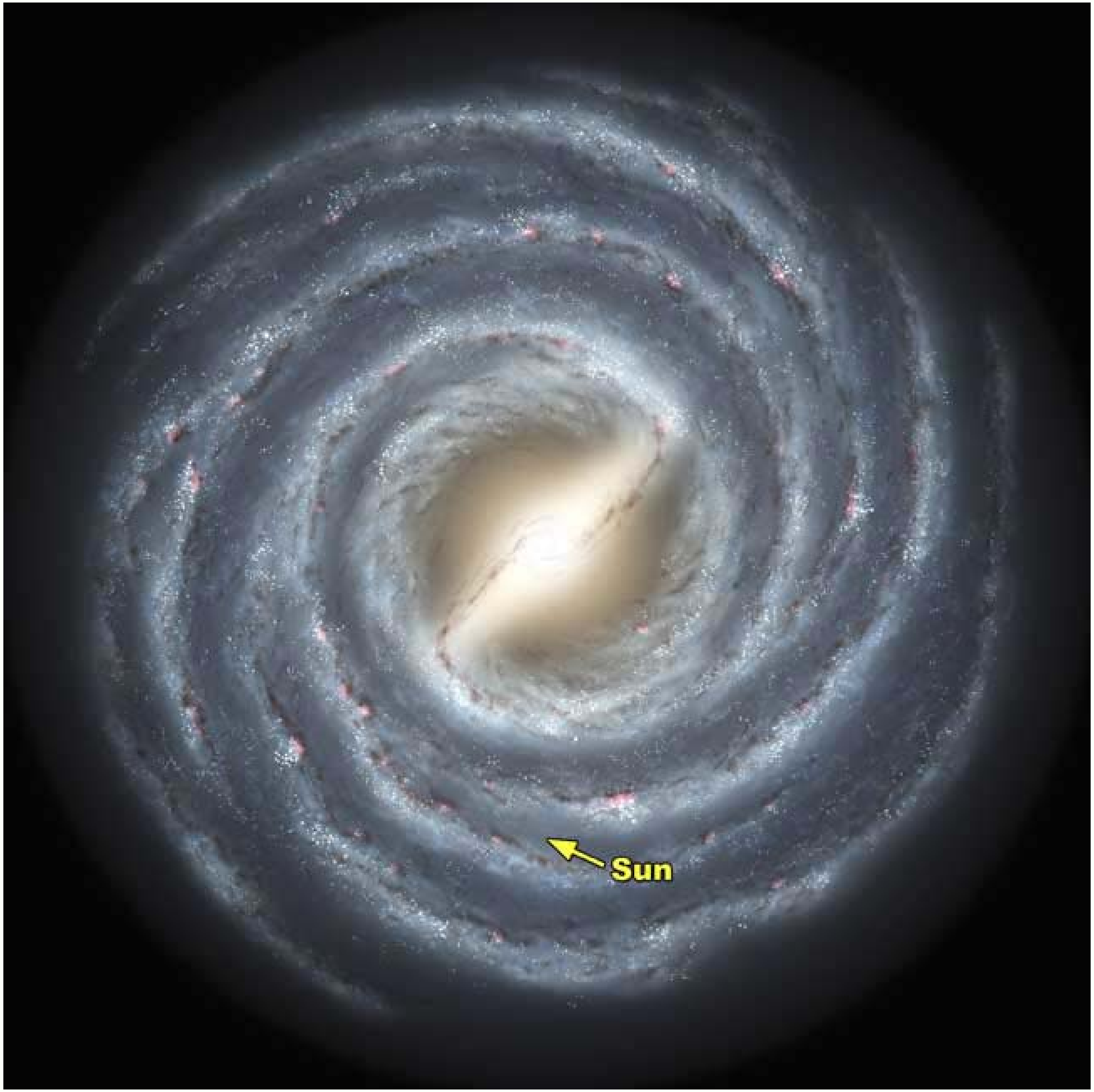
Galactic Cosmic Rays are the main focus.

- 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.

The Parker Equation.

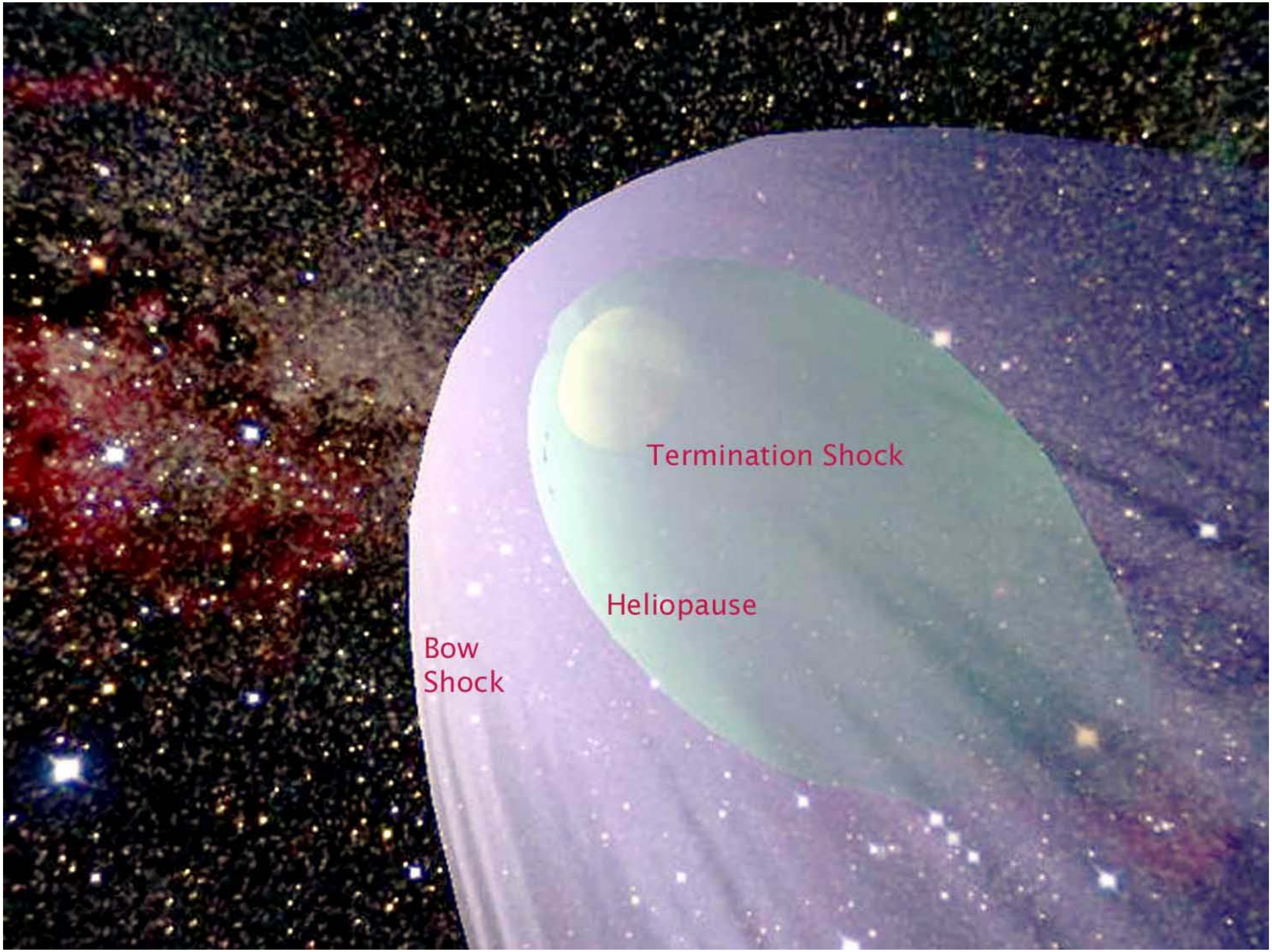
- The major tool for understanding cosmic rays is the Parker transport equation. It is applicable and an excellent approximation nearly all of the time.
- The problems which I prepared are all based on this equation.


Sun

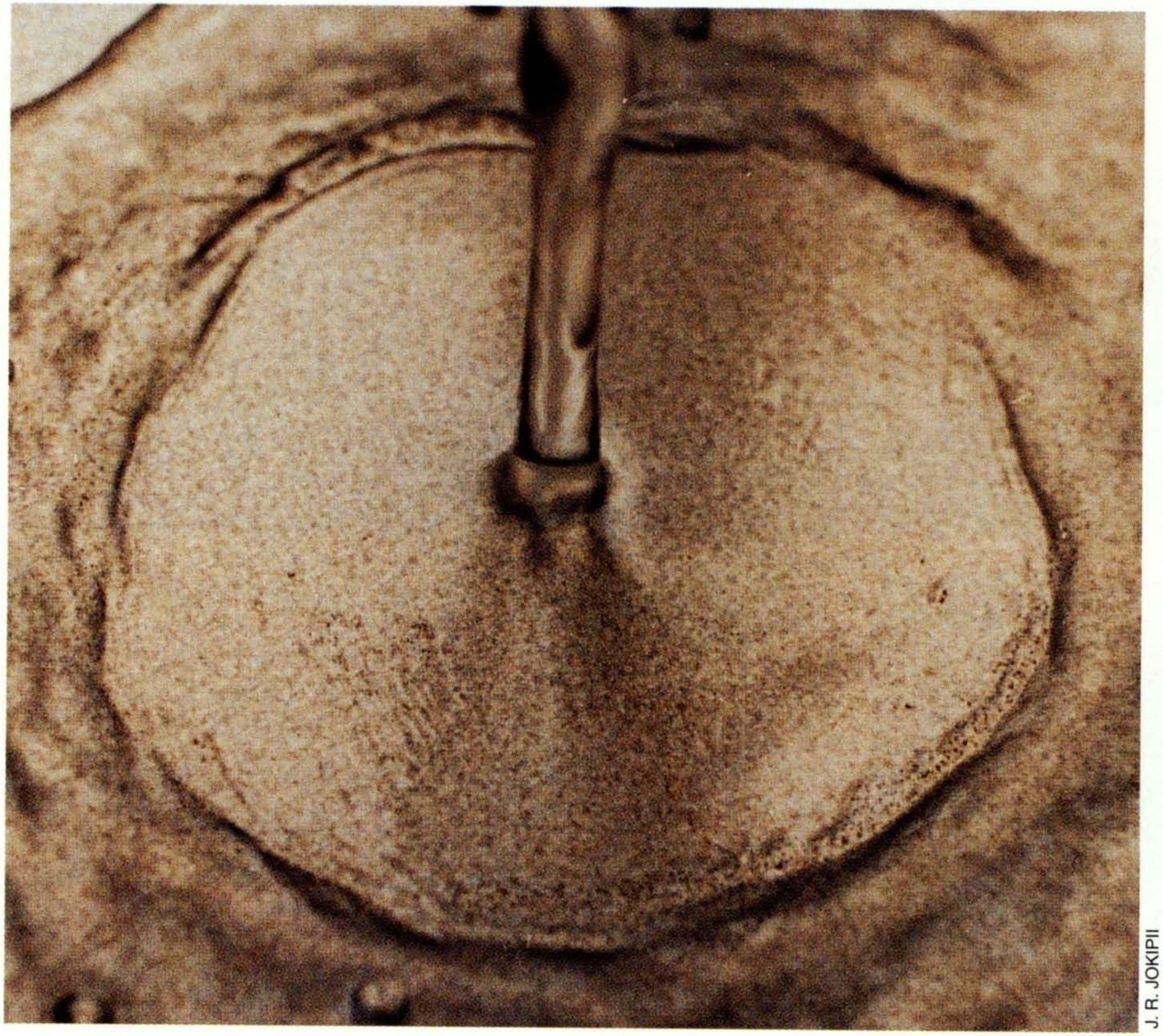
SOLAR CORONA – SEEN DURING A TOTAL ECLIPSE

Total Solar Eclipse 1999

© 2004 Miloslav Druckmüller


Termination Shock
Heliopause
Bow
Shock

An instructive analog may be seen in a kitchen sink.



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

Cosmic Rays =
Energetic (charged) Particles

- They are present wherever the ambient density is low enough to permit them to exist.

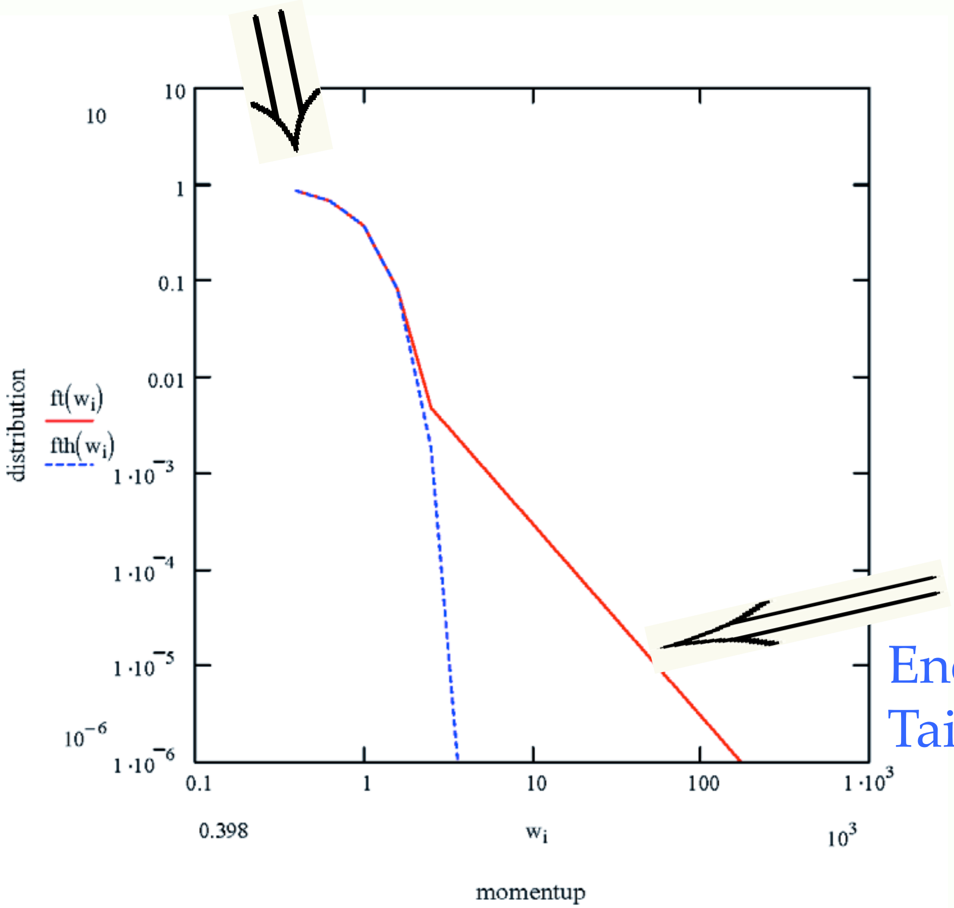
- They exist from above thermal energies to more than 10^{20} eV, have with few exceptions a normal composition, and are almost always ***isotropic in direction of arrival.***

- They are interesting in their own right, ***but also serve as probes to determine conditions in space far away or long ago*.**

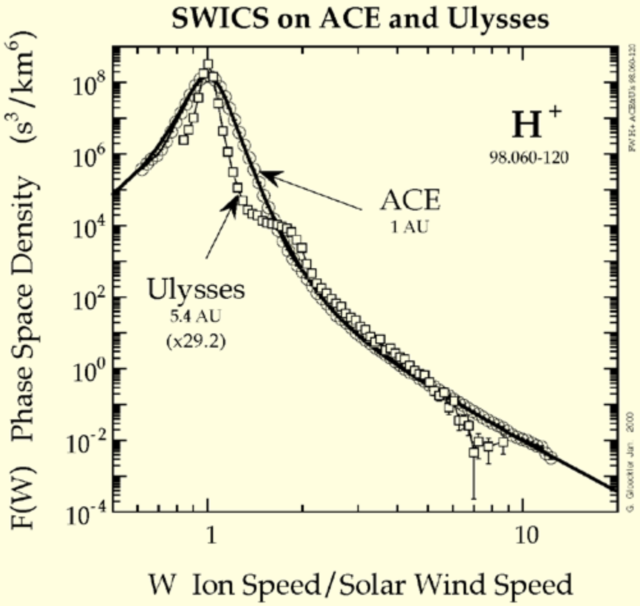
- They also pose a significant hazard in space for both instruments and especially humans.

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

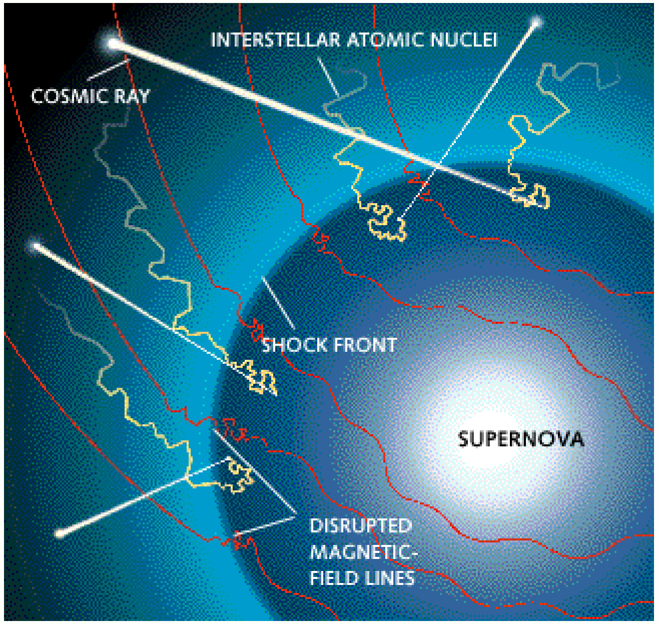


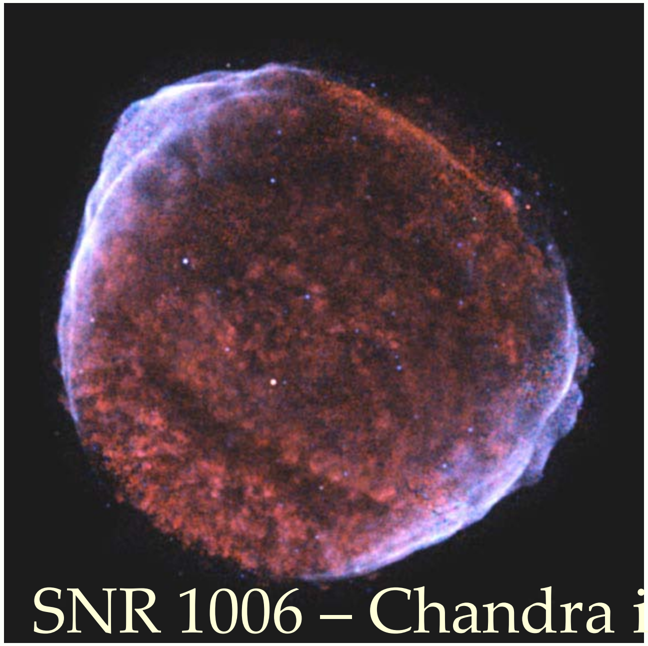
Energetic Tail



The origins of galactic cosmic rays

- Pinpointing a direct source is impossible (except for, perhaps, the highest-energy cosmic rays)
  - – Individual cosmic rays move along random paths in the turbulent magnetic fields.
  - – Observed to come from all directions in the night sky (at any point they are isotropic in arrival direction.
- Indirect methods indicate that most cosmic rays < 10^{15} eV are from shock waves driven by *supernova explosions*





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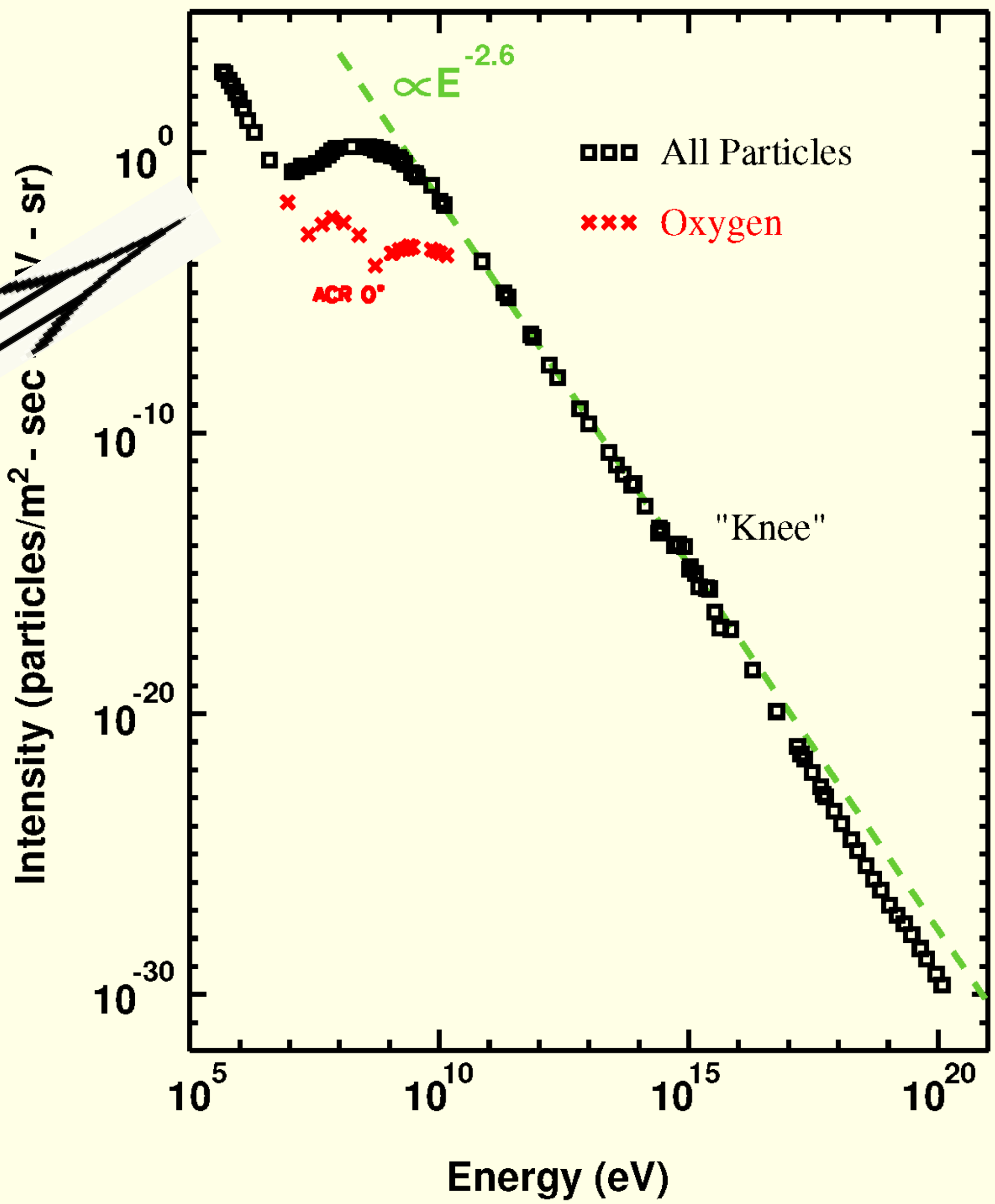
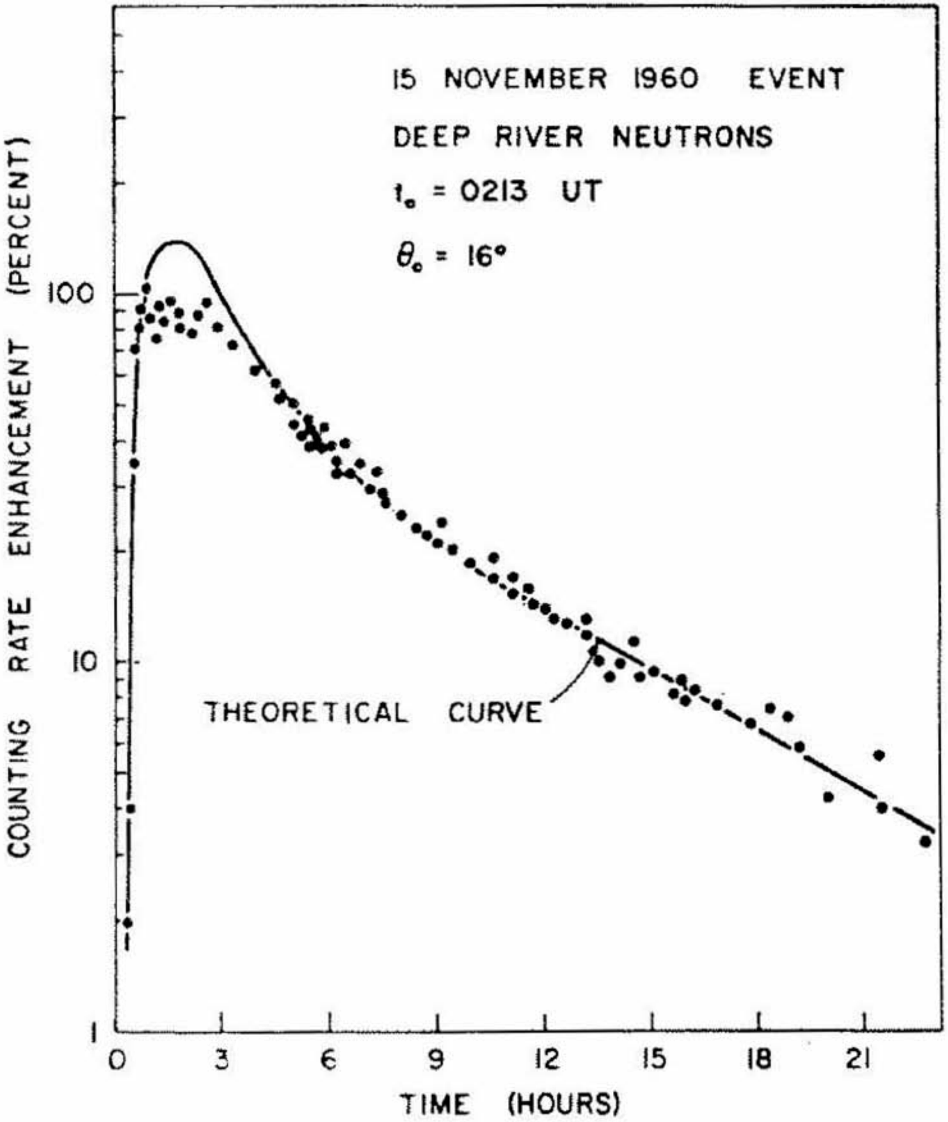
Cosmic-Ray Spectrum



Heliospheric
effects

There are also solar energetic-particle events.



