Cosmic-Ray Transport in the Heliosphere

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