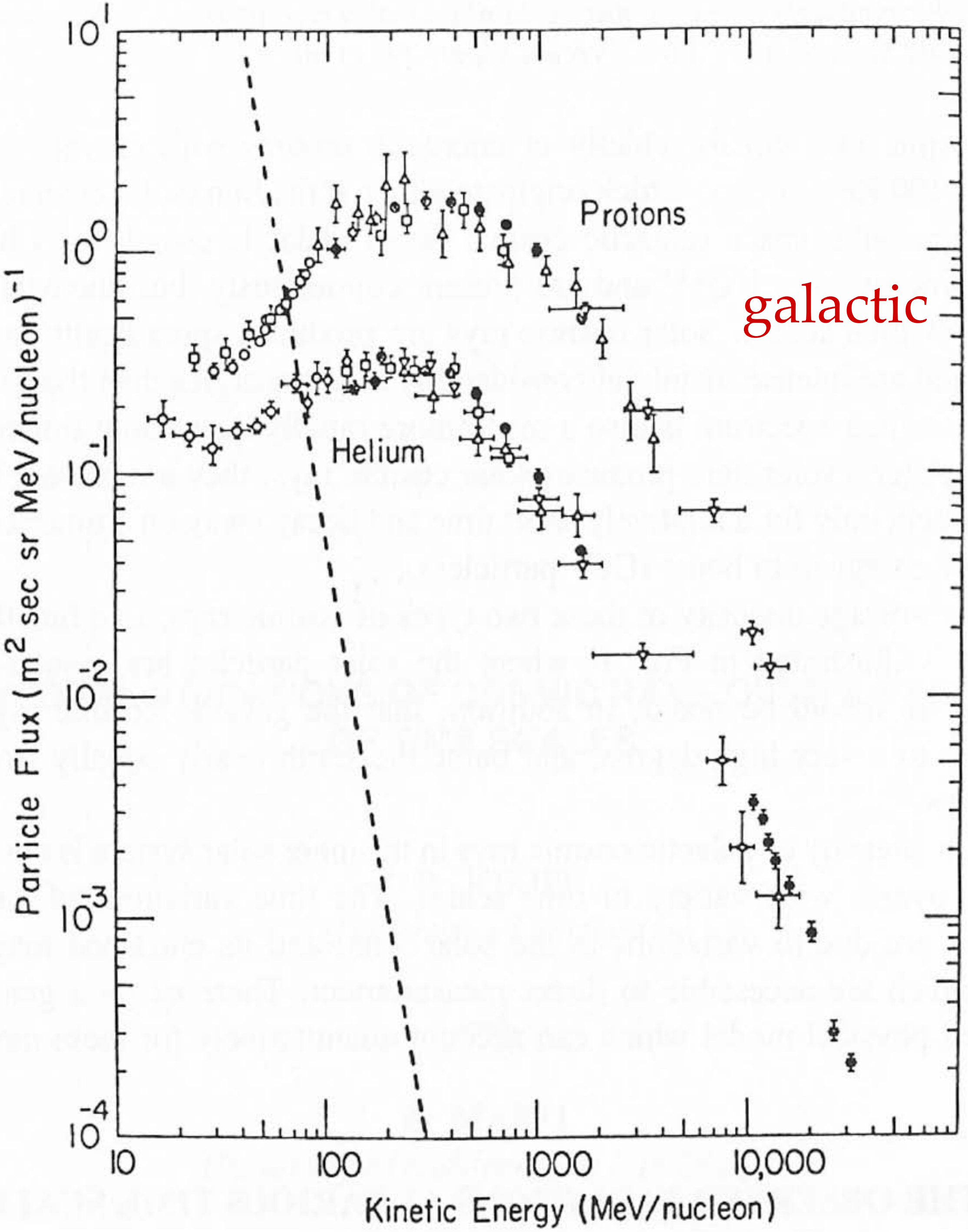
Theoretical fit, using equation 122, to the Deep River neutron monitor data for the November 15, 1960, event. θ_0 is the angle between the flare and the foot of the average magnetic field line passing through the point of observation [*Burlaga*, 1967].

Solar

Average galactic cosmic rays with transient solar particles superimposed.

The solar event lasts hours to a day or so.

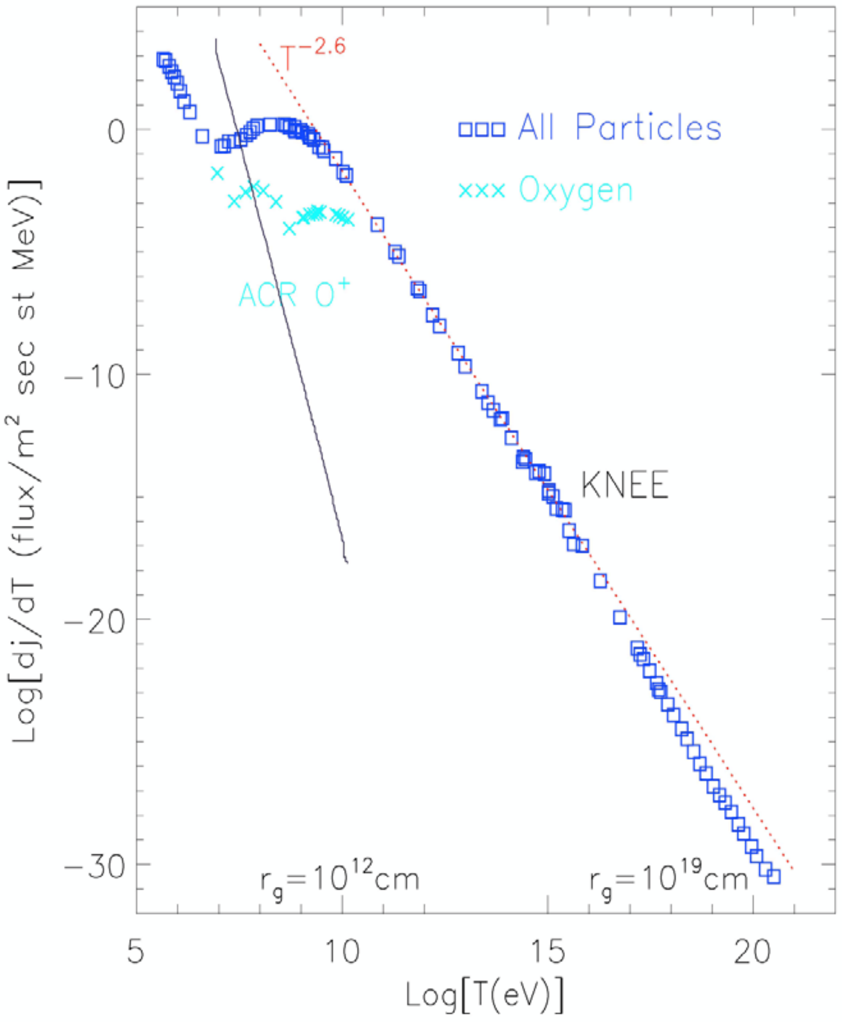
The average intensity at energies >≈ 100 MeV is dominated by galactic cosmic rays.



galactic

The anomalous cosmic rays:

Voyager 1 observations of
Cummings, Stone and Webber, 1996



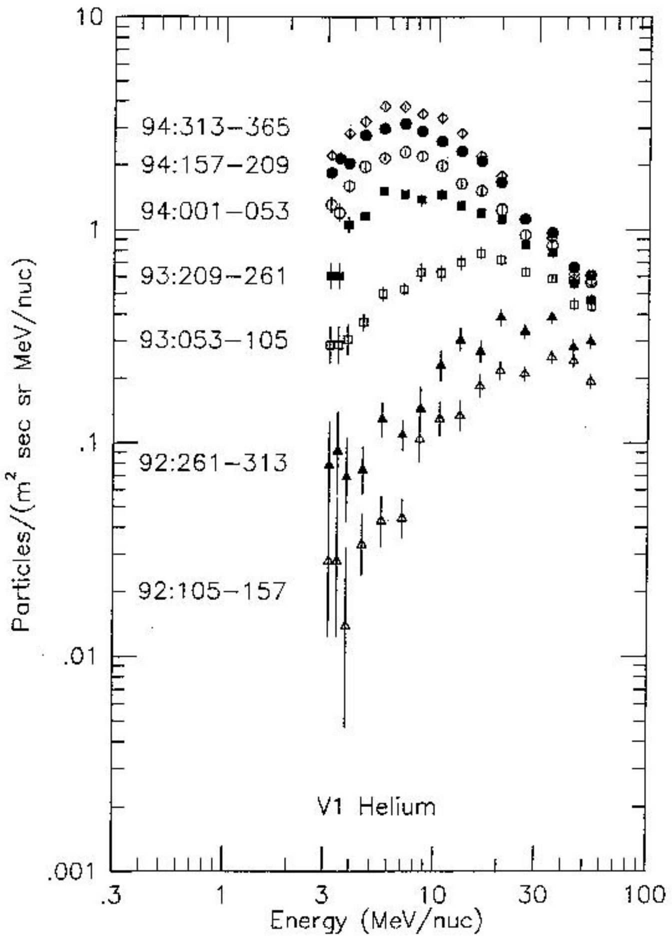
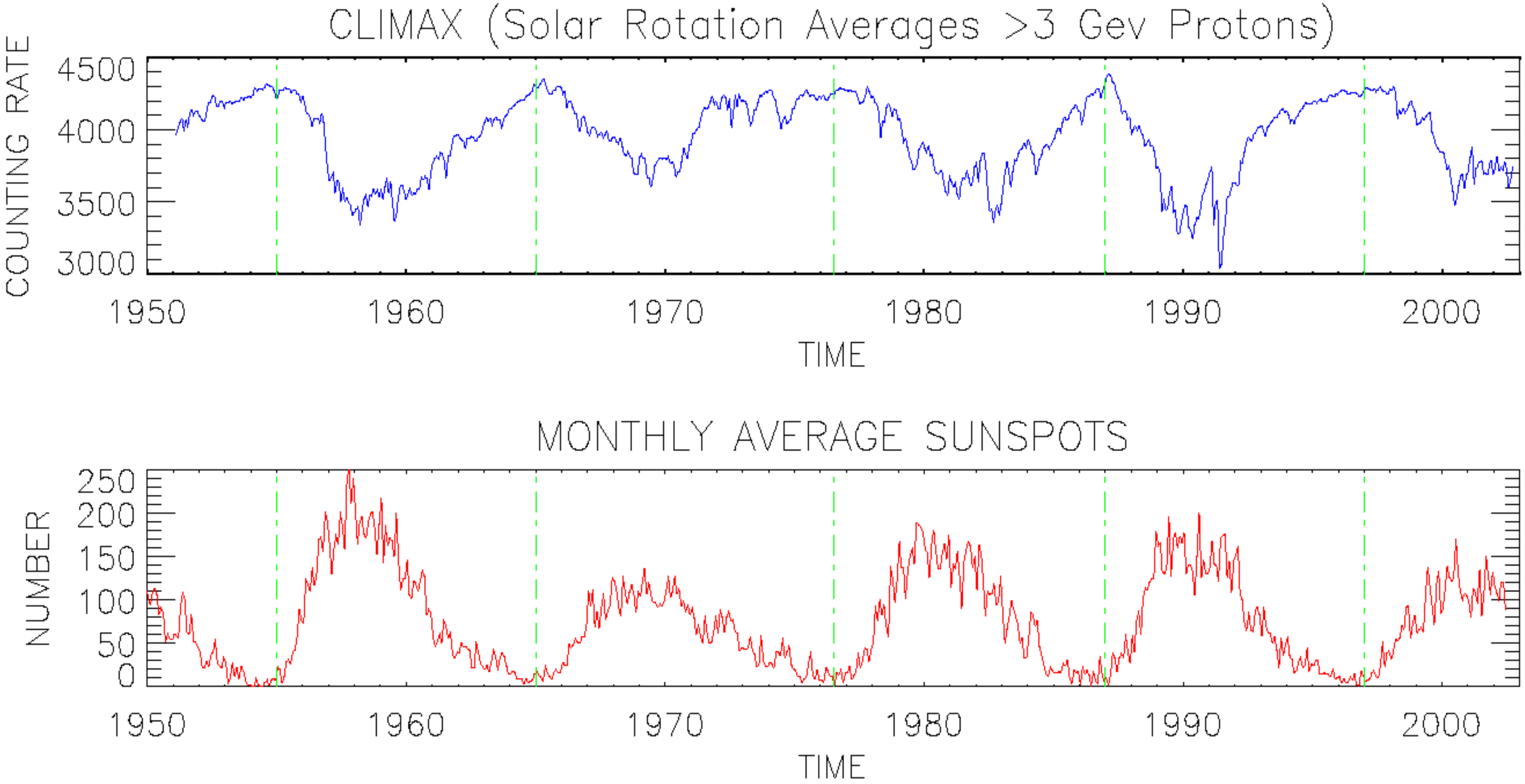


Figure 3. Energy spectrum of helium measured at V1 for seven time periods.

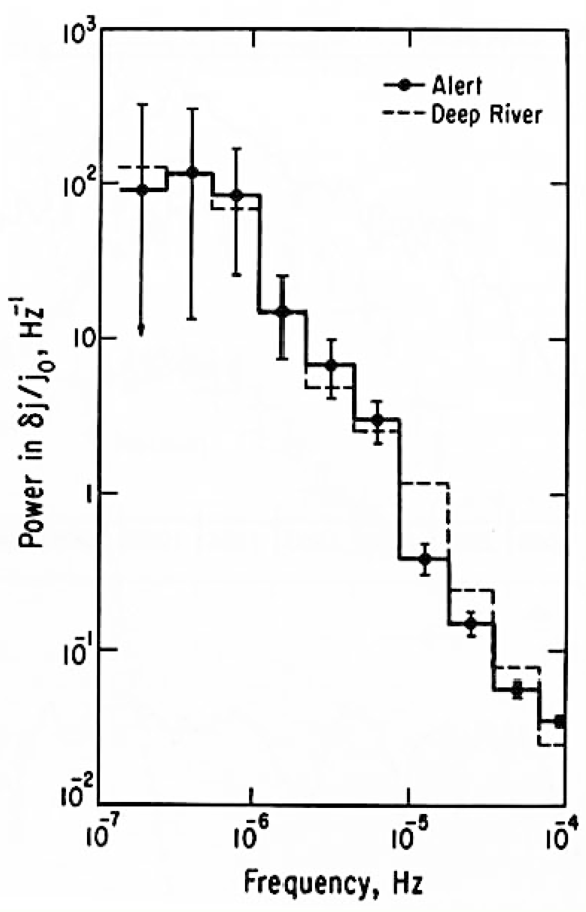
They include many elements – He, O, Ne, etc, but very little C. A major clue regarding their origin is that most are observed to be singly charged.

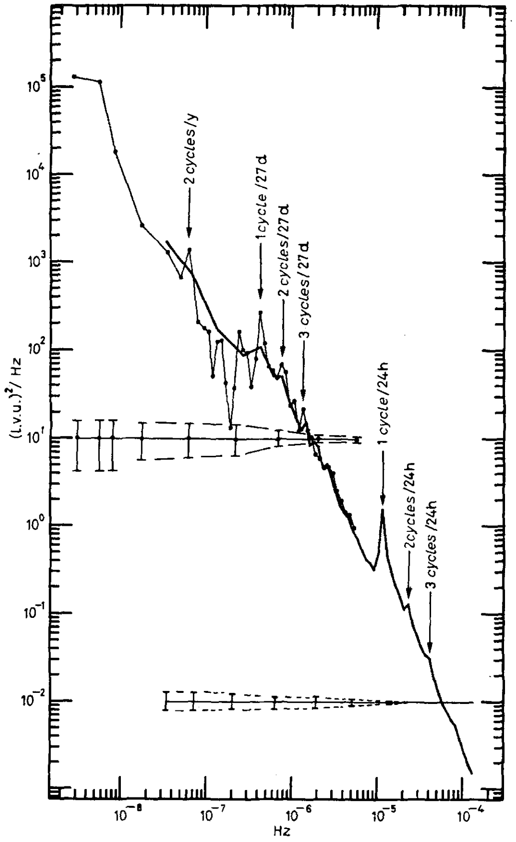
The variation of > 3 Gev protons at Earth and sunspots since 1950.



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 Cosmic-Ray Time Variations

- Short, irregular flucturations caused by solar wind variations – both from irregular solar effects and co-rotating with the Sun.
- Quasi-periodic 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.
- There are also related *spatial* variations.

Forces acting on energetic charged particles in a collisionless plasma such as the solar wind:

- Lorentz force in cgs units (note: astrophysicists nearly all use cgs units, not mks).

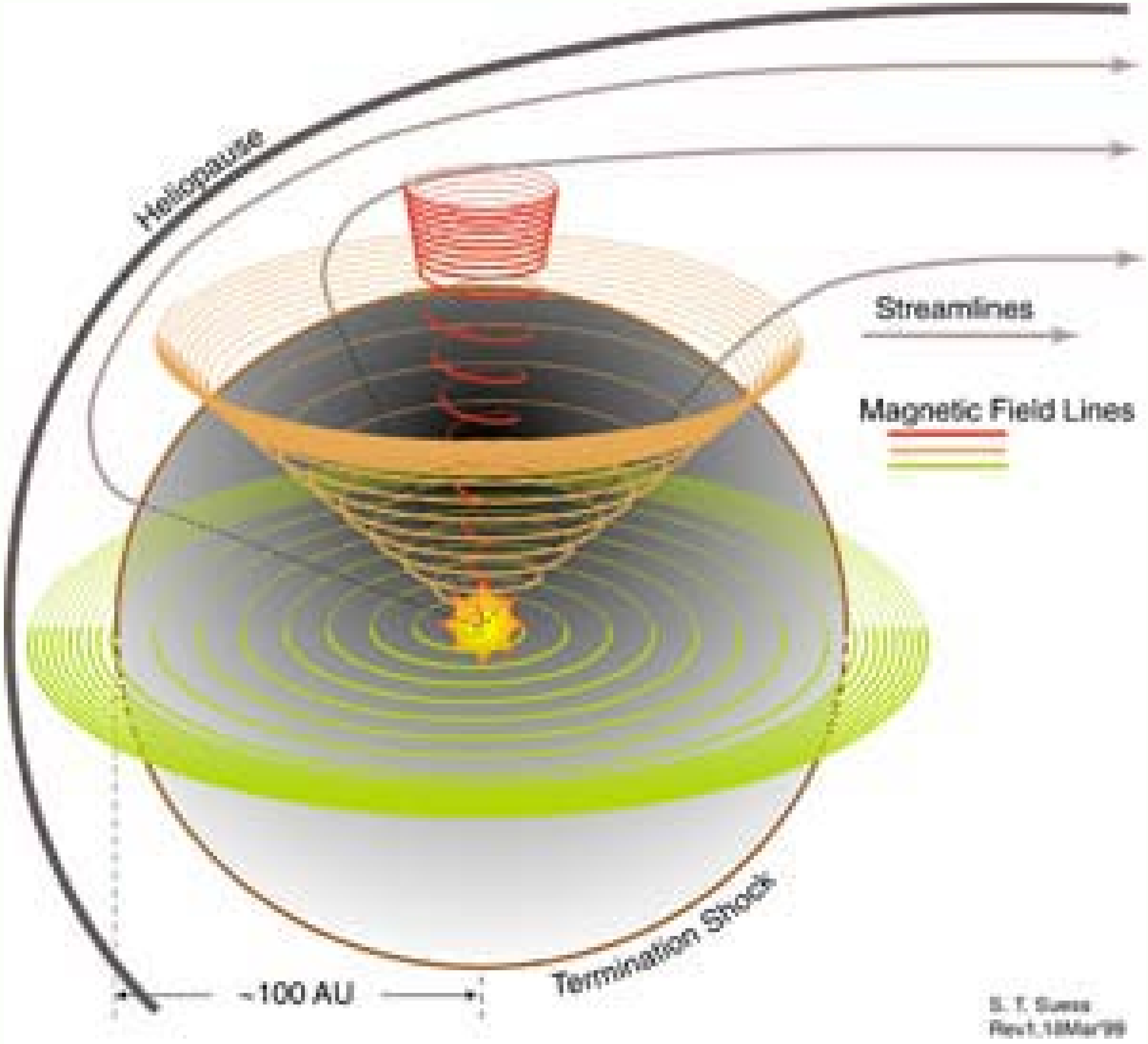
- Other forces are generally small for most applications in the heliosphere and interstellar medium, but can be added as needed (e.g. collisions, gravity, radiation pressure, etc.)

Parker Spiral Magnetic Field

- 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 lead to a spiral shape. We can write:

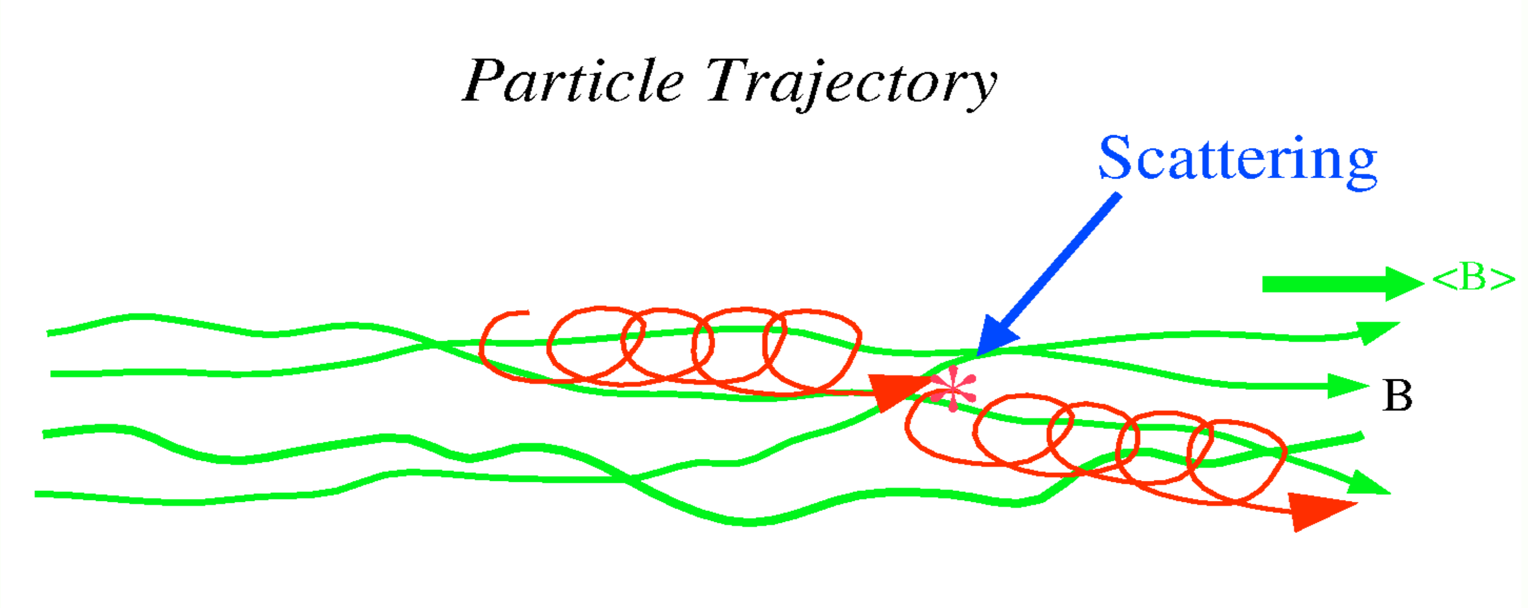
Here, A is generally nearly constant in magnitude around the Sun, but changes from positive to negative at a current sheet, called the heliospheric current sheet.

In the heliosphere cosmic rays move in the interplanetary magnetic field. They gyrate about the magneic field and undergo gradient and curvature drifts.

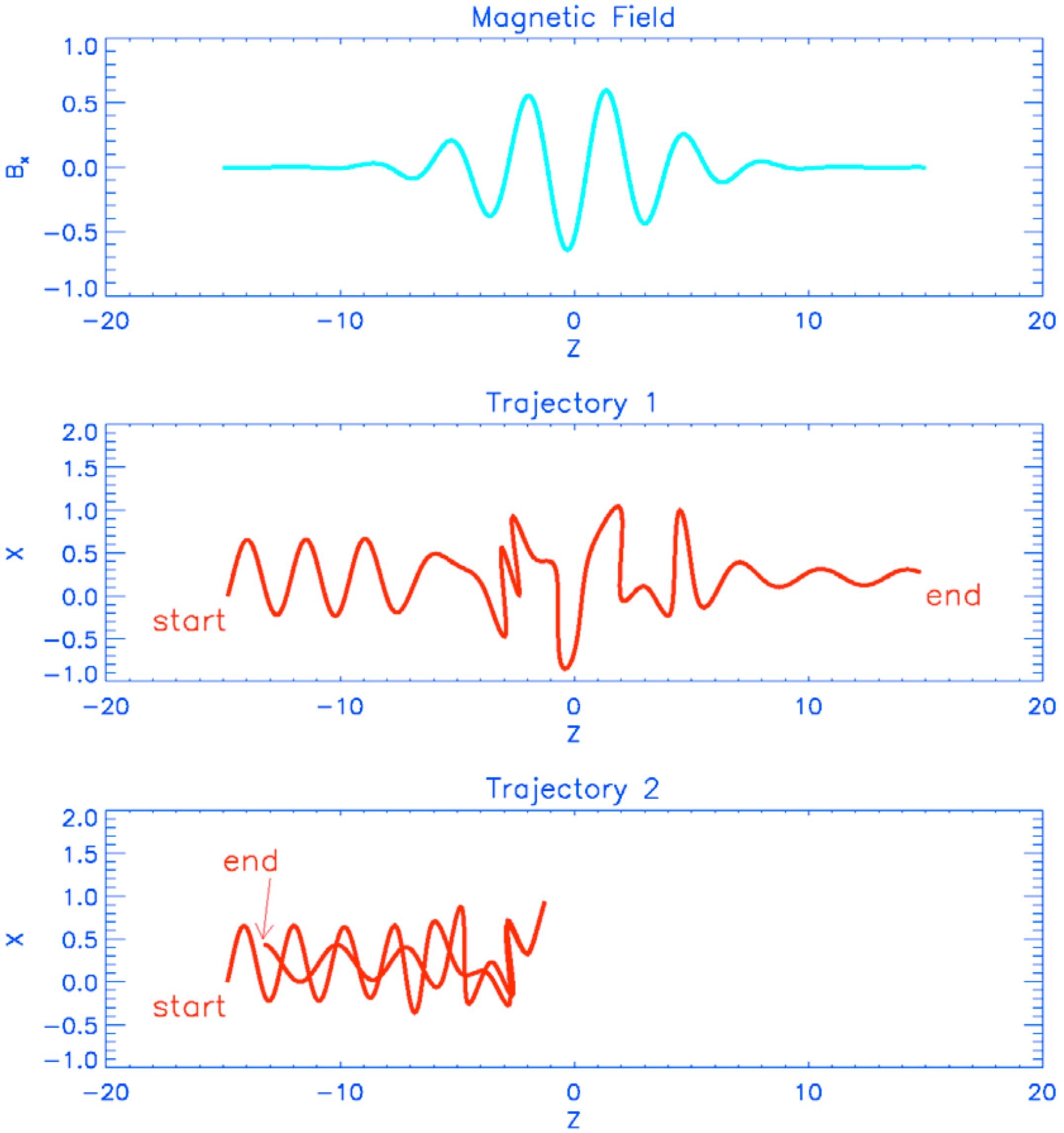


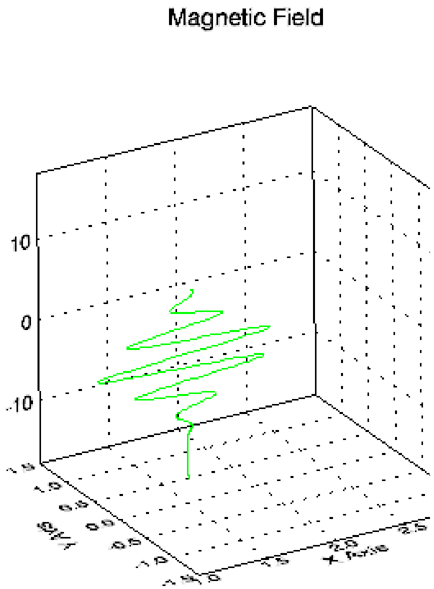
The magnetic field is also fluctuating and turbulent.

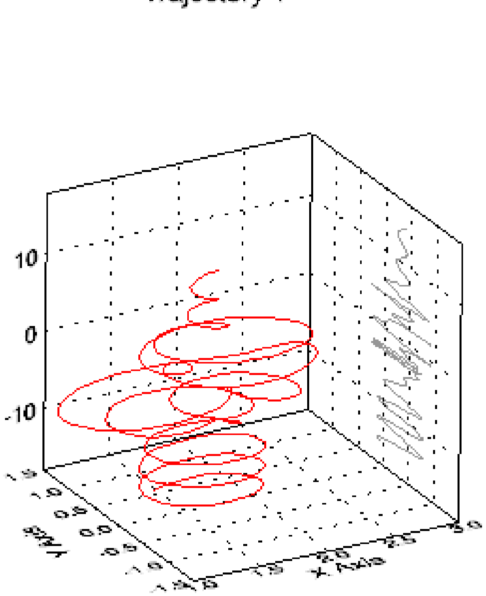
Following Fermi, the transport of cosmic rays in a turbulent magnetic field is described statistically. The turbulent electromagnetic field is described statistically. The particles are ‘scattered’ by magnetic fluctuations at ~ r_g.

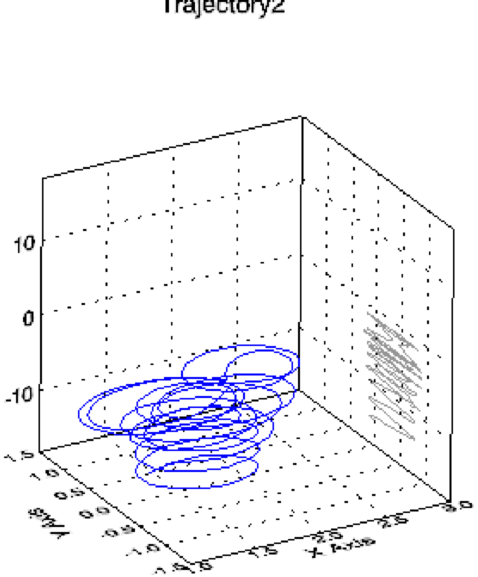


Motion in an irregular magnetic field is sensitive to initial conditions (chaotic).









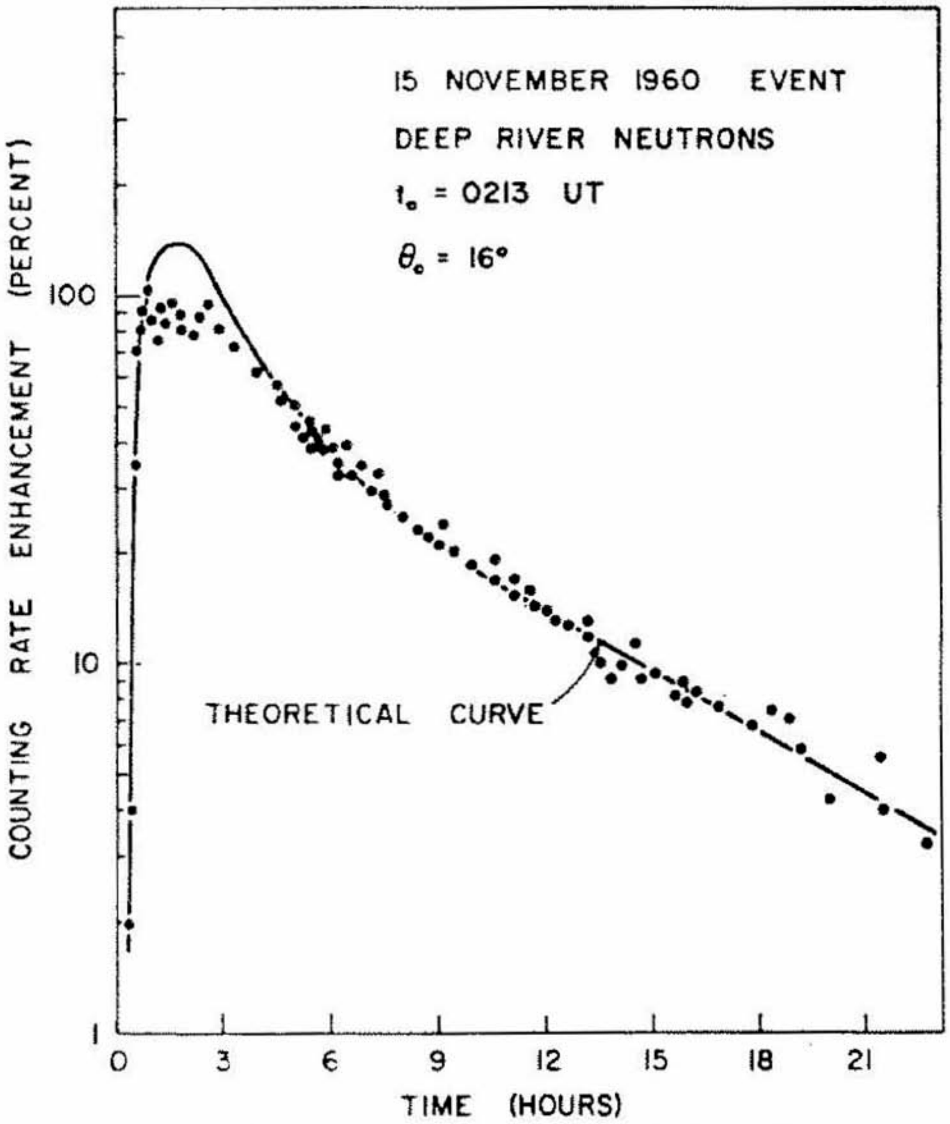
Partilces may be thought of as being ‘scattered’ by the magnetic irregularities. As pointed out two days ago by Bhattacharjee, this leads to diffusive behavior.

In general magnitude, the scattering mean free path $\lambda \sim n\ r_g$
Then the diffusion coefficient $\kappa \sim n\ r_g\ w/3 \sim 10^{22}\ \mathrm{cm}^2/\mathrm{sec}$.

In this case neglecting the background fluid velocity , we can understand a solar cosmic-ray event using only standard diffusion

The solution to this is the usual diffusion solution:

Of course, this must be really done in a more-general geometry, such as spherical. Also, other effects must be included.



Theoretical fit, using equation 122, to the Deep River neutron monitor data for the November 15, 1960, event. θ_0 is the angle between the flare and the foot of the average magnetic field line passing through the point of observation [*Burlaga*, 1967].

Diffusion corresponds to a random walk.

$x = x_0 \; +/- \lambda \; +/- \lambda \quad \ldots\ldots$

Thus, in a given time Δ t,

$(x-x0)^2$ is ~ $\kappa \, \Delta$ t

The time to diffuse a given distance scales as the square of the distance.

For a ~GeV cosmic rays in the inner heliosphere, r_g ~ .01 AU ~ 10^{11} cm. Hence κ ~ 10^{22} cm^2/sec. The time to diffuse 100 AU ~ 10^{15} cm is ~ few years.

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

- Diffusion: caused by the scattering of the cosmic rays by the irregularities in the magnetic field. The associated diffusion κ_{ij} is significantly larger along the magnetic field than normal to it.
- Convection: Outward from the Sun at the solar wind velocity $V_{\mathbf{w}}$.
- Guiding-center drifts: given in terms of the average magnetic field B0, the particle charge q by

  $V_d = pcw/3q) \nabla \times (\mathbf{B}_0/|B_0|^2)$
- Energy Change: caused by expansion/compression of the background fluid $\nabla \cdot U$.
- These are combined in Parker's transport equation, first written down nearly 50 years ago.

The Parker Transport Equation:

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

) Diffusion

$$-\mathbf{U} \cdot \nabla f$$

) Convection w. plasma

$$-\mathbf{V_d} \cdot \nabla f$$

) Grad & Curvature Drift

$$+\frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ell np}\right]$$

) Energy change

$$+Q$$

) Source

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

$$\mathbf{V_d} = \frac{pcw}{3q}\nabla \times \left[\frac{\mathbf{B}}{B^2}\right], \qquad |\mathbf{V_d}| = O\left(\frac{r_c}{L}w\right)$$

It is difficult to overstate the importance of this equation. It is the basis of 95% or more analyses of energetic particles and cosmic rays – Sun, Heliosphere, galaxy, intergalactic, etc.

Anisotropy

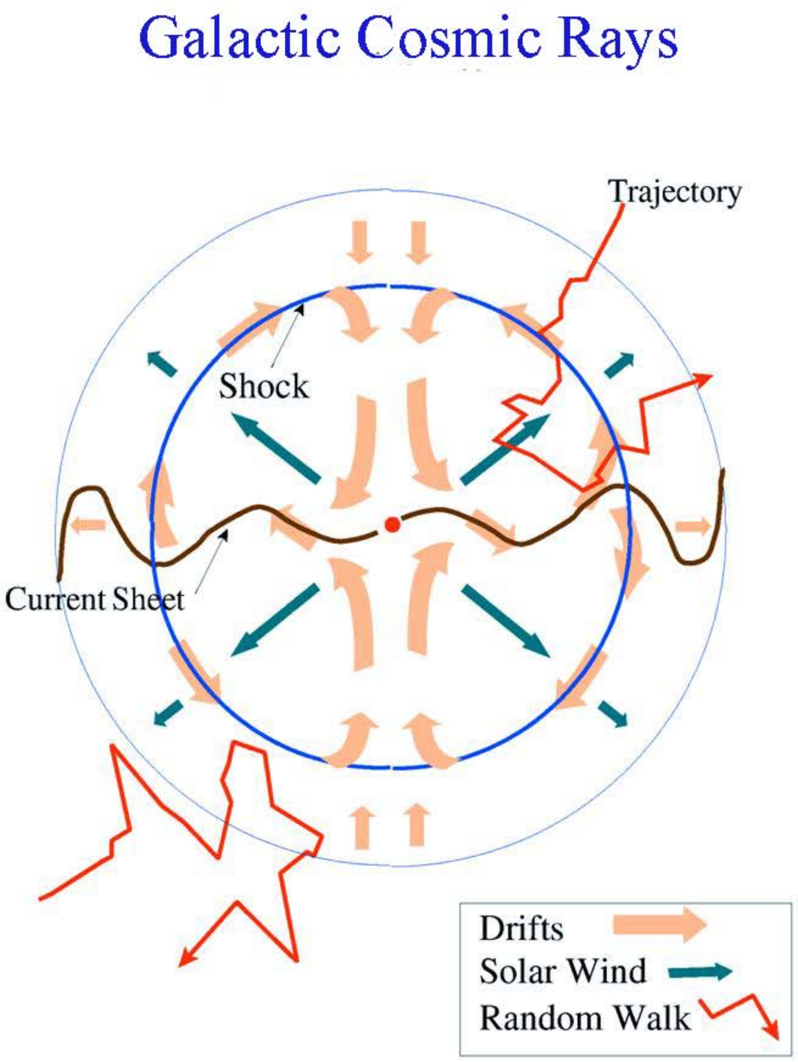
- The Parker transport equation is generally applicable for cases in which the anisotropy is small. The (small) anisotropy is given by:

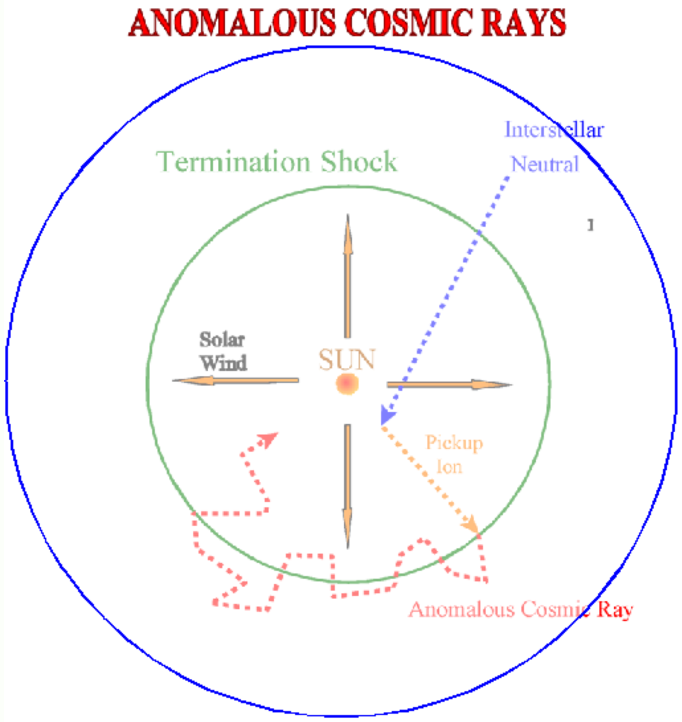
Anisotropy

Streaming Flux

- This should be routinely monitored for any given problem. If it is not satisfied, or is only marginally satisfied, other approximations are required (or use a brute-force orbit integration).

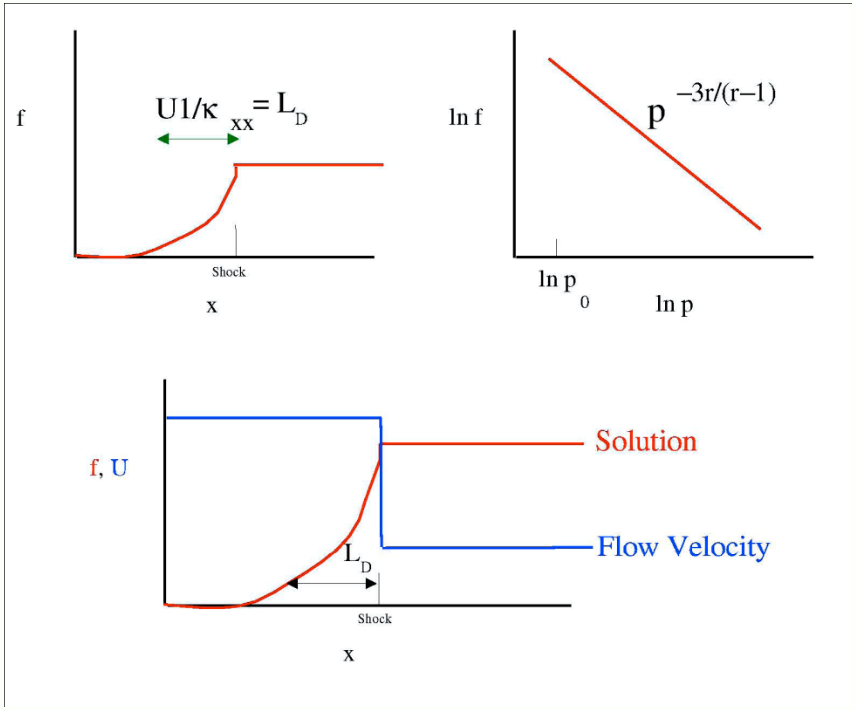
The standard paradigm for galactic and anomalous cosmic rays in the outer heliosphere





How are Cosmic Rays Accelerated to High Energies?

- The Parker equation applies to the high energies.
- The energy change appears in the term proportional to $\nabla \cdot \mathbf{U}$. Compression is important!
- Shocks involve compression. Compressions small in other places (reconnection, turbulence, etc). This implies slow acceleration.
- Hence, shocks have been the focus of most explanations of charged-particle acceleration



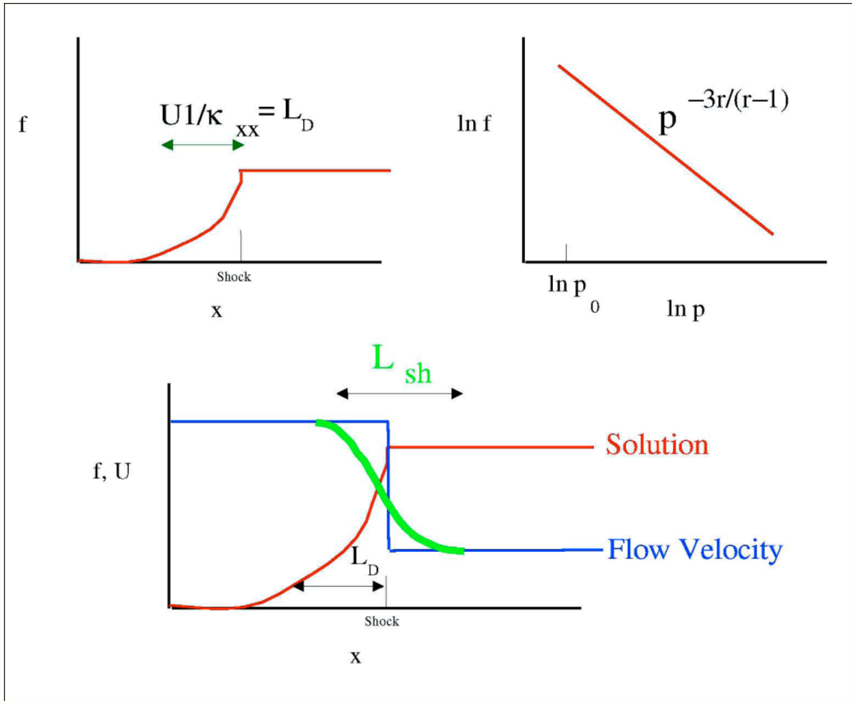


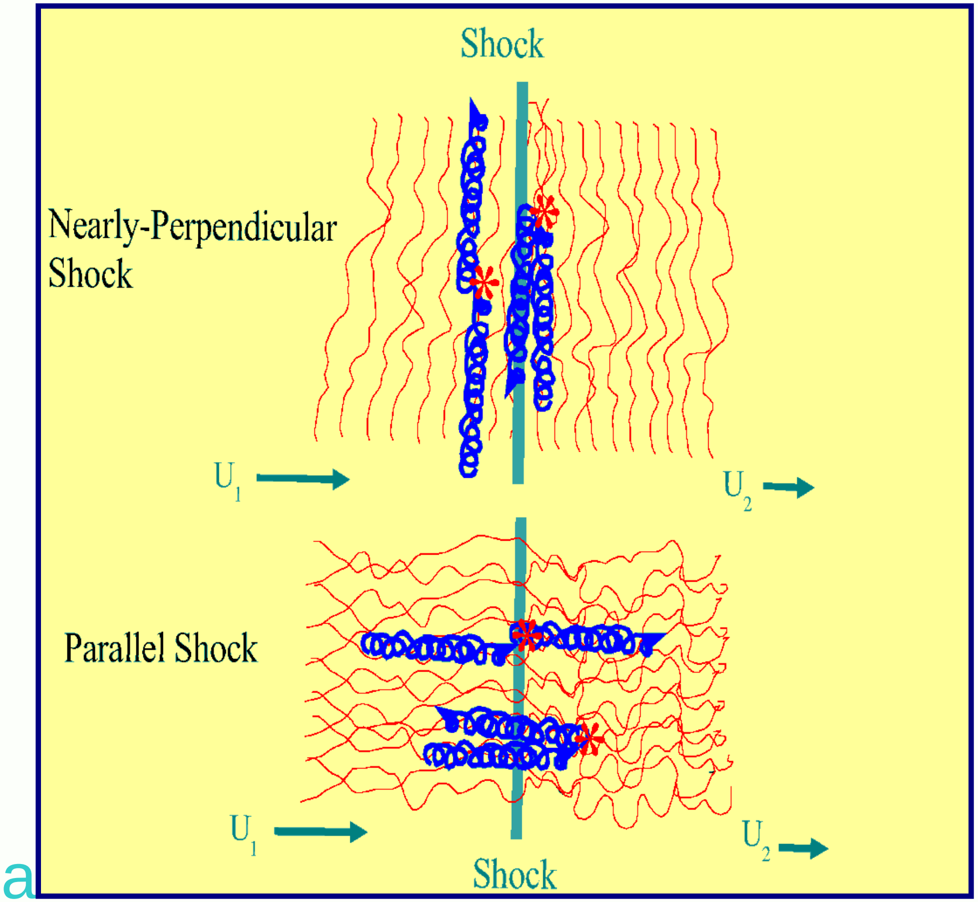
Illustration of the time-asymptotic solution to Parker's equation for a one-dimensional shock.

The spectrum is a power law in momentum with index depending *only* on the shock ratio r.

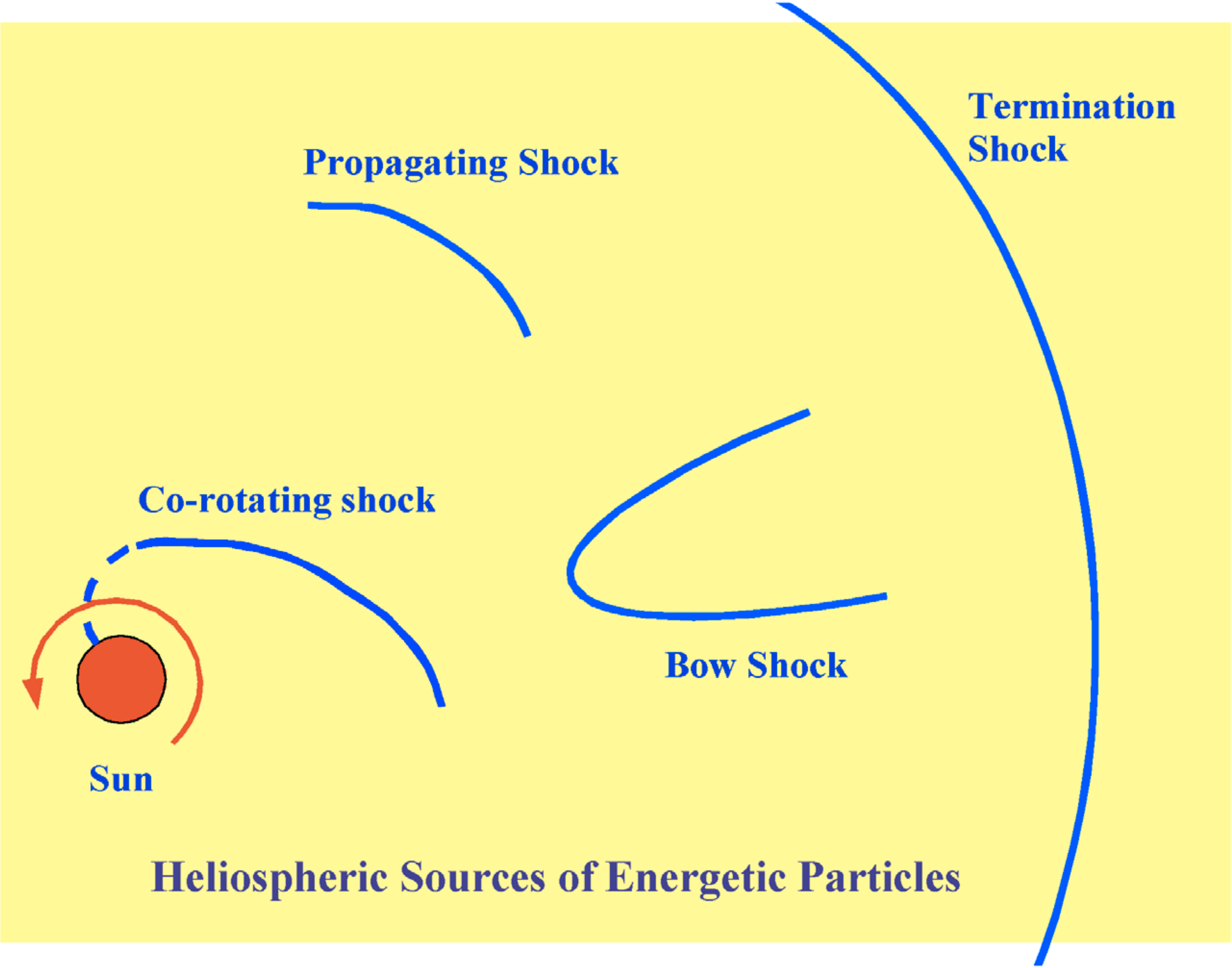
Diffusive Shock Acceleration

- Discovered by four independent teams:
  - *Bell (1978), Krymsky (1977),*
    Axford et al (1977),
    Blandford & Ostriker (1978)

- Particles diffuse back and forth across a converging flow (a shock), being accelerated at each crossing.
- Applies also at more-gradua compressions.



Heliospheric Particles

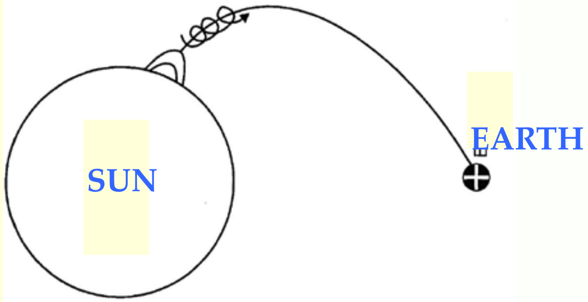


Heliospheric Sources of Energetic Particles

Solar-Energetic Particle (SEP) Paradigms

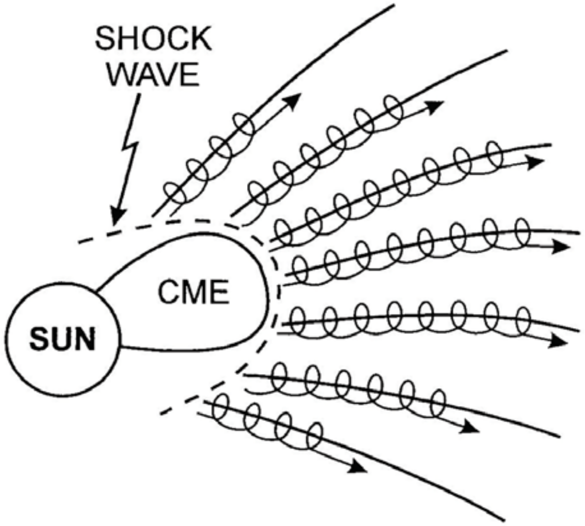
The initial view was that *ALL* SEPs originated from flares

Impulsive Events

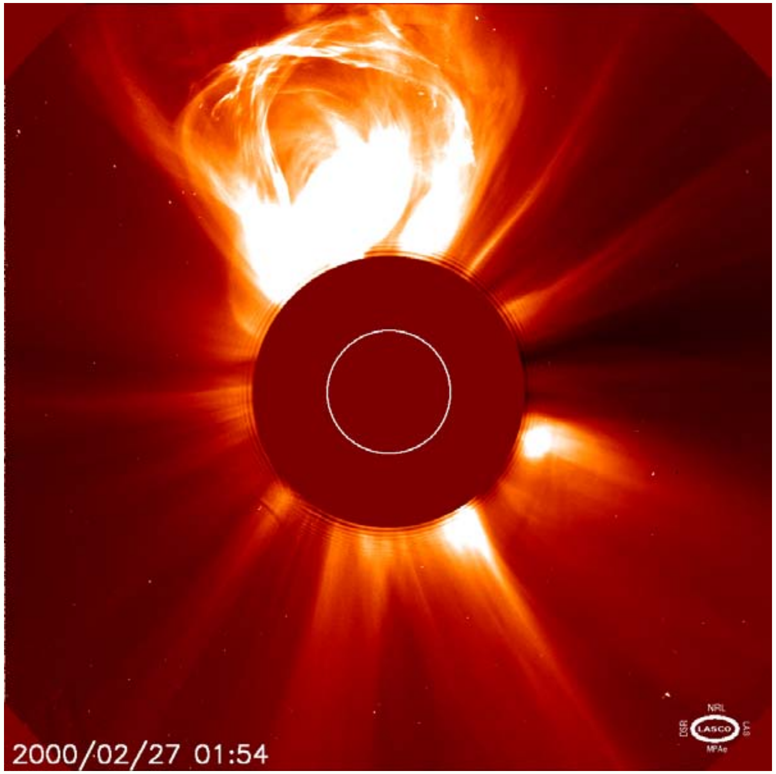


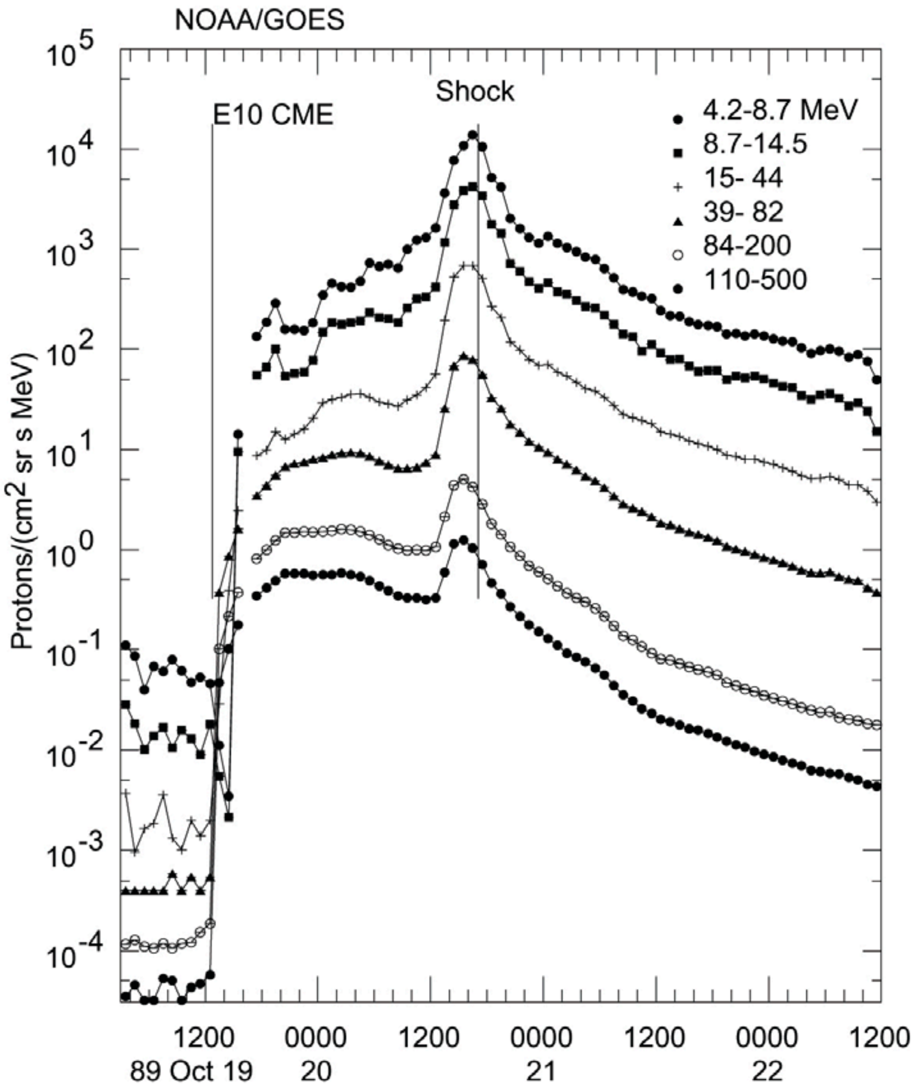
In the early-mid 1990's, the two-class paradigm was suggested

Gradual Events



Large CME-related SEP events





Reames.SSR, 1999

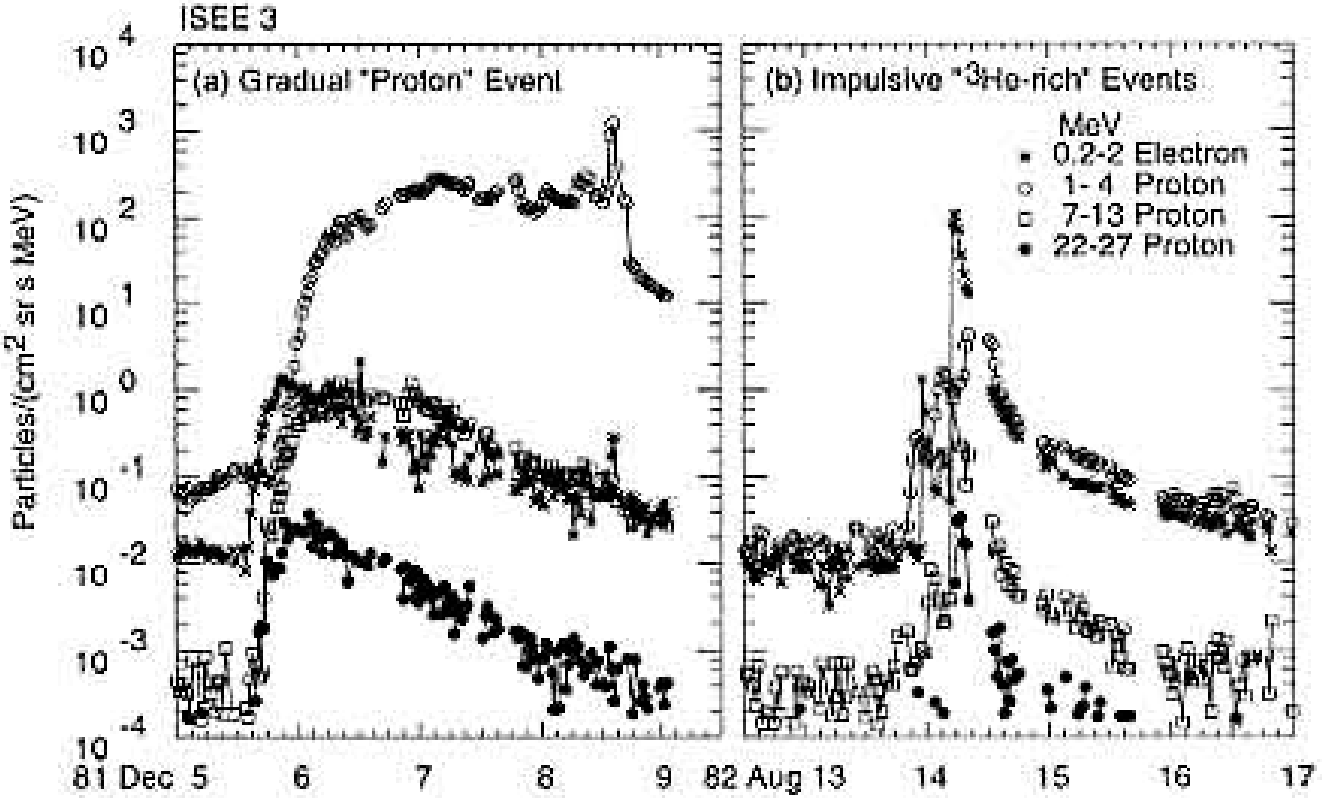
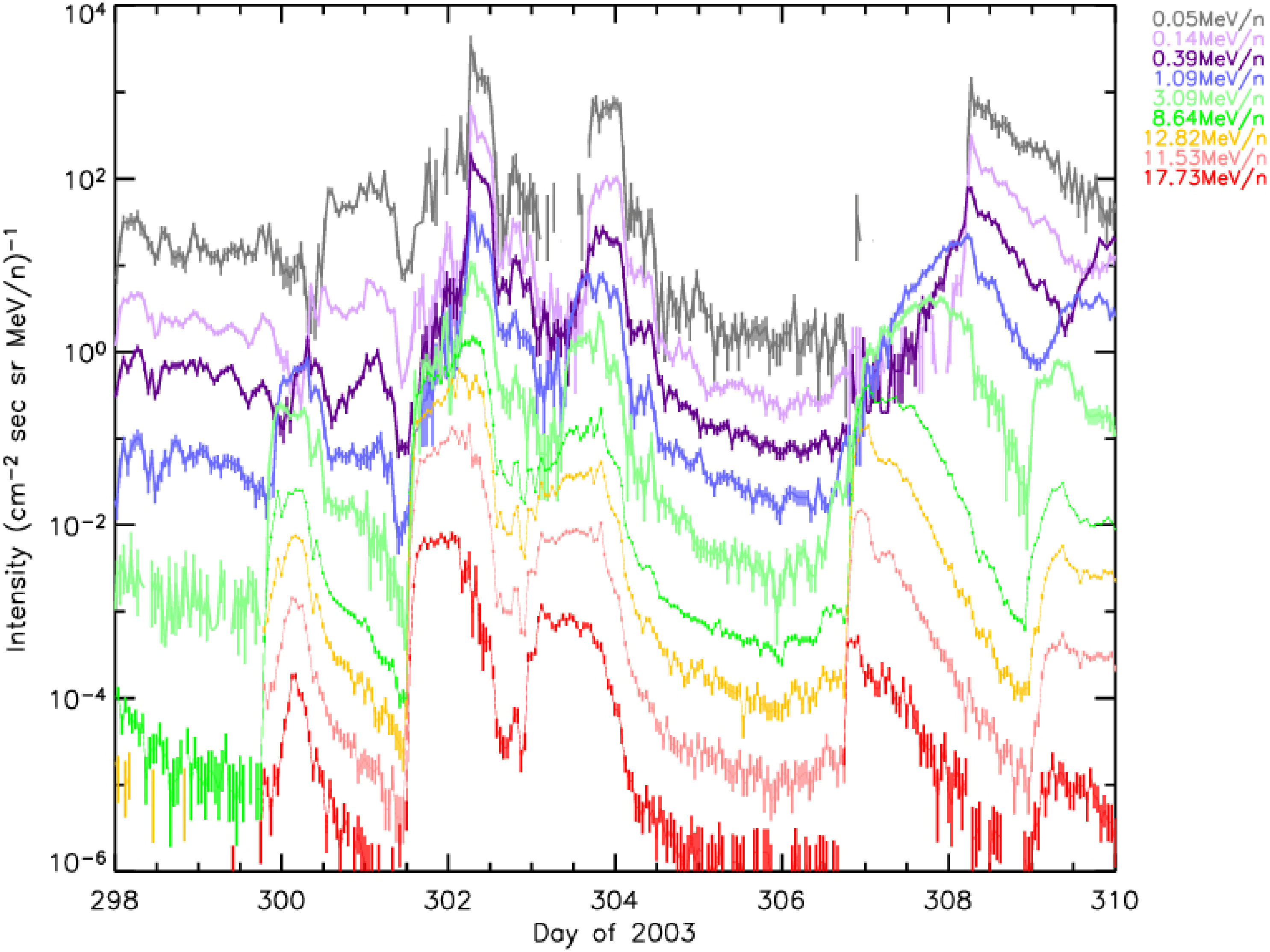
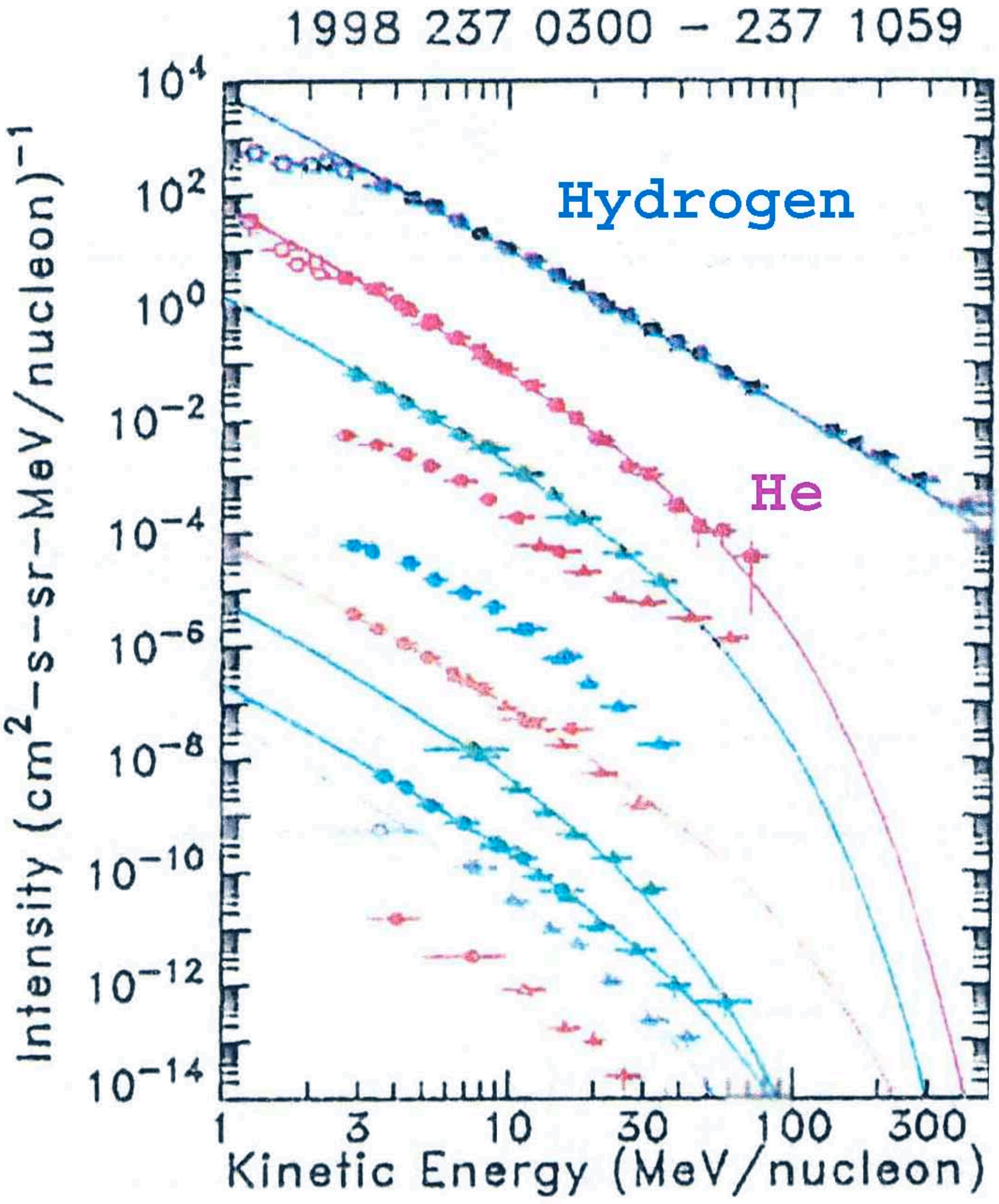


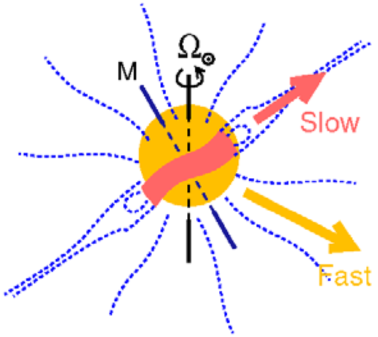
Figure 2.2. Intensity-time profiles of electrons and protons in 'pure' (a) gradual and (b) impulsive SEP events. The gradual event is a disappearing-filament event with a CME but no impulsive flare. The impulsive events come from a series of flares with no CMEs.

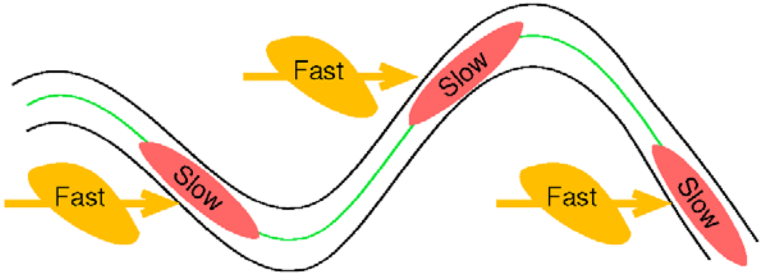
ACE Observations (1AU)

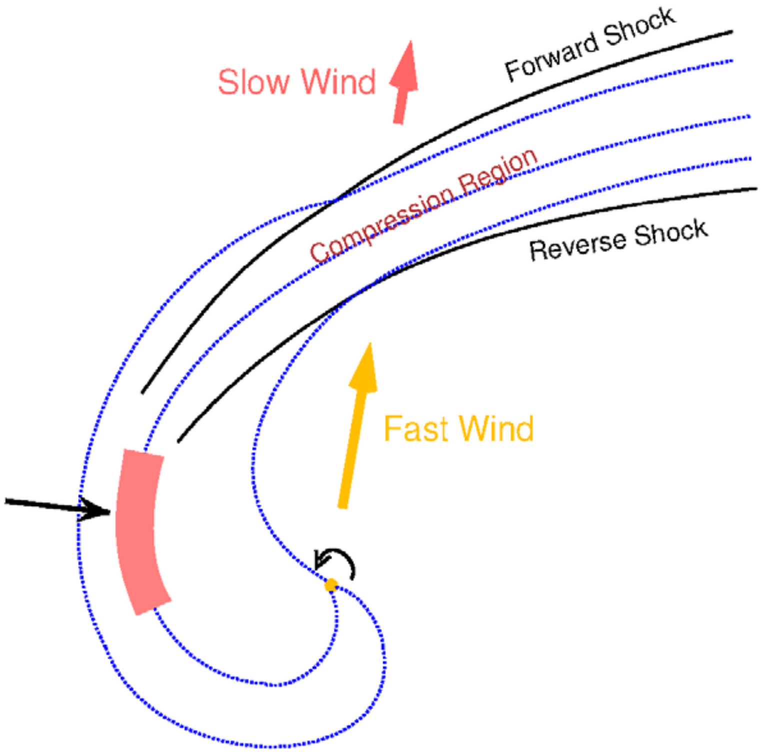



1998 237 0300 - 237 1059
Hydrogen
He
Intensity (cm^2-s-sr-MeV/nucleon)$^{-1}$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
1
3
10
30
100
300
Kinetic Energy (MeV/nucleon)

Co-rotating Interaction Regions



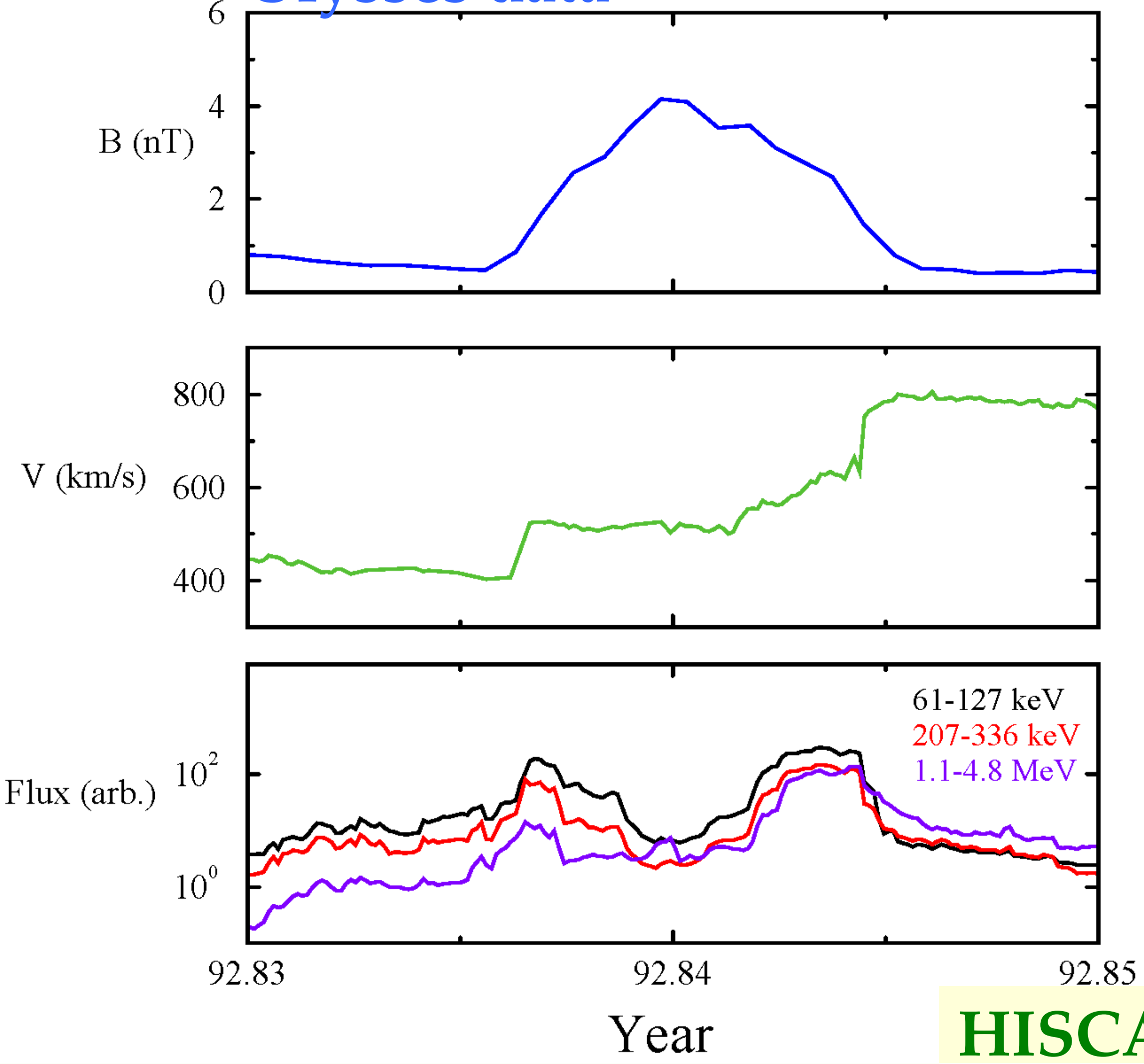




Gradual Compression (no shock)

Corotating Interaction Regions

Ulysses data



Compression of the magnetic field within CI

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

Energetic Particles peakin The F/R shocks, with a larg intensity at the reverse sho

HISCALE data courtesy Tom Arn

- These all contribute to the energetic-particle environment at Earth.

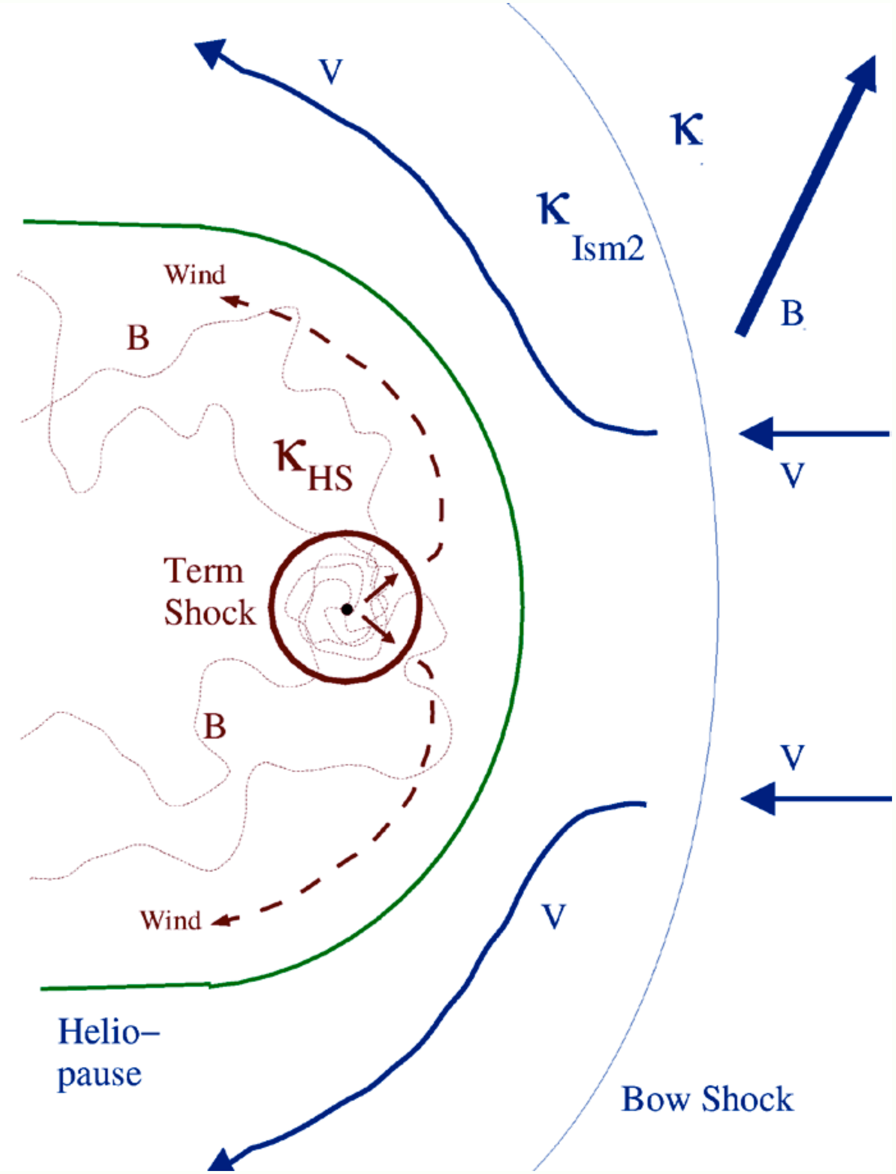
- But important effects comes from energies >≈ 100 MeV and higher. These are primarily galactic cosmic rays, coming into the heliosphere from the galaxy. They are a primary hazard to humans in space

- Below some 10^{13} eV, they are significantly modified by the heliosphere.

- Galactic cosmic rays ≈ 100 MeV-10GeV will be the focus of the rest of this lecture.

This is a schematic illustration of cosmic rays in the heliosphere. There is an isotropic, spatially homogeneous intensity coming from large distances.

The goal is to determine the important physical processes and obtain quantitative models of the effects of the heliosphere on observations.



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 then 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 >> 10^5 yrs.

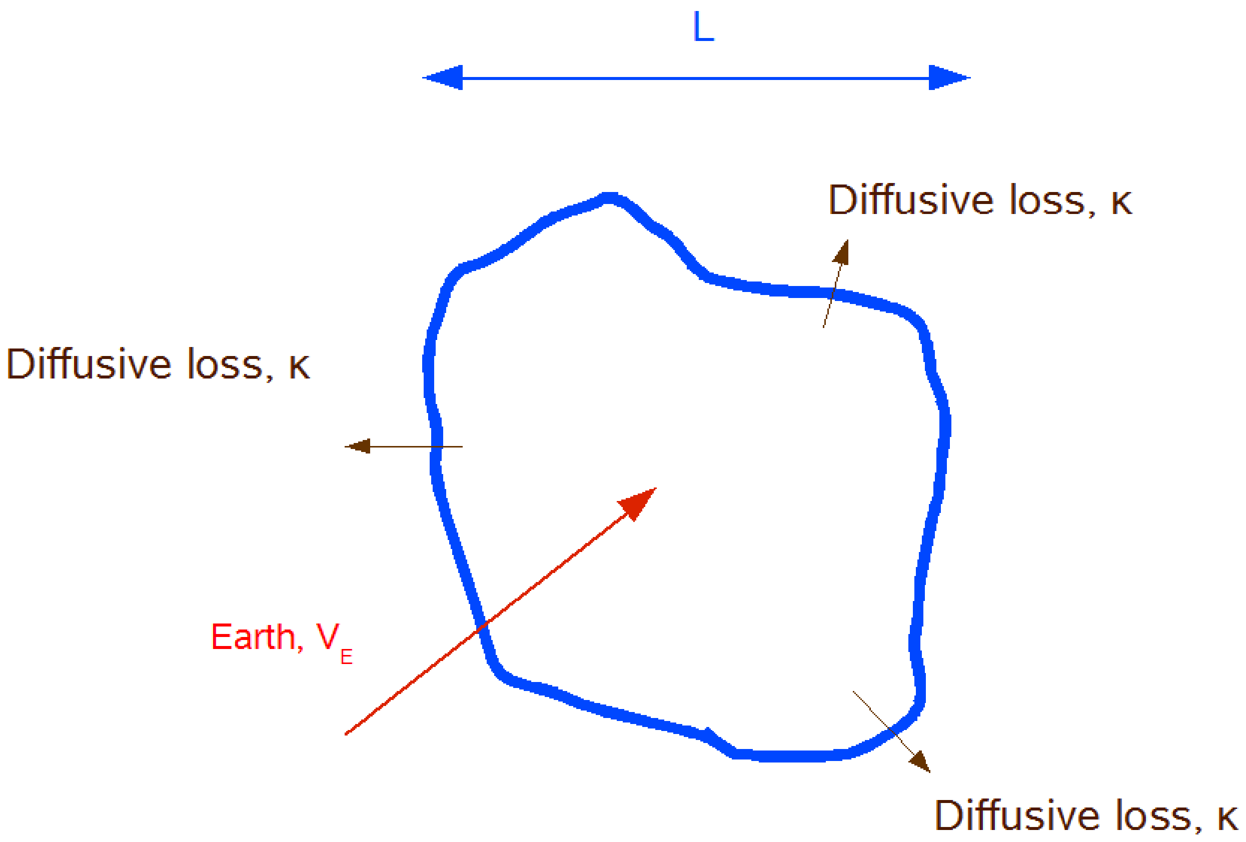


Illustration of the Earth passing through a quasi-static region of spatial scale L. The diffusive loss time is ≈ L^2/κ. The Earth passes through the region in ≈ L/V_E.

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 $\cdot_{\mathrm{ism}}$ the diffusion coefficient in the local ISM. There are two important dimensionless parameters which will determine the nature of the boundary condition. They are

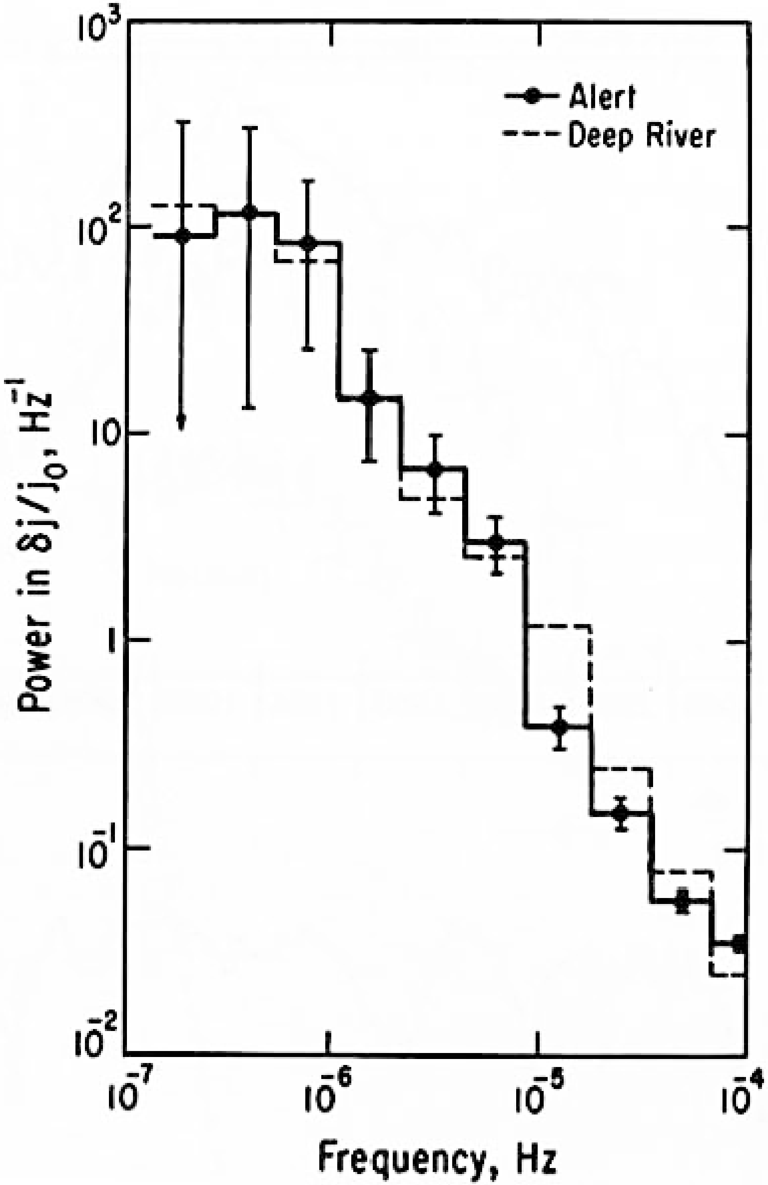
It is readily seen that if $\cdot_{\mathrm{ISM}}$ is large enough that both (T) and r·(T) are much less than unity, the diffusion in the local ISM is very rapid, and the boundary may be taken to be a standard ``free escape'' boundary at the heliopause. At the heliopause we set the distribution function to be interstellar.

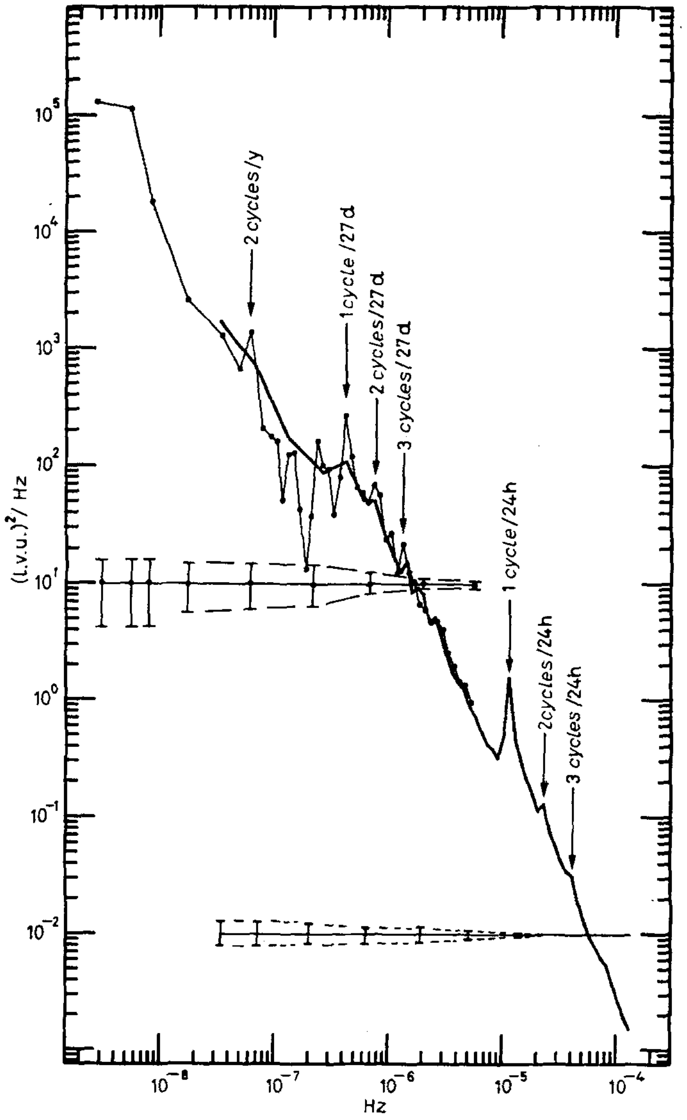
Heliospheric Causes of Galactic Cosmic-Ray Time Variations

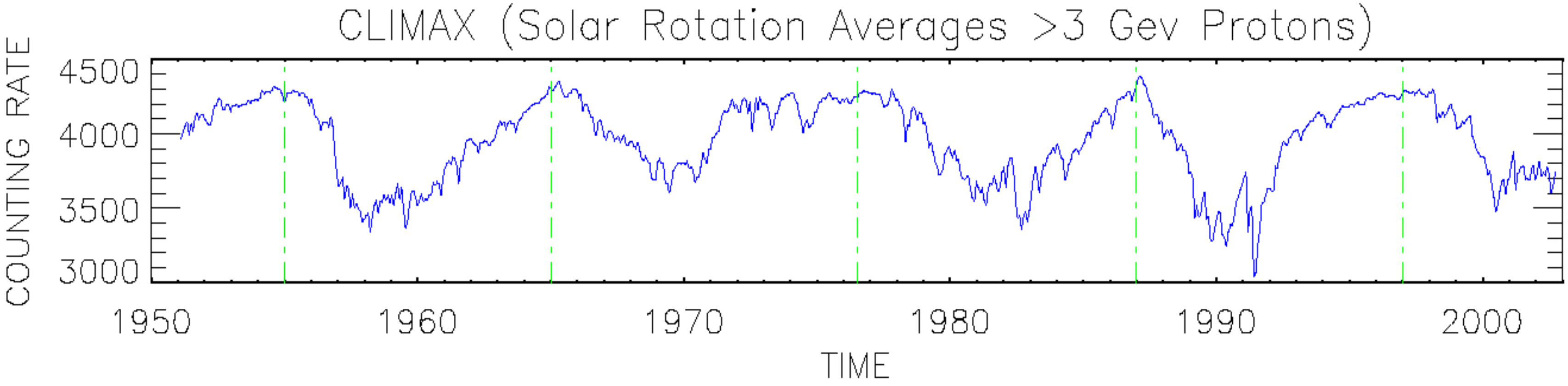
- Variations with time scales less than about 10^5 years are probably *heliospheric* in origin.

- These variations are caused by solar-wind fluctuations and and changes in the Sun and heliosphere.

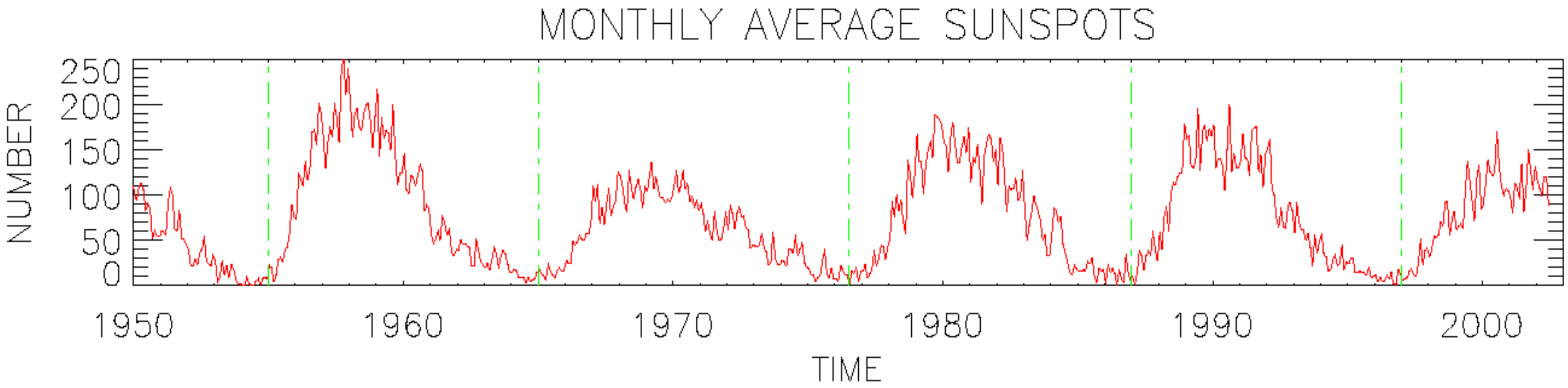
There is a broad, continuous spectrum of fluctuations, with spectral peaks at certain periods (solar cycle, etc.



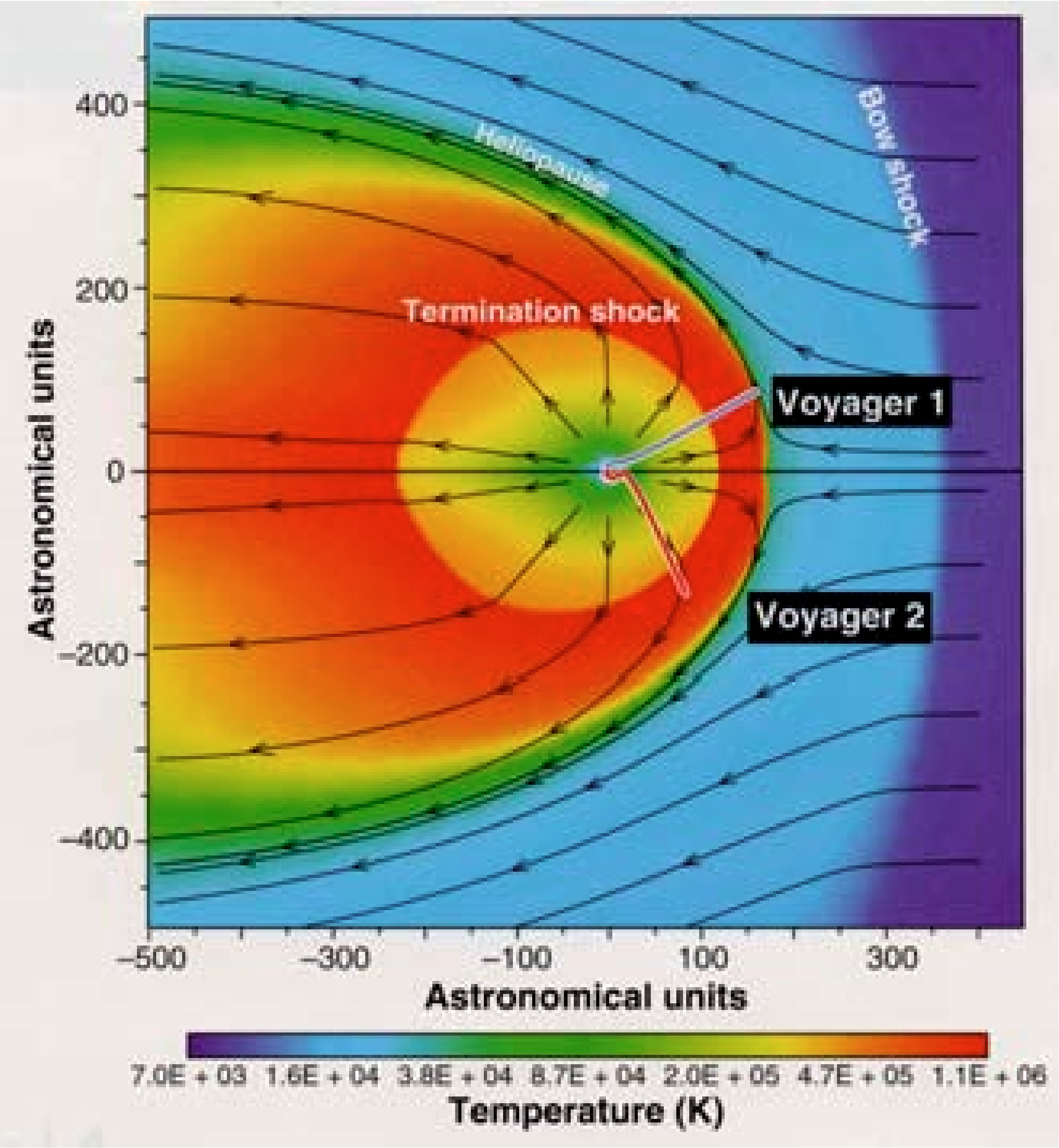


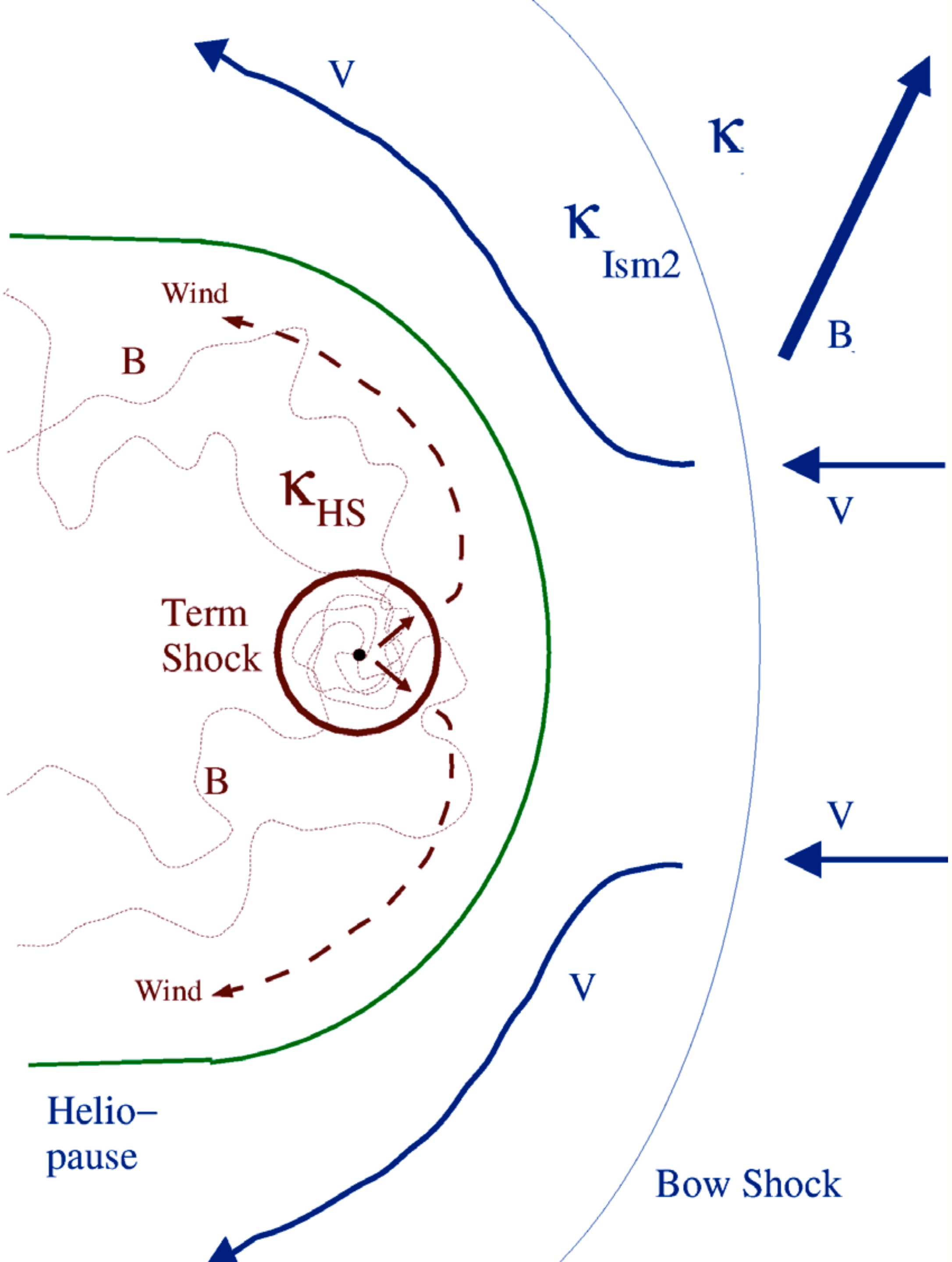


CLIMAX (Solar Rotation Averages >3 Gev Protons)

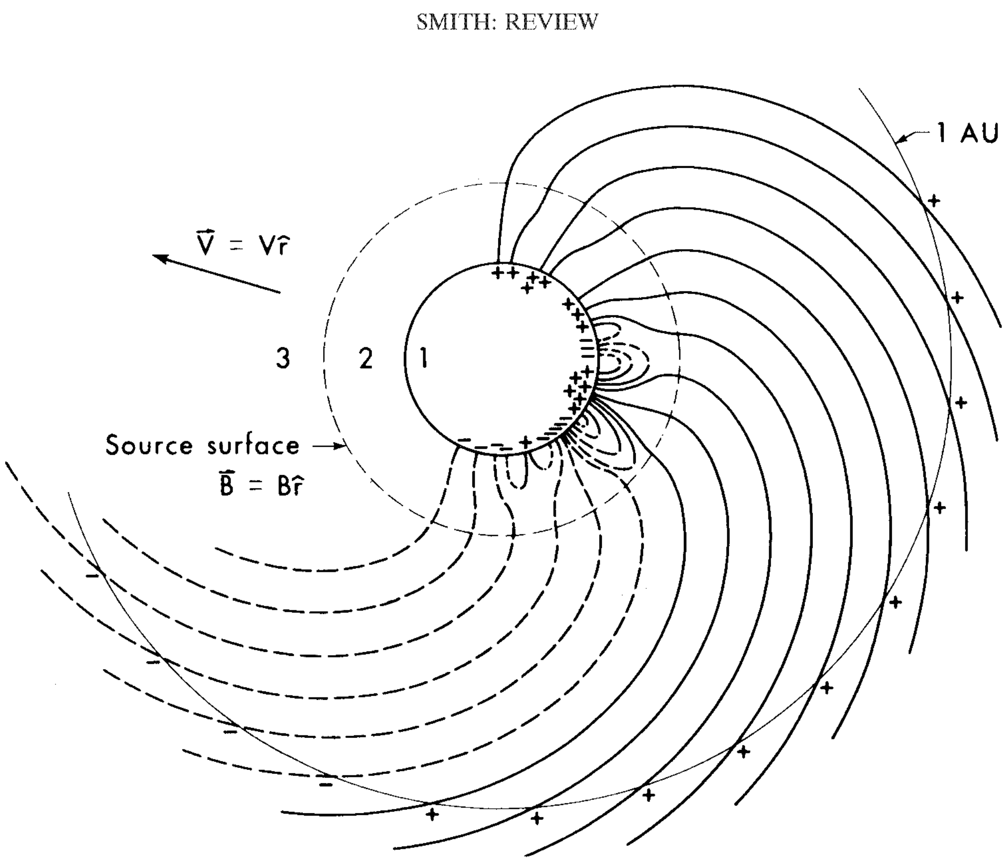


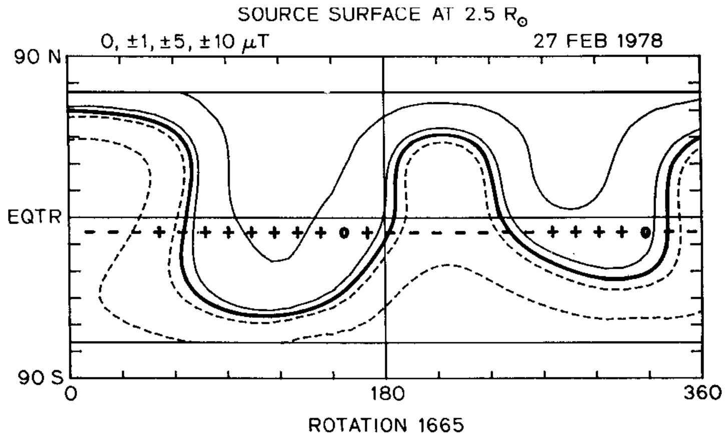
MONTHLY AVERAGE SUNSPOTS


Heliopause
Bow shock
Termination shock
Voyager 1
Voyager 2
400
200
0
−200
−400
Astronomical units
−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)

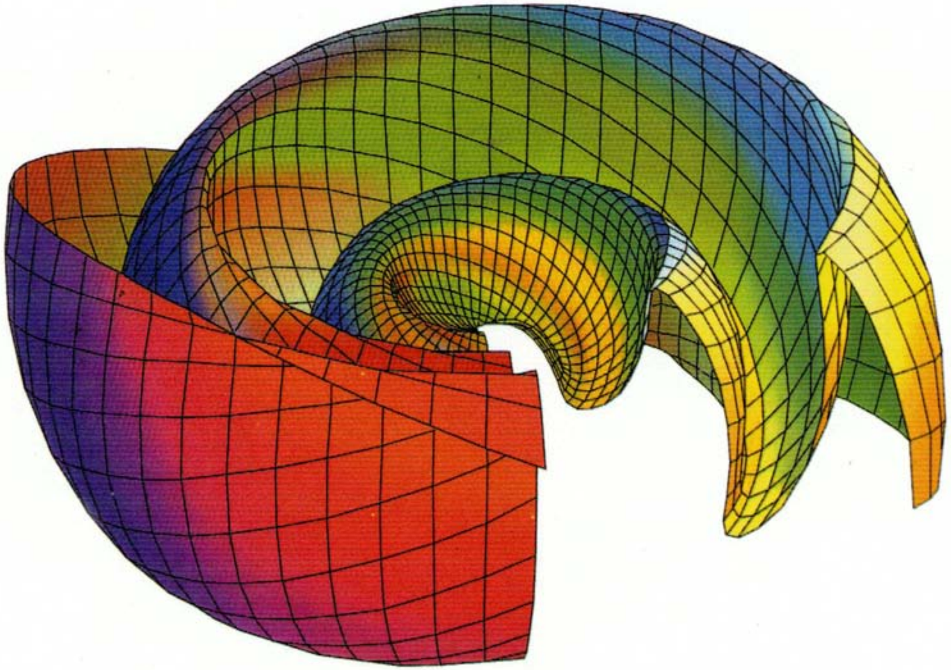

V
κ
κ Ism2
B
V
V
V
Wind
B
κ HS
Term Shock
B
Wind
Helio–pause
Bow Shock

Magnetic sector structure.

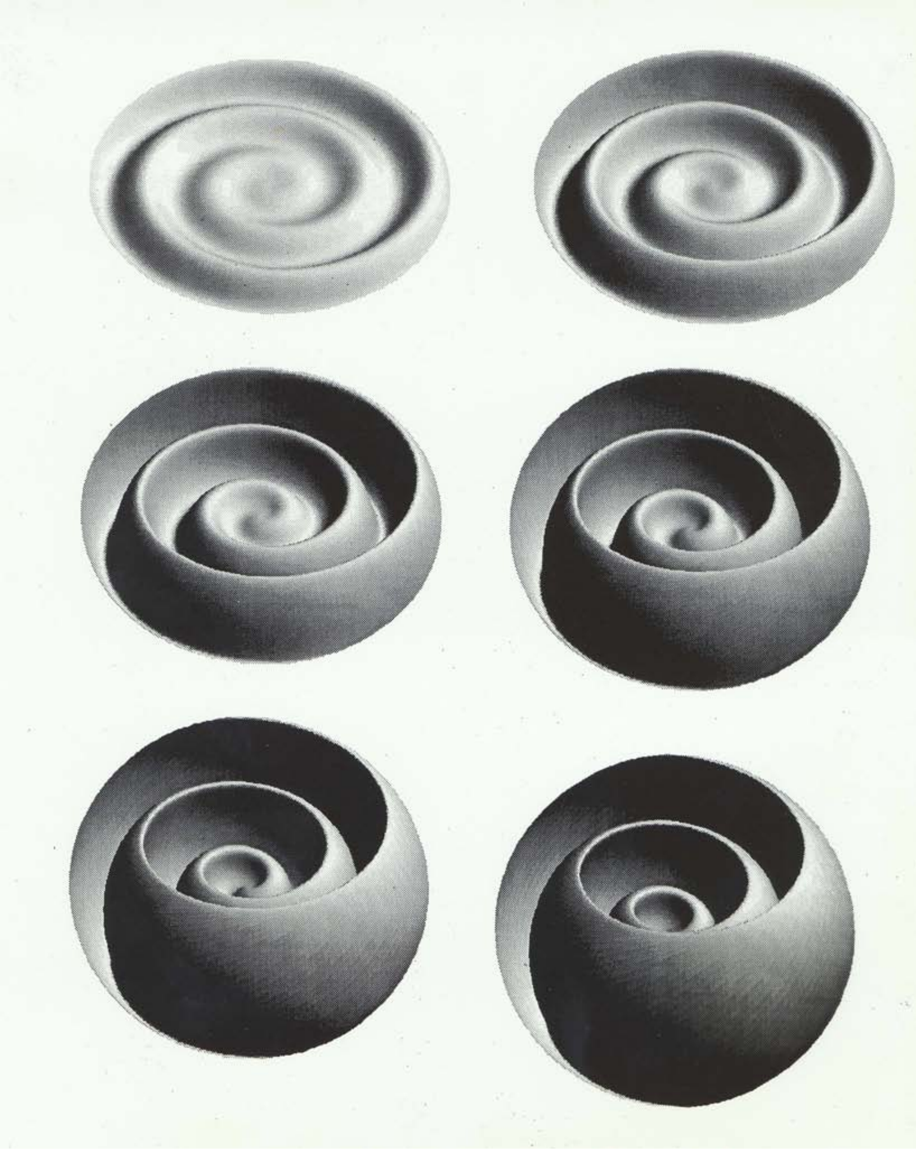




The heliospheric magnetic field for much of a sunspot cycle is organized by the heliospheric current sheet, which separates the northern and southern heliospheric magnetic field.



The current sheet changes from sunspot minimum to sunspot maximum



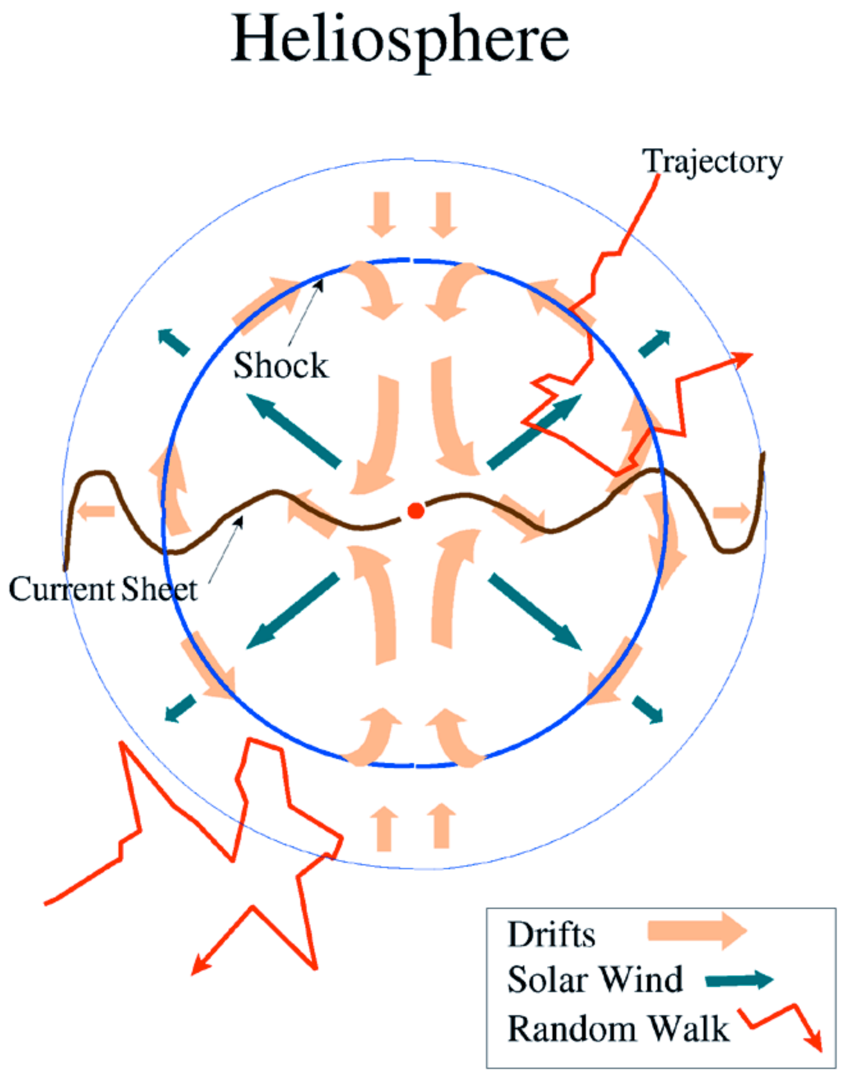
The Physical Picture of Galactic Cosmic Rays in the Heliosphere

- 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.

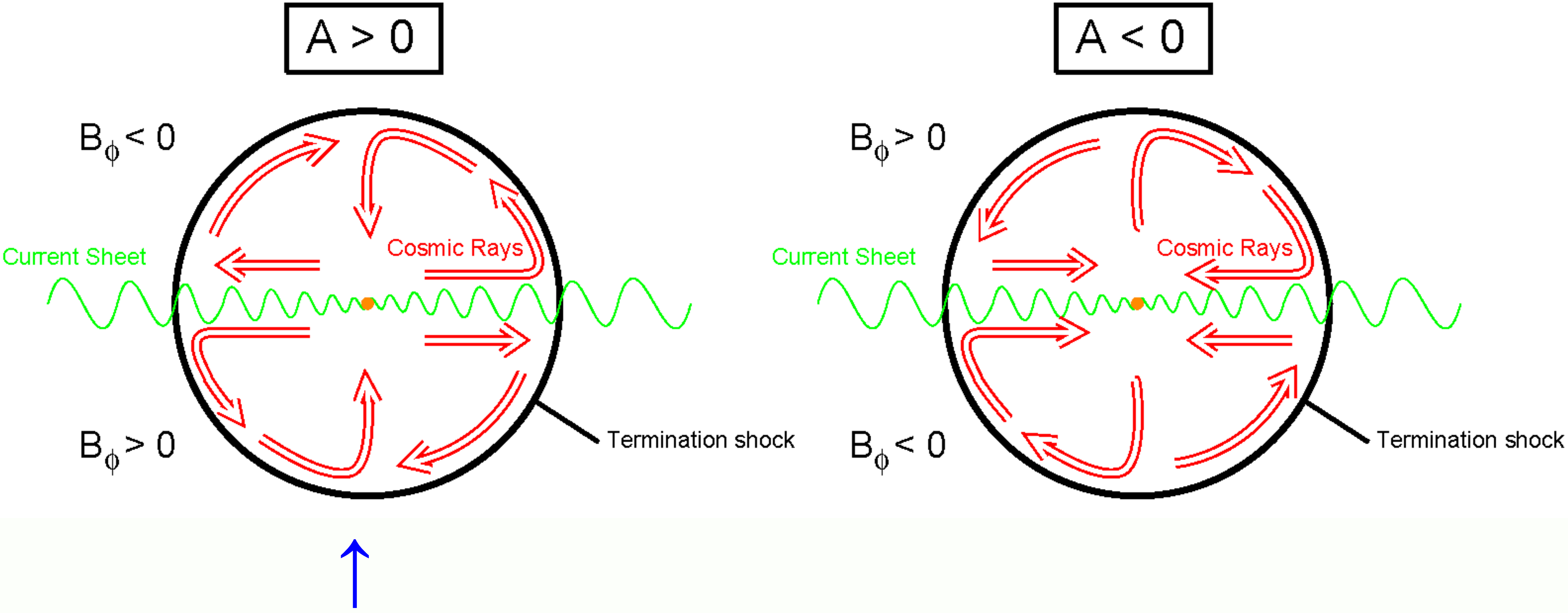
The galactic cosmic rays enter the heliosphere through a combination diffusion (random walk) and drift.

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

The drift motions are very significant.



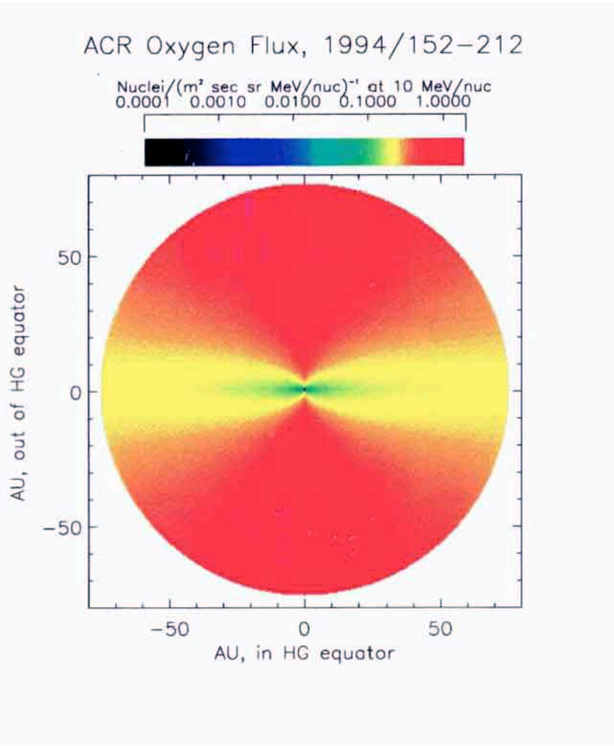
Cosmic-Ray Transport in the Heliosphere



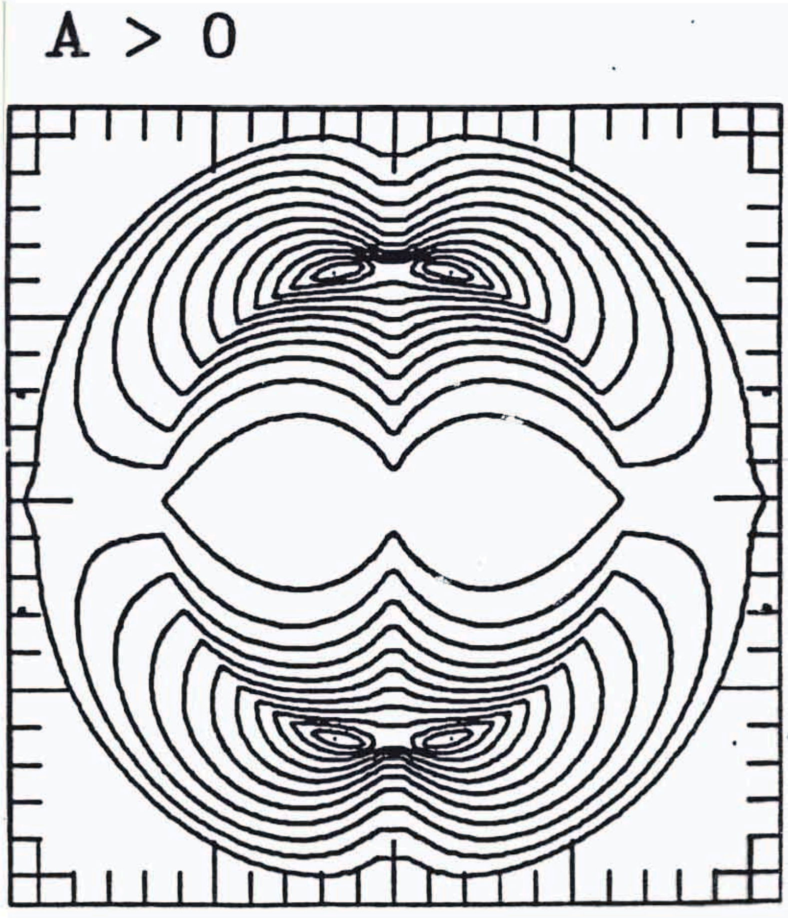
This is the current solar cycle

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

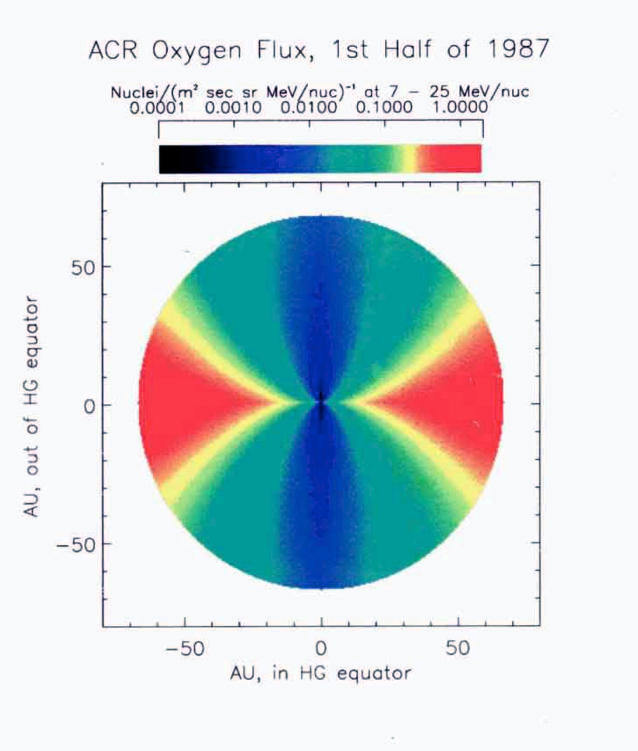
Multi-spacecraft observations



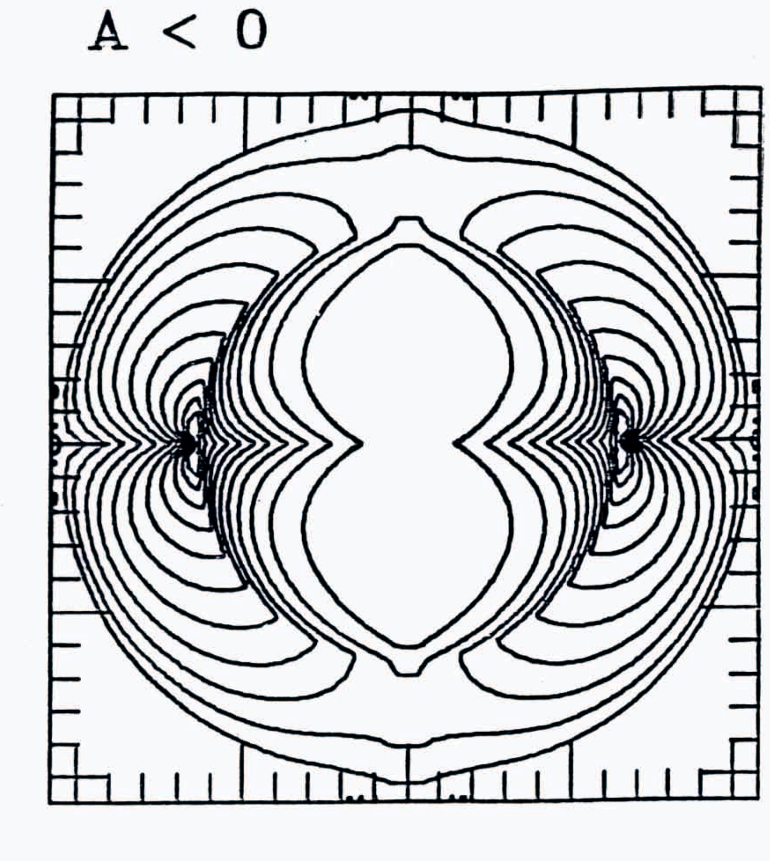
Model Calculation

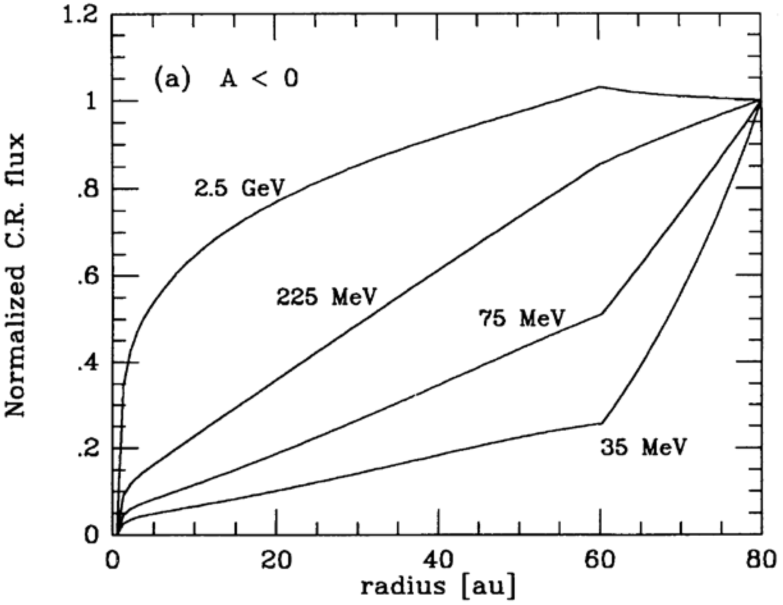


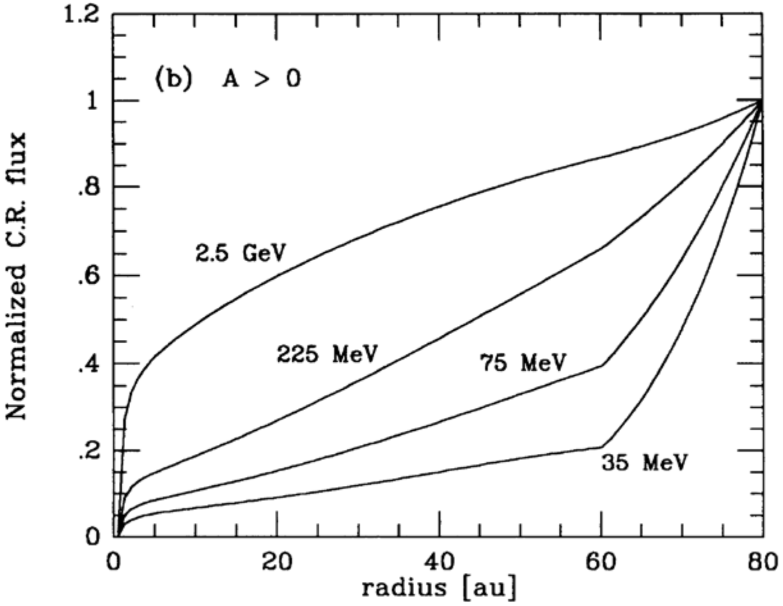
The latitudinal distribution for A>0



Model Calculation

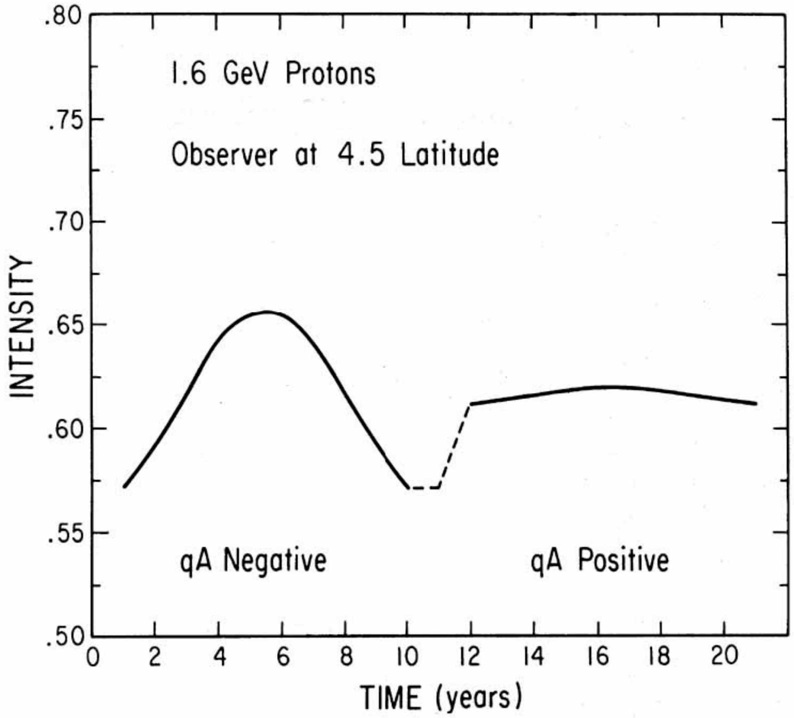



(a) A < 0
2.5 GeV
225 MeV
75 MeV
35 MeV
Normalized C.R. flux
radius [au]
0
.2
.4
.6
.8
1
1.2
0
20
40
60
80

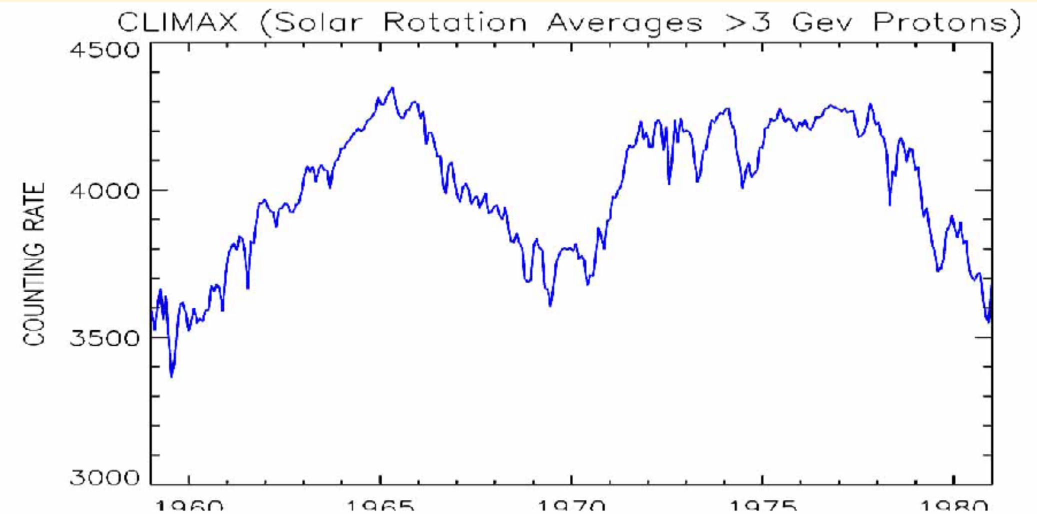

(b) A > 0
2.5 GeV
225 MeV
75 MeV
35 MeV
Normalized C.R. flux
radius [au]
0
.2
.4
.6
.8
1
1.2
0
20
40
60
80

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

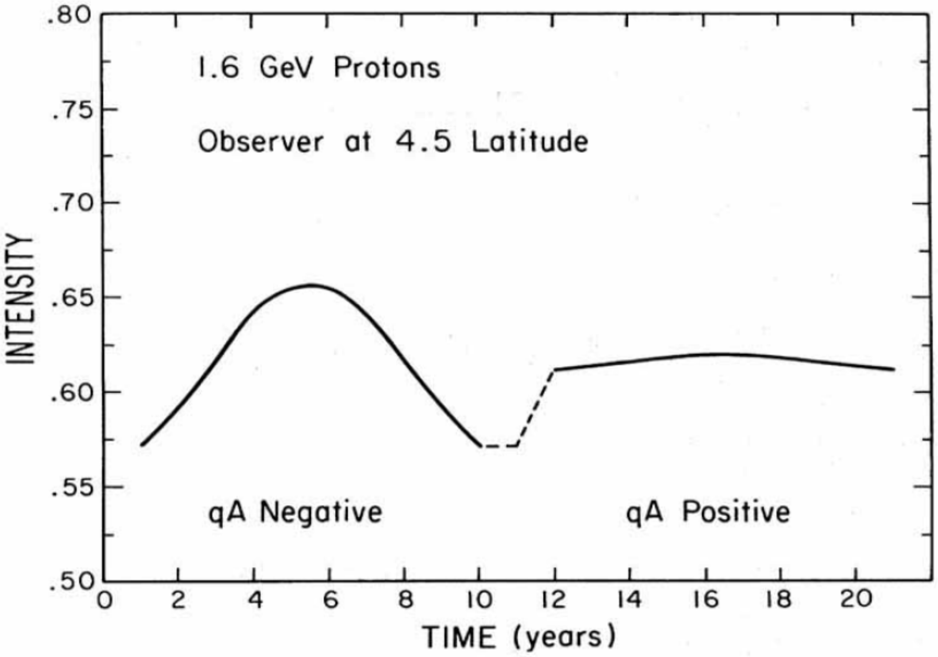
KÓTA AND JOKIPII (Ap J 1983)



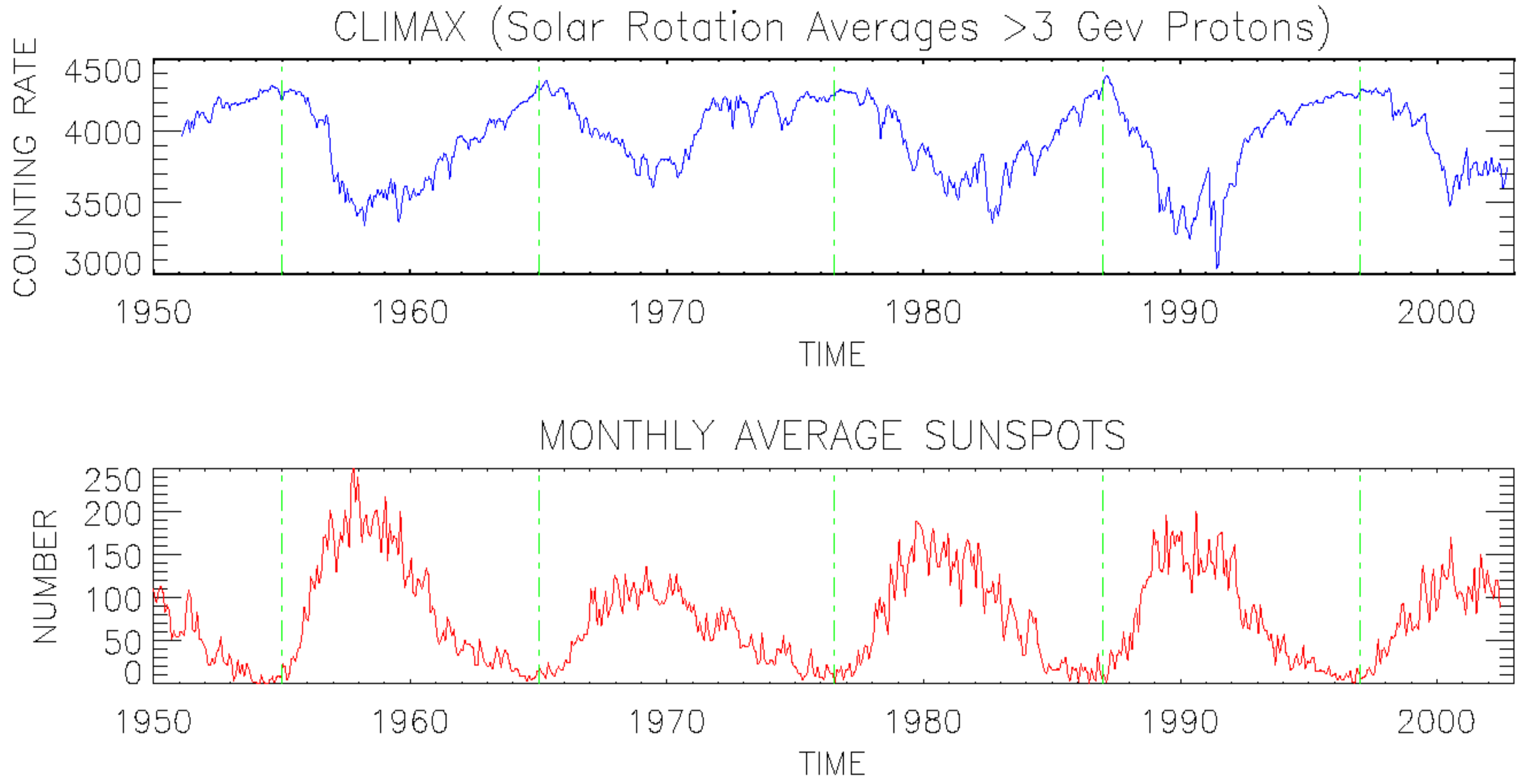
This basic picture provides a robust interpretation of many observations.



KÓTA AND JOKIPII (Ap J 1983)



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

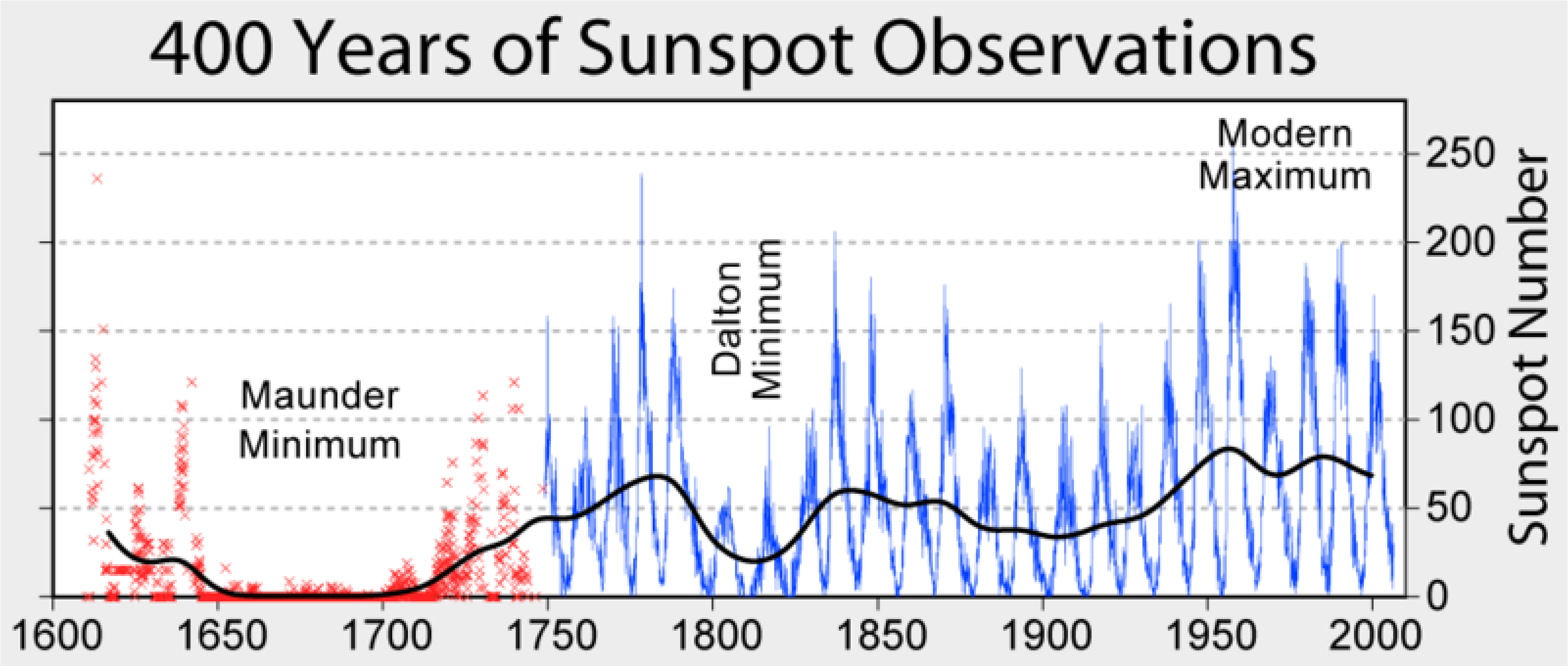


Further Back: The Maunder Minimum

- The Maunder Minimum is the name given to the period spanning roughly the years 1645 to 1715, when sunspots were exceedingly rare.

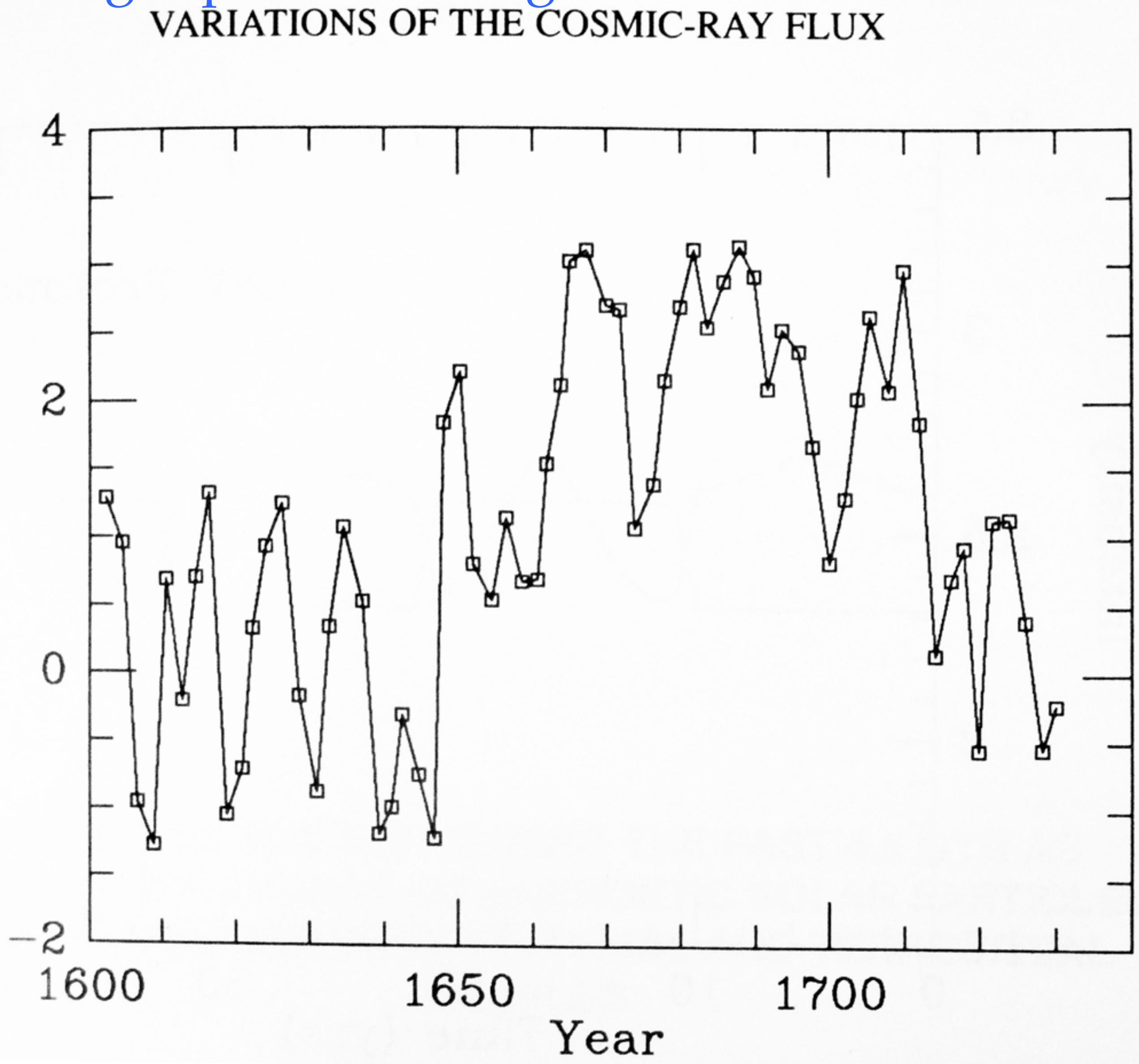
- It was possibly associated with a period of cold.

- The cosmic rays could only be measured by proxy.

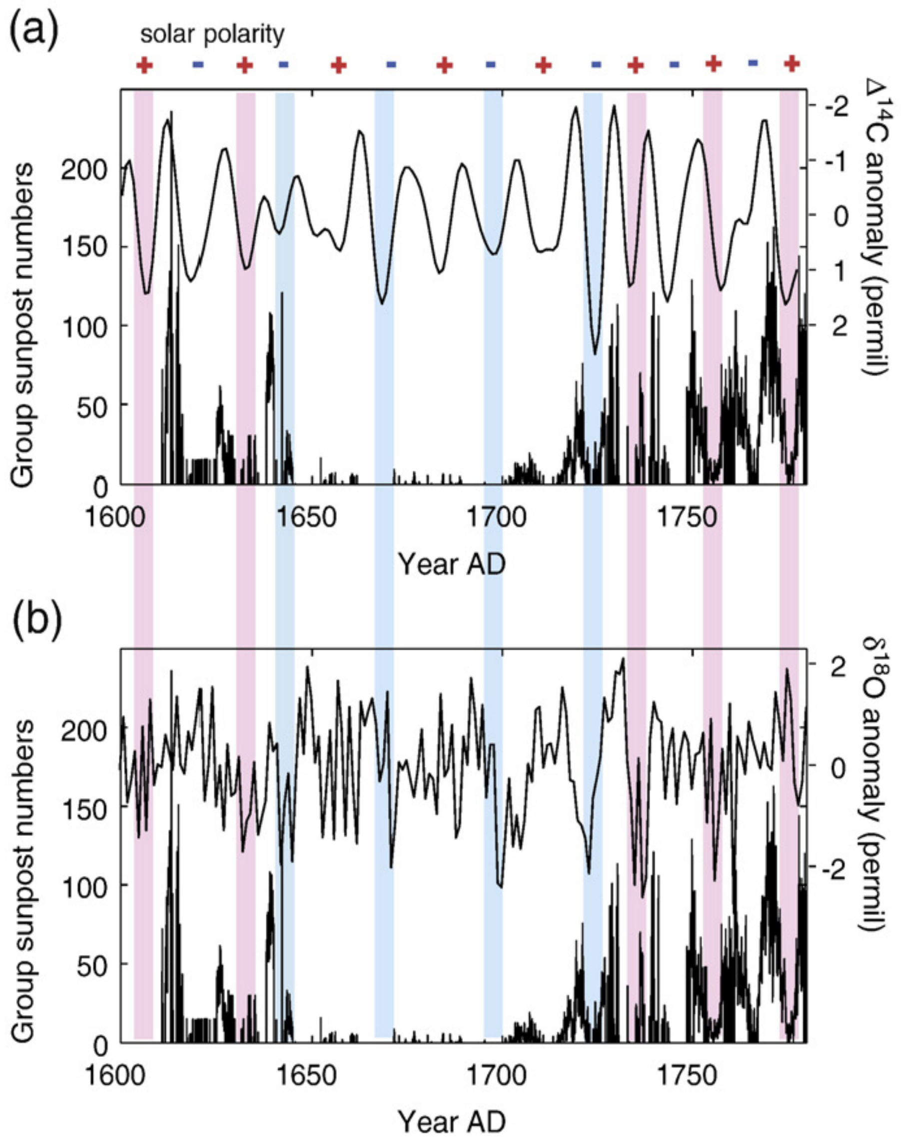


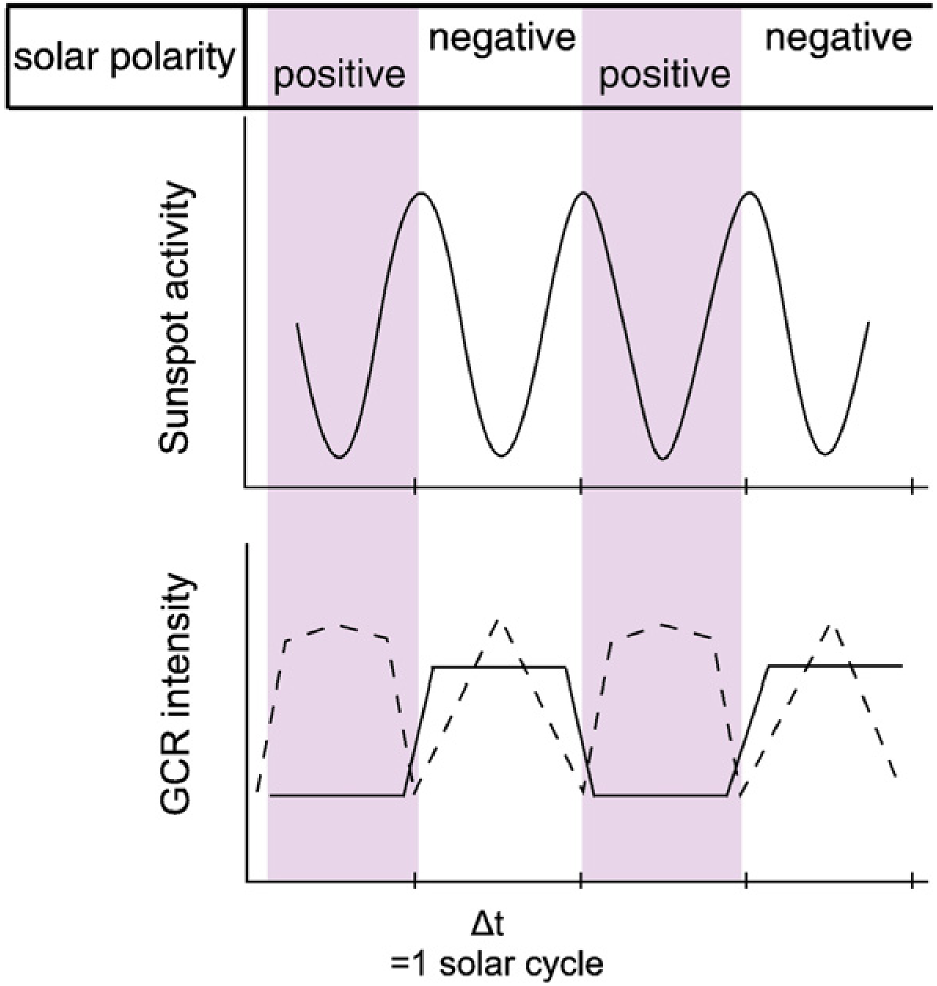
400 Years of Sunspot Observations

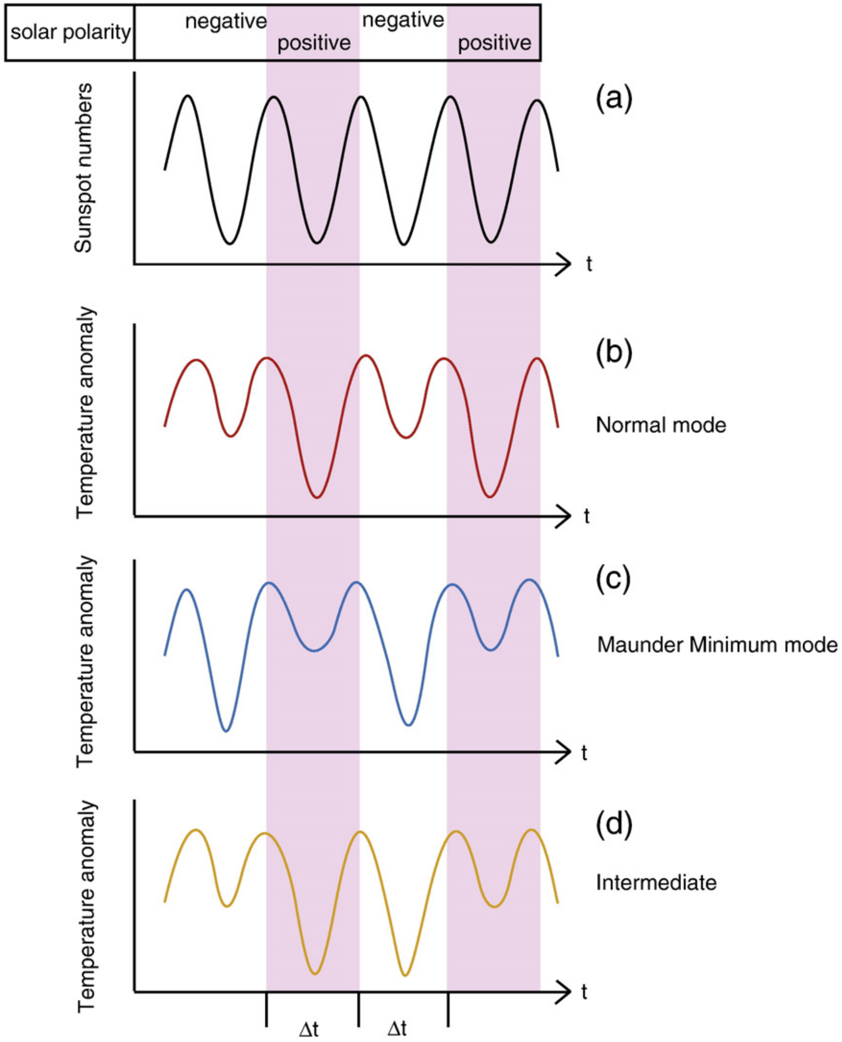
Data from Kocharov (1987) during the Maunder Minimum. Note the longer period during the Maunder minimum.


VARIATIONS OF THE COSMIC-RAY FLUX

More-recent data on the Maunder Minimum in a recent paper by Miyahara, et al, 2008. This data has been filtered to show only variations > 18 years.




solar polarity
positive
negative
positive
negative
Sunspot activity
GCR intensity
Δt
=1 solar cycle


solar polarity
negative
positive
negative
positive
Sunspot numbers
(a)
t
Temperature anomaly
(b)
Normal mode
t
Temperature anomaly
(c)
Maunder Minimum mode
t
Temperature anomaly
(d)
Intermediate
t
Δt
Δt

Causes of Longer-Term Variations

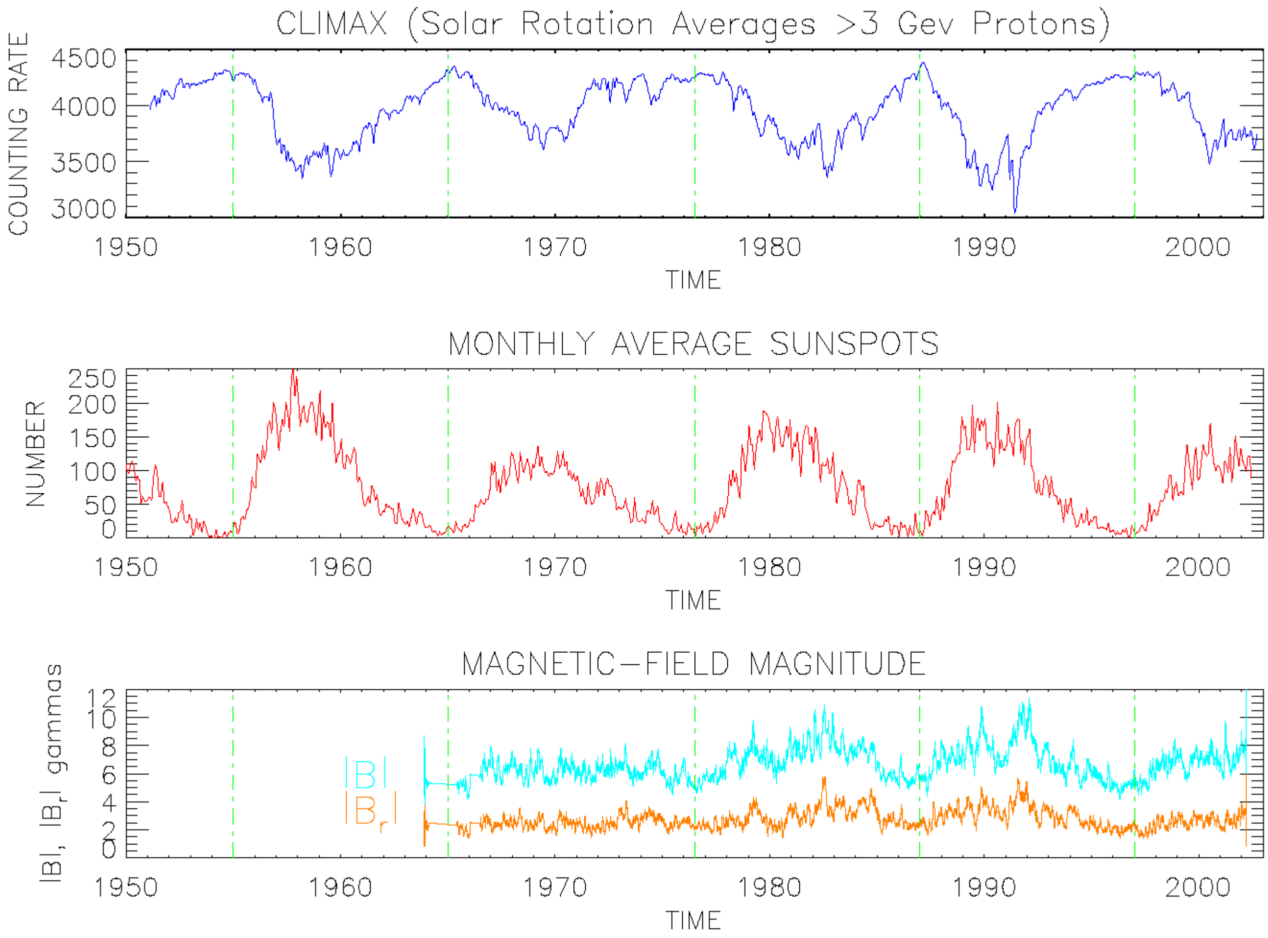
- Relating the longer-term variations to detailed physical processes is more difficult.

- It is clear that variations in the solar wind and its fluctuations are a likely cause.   But varyiations in the interplanetary magnetic field are also likely to be very important.

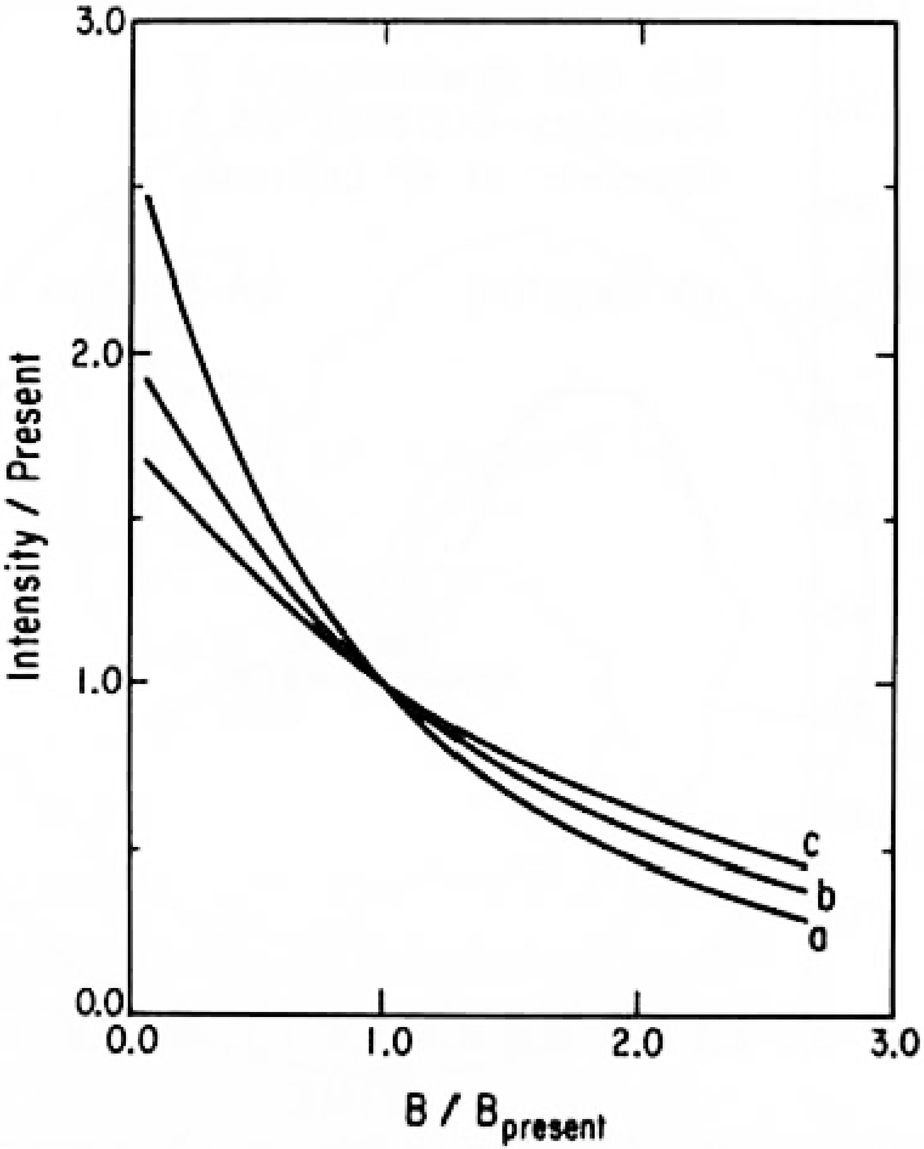
- Beyond some 50,000 years, interstellar causes remain likely.

- 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.



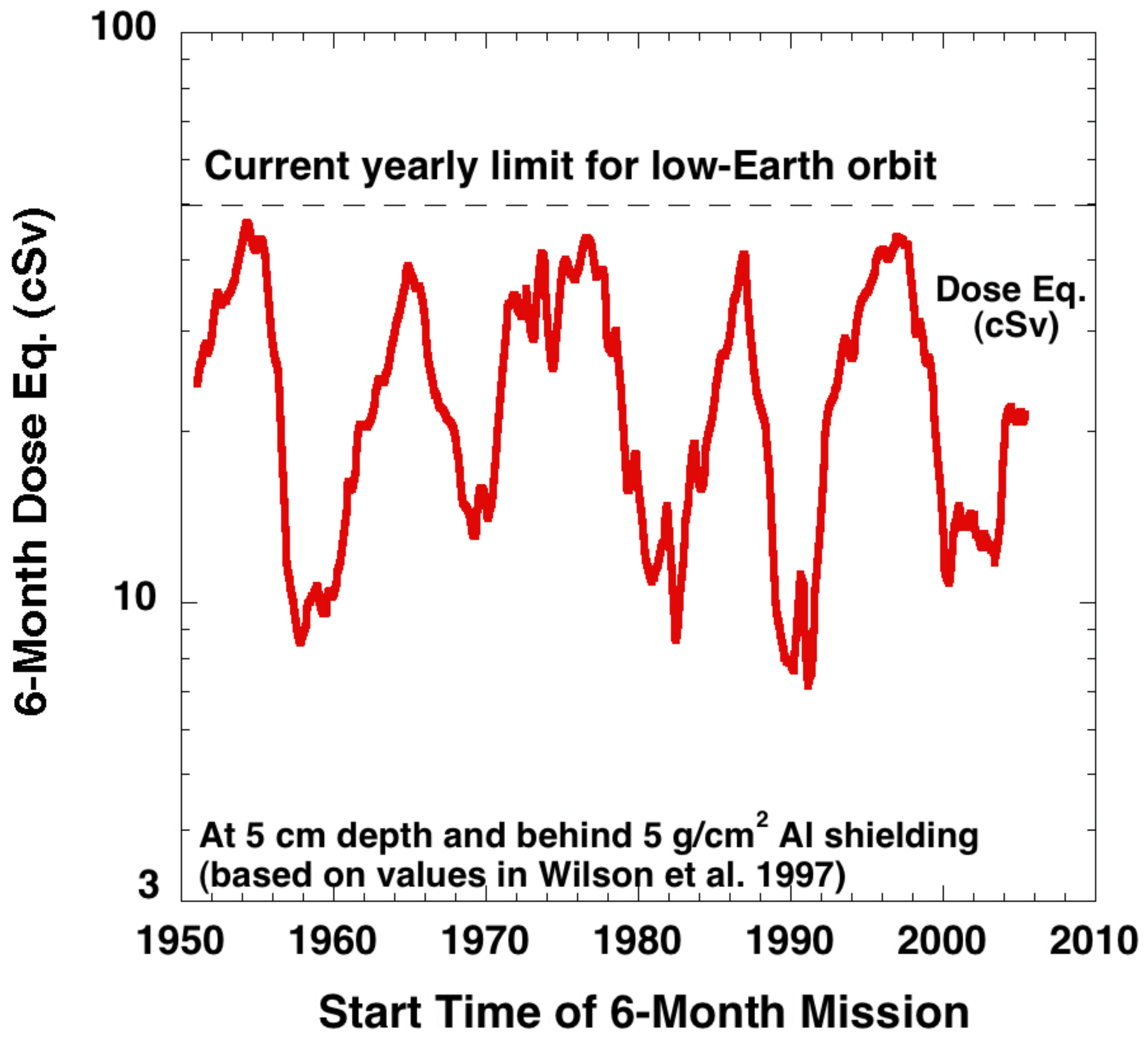
Radiation Hazards to Humans

- 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.

The solar minimum intensity of Galactic cosmic rays (for a 9-month journey to Mars) is enough to exceed the current radiation limits for astronauts in low Earth orbit



Mewaldt et al. 2006

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

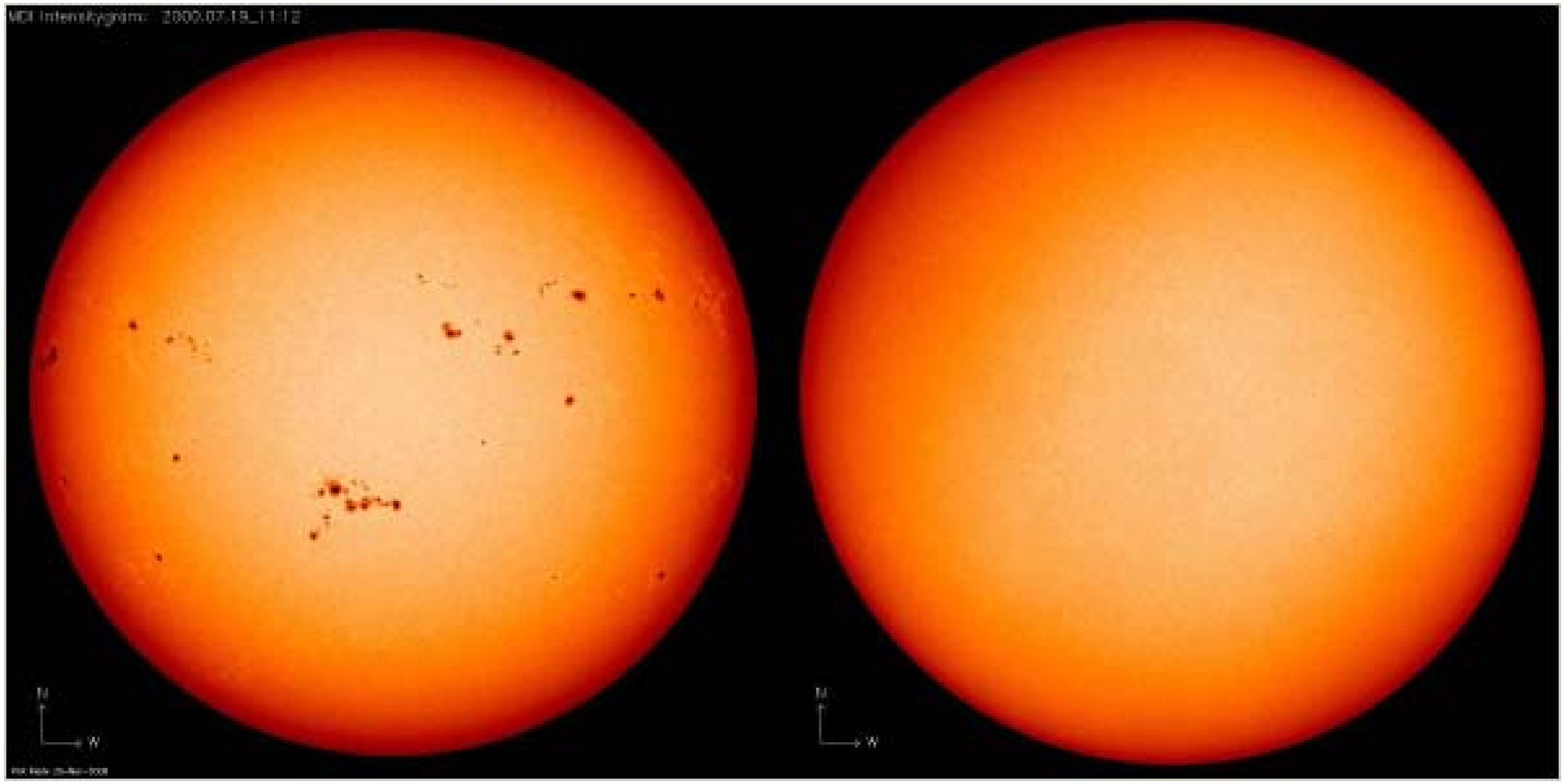
Spacecraft can be constructed out of hydrogen-rich plastics, rather than aluminum.

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.

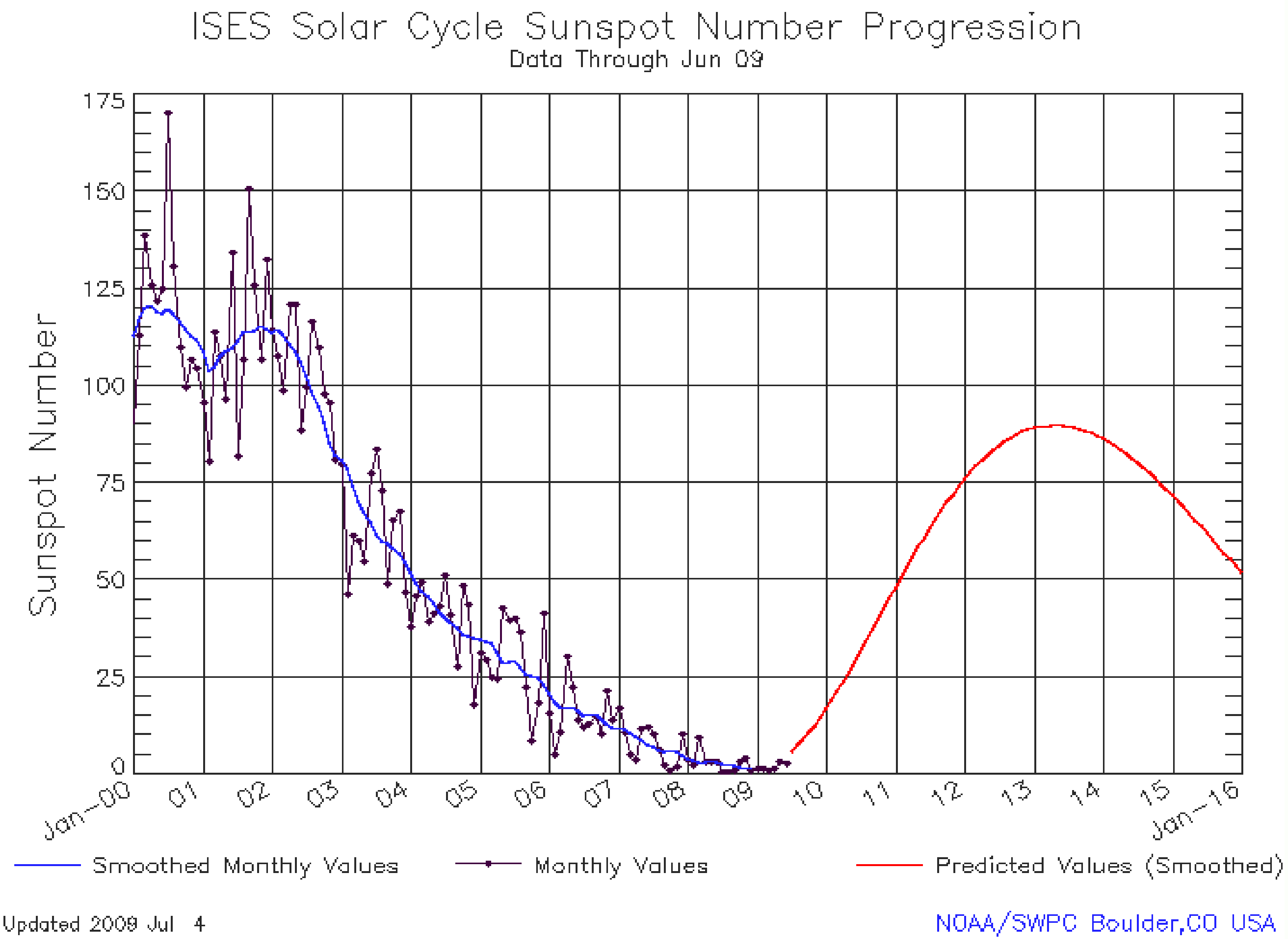
Electromagnetic fields may also be a possibility.

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



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FEATURE

Solar Wind Loses Power, Hits 50-year Low

09.23.2

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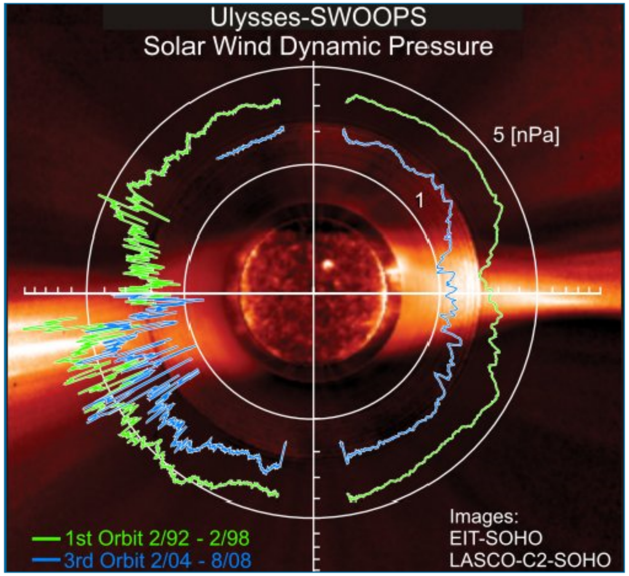
Sept. 23, 2008: In a briefing today at NASA headquarters, solar physicists announc that the solar wind is losing power.

"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 Antoni 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 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 2004-20 [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.

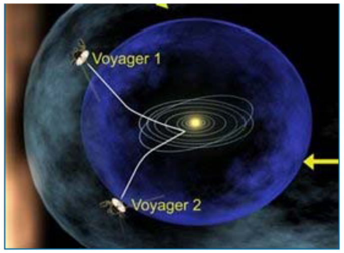
"What we're seeing is a long term trend, a steady decrease in pressure that began sometime in the mid-1990s," explains Arik Posner, NASA's Ulysses Program Scientist in Washington DC.

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."

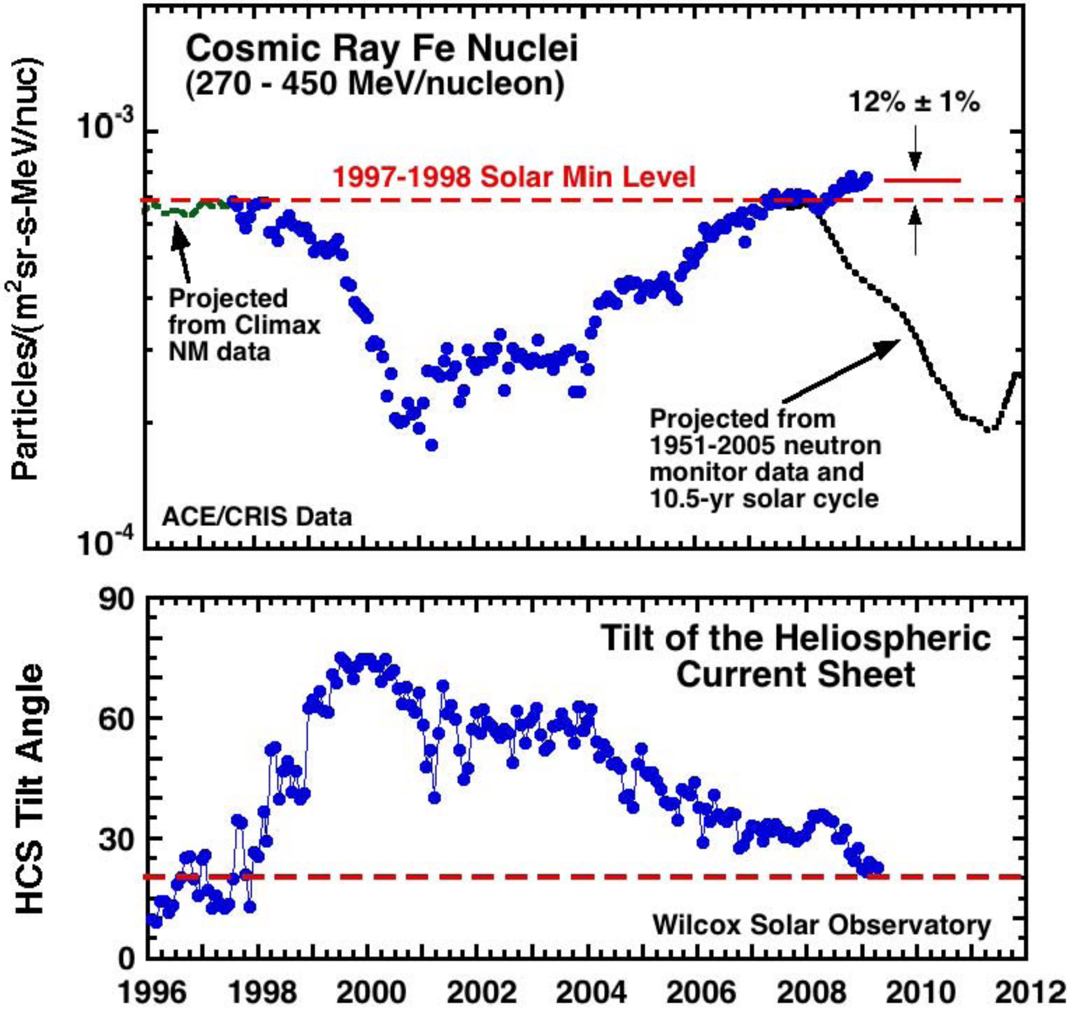
In addition to weakened solar wind, "Ulysses also finds that the sun's underlying magnetic field has weakened by more than 30% since the mid-1990s," says Posner. "This reduces natural shielding even more."

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.

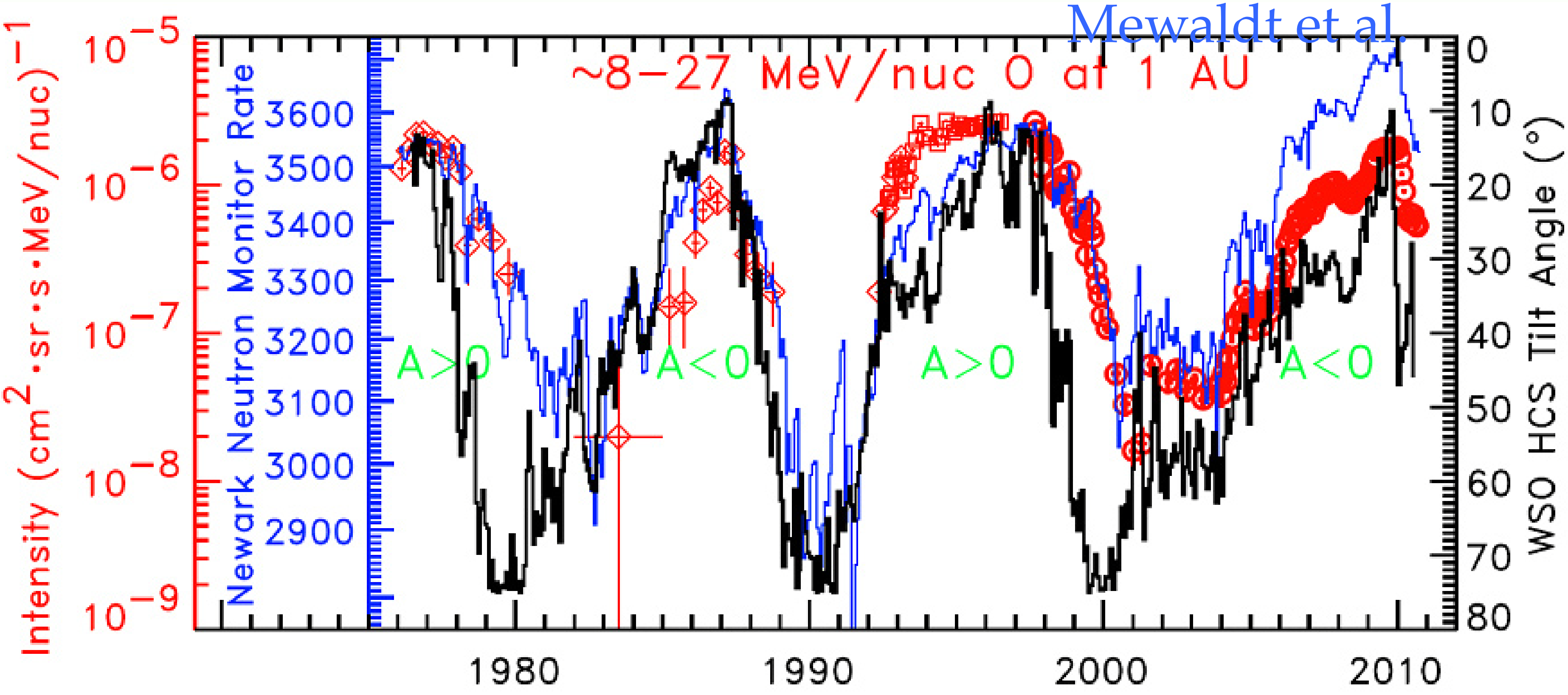
Cosmic-Ray Fe Intensity Reaches Record Levels in 2008-2009



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.

Now, consider the difference between the ACR and GCR, illustrated below.

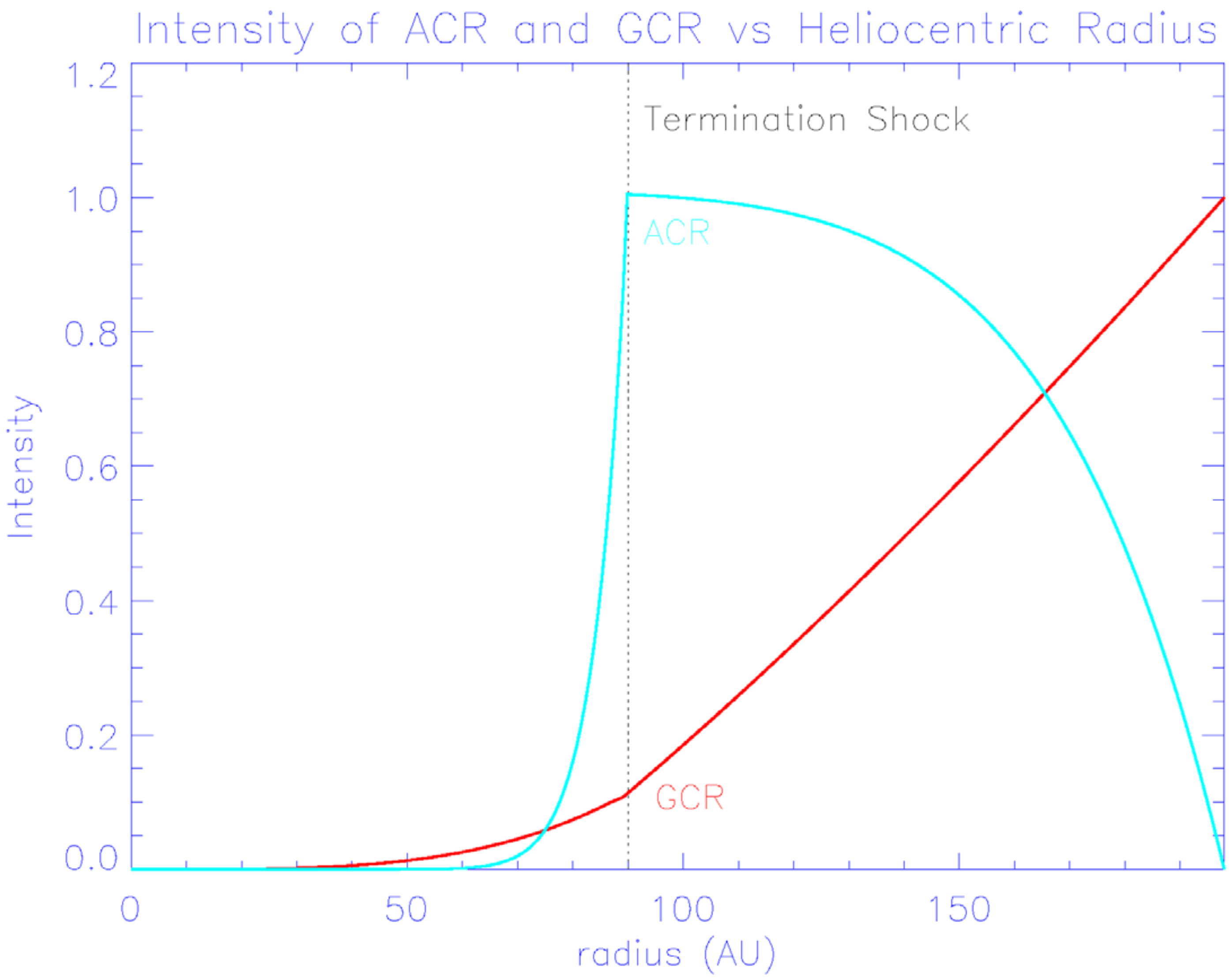
Observations from ACE News 136 – Mewaldt et al.



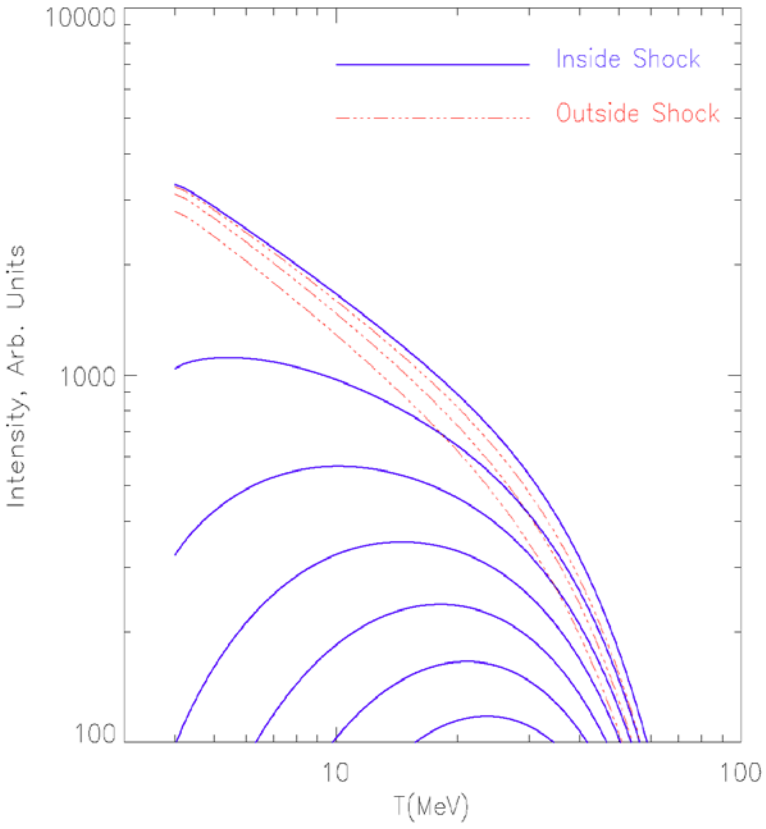
The Different Response of ACR and GCR to the Changes

- The observations show that the ACR and GCR behaved quite differently during the last minimum.
- The GCR increases was as expected from the faster transport in the weaker magnetic field.
- The ACR are subject to the same change in transport, so their *decrease* would suggest a weaker source.
- The smaller magnetic field and larger diffusion coefficient would, indeed, produce a smaller ACR source.
- We can test this idea by using a simple model.

The radial intensity profile from a simple analytic spherically symmetric profile.



Illustrative ACR model spectra, showing the ‘unfolding’ of the energy spectrum with increasing radius inside the shock and decreasing intensity beyond.



Voyager 1 observations of Cummings, Stone and Webber, 1996

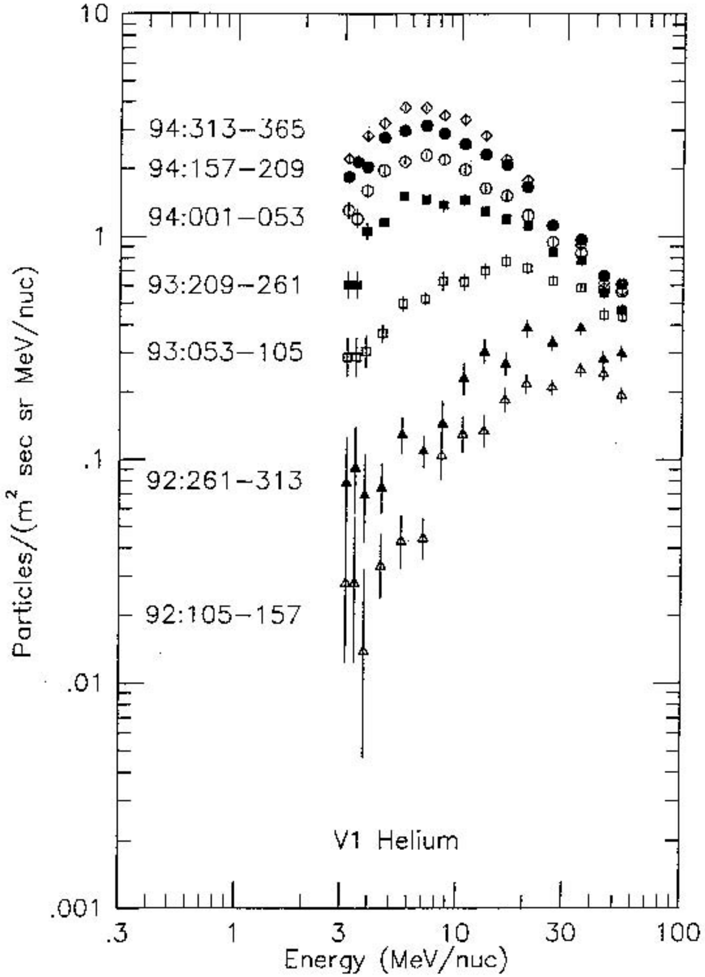


Figure 3. Energy spectrum of helium measured at V1 for seven time periods.

A Rediscovery of a Relevant Old Observation

- Because it is increasingly recognized that the alternative mechanisms have difficulties in the inner heliosheath, the proponents *have moved the site of ACR acceleration out to near the heliopause*.
- But there is a nearly forgotten observation which argues strongly against this and for an ACR origin near the termination shock.
- The data is from 1990-1996 Voyager data, taken well inside the termination shock (McDonald, et al, 2000, see also Jokipii and Kóta, 2001.

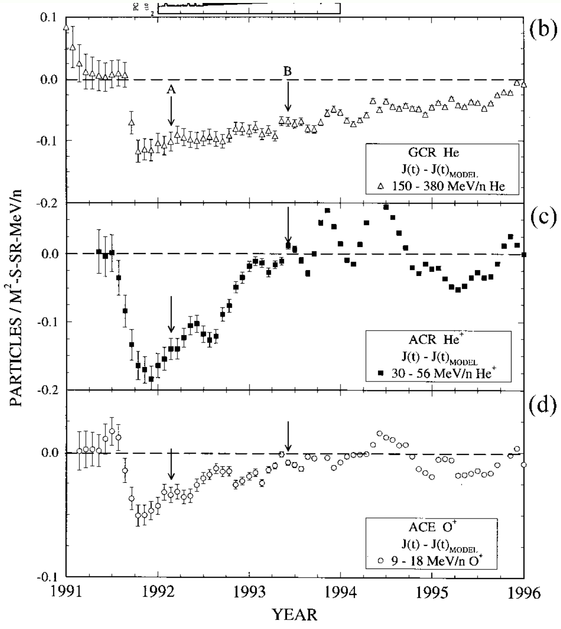
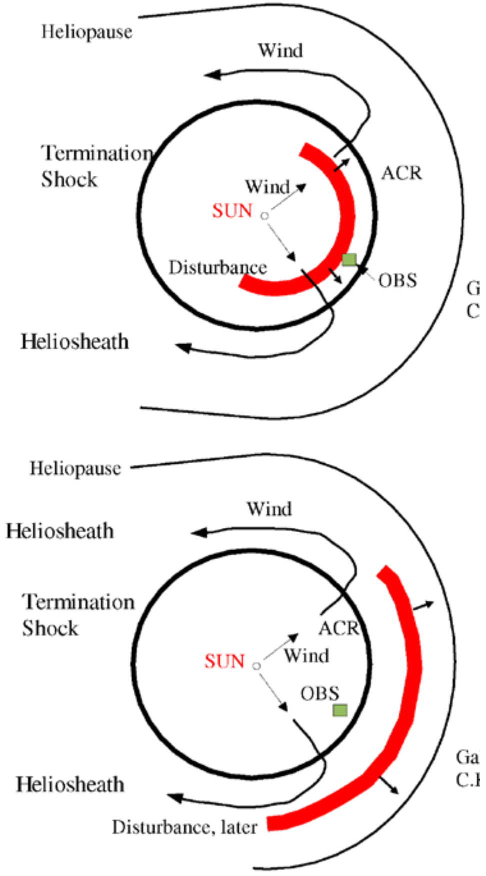
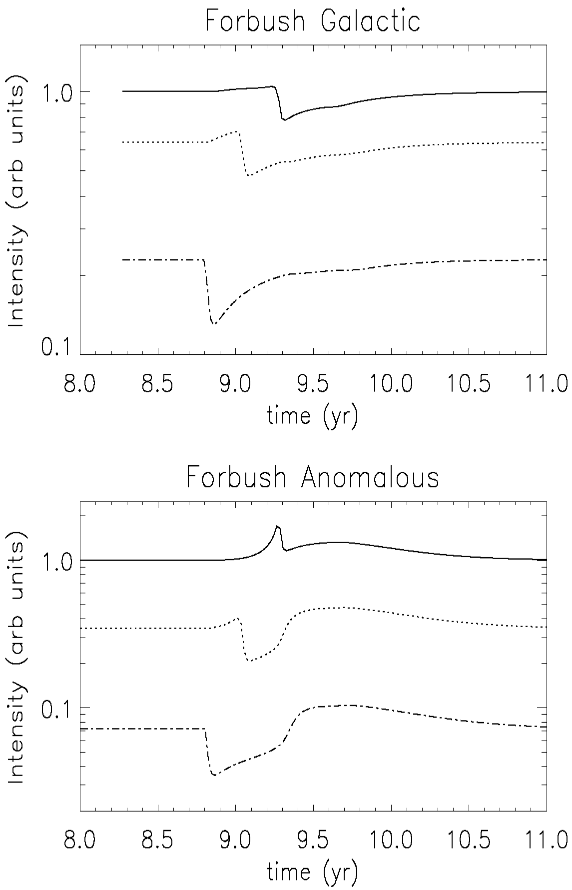


Figure 6. The estimated decrease in the GCR He$^+$ an ACR He$^+$ and O$^+$ due to the passage of the 1991 GMIR. Th decrease was obtained by subtracting the extrapolated recove curve of the pre-GMIR period (Figures 4a, 4b, and 4c) fro the actual gradient-corrected data. The two arrows marks t same time as those in Figures 3 and 5. Three period movi averages have been used to reduce statistical fluctuations. T data shown in Figure 6a are the Voyager 1 plasma were [*Gu nett et al.*, 1993; *Gurnett and Kurth*, 1996] of the 1.78 K H spectral power density plotted on the same timescale as t cosmic ray data.





Left, observations which strongly argue for a source of ACR at or near the termination shock . The center cartoon illustrates the picture. The far right is the result of computer modeling of a heliosphere with a propagating disturbance.

- Consideration of the recently proposed scenarios leads to conclusions that:
  - Direct acceleration in the electric field requires too much distance for $V \sim V_a$.
  - Statistical acceleration is far too slow.
  - Reconnection is not ruled out, but requires high anisotropies.
- Because the associated velocity and hence electric field at the *termination shock* is several times larger (~400 km/sec as opposed ~20-60) it can readily accelerate ACR in the available time and space. It, however, has other perceived difficulties.

Conclusions

- Galactic cosmic rays dominate the average (over scales of weeks) energetic-particle intensity at energies >≈ 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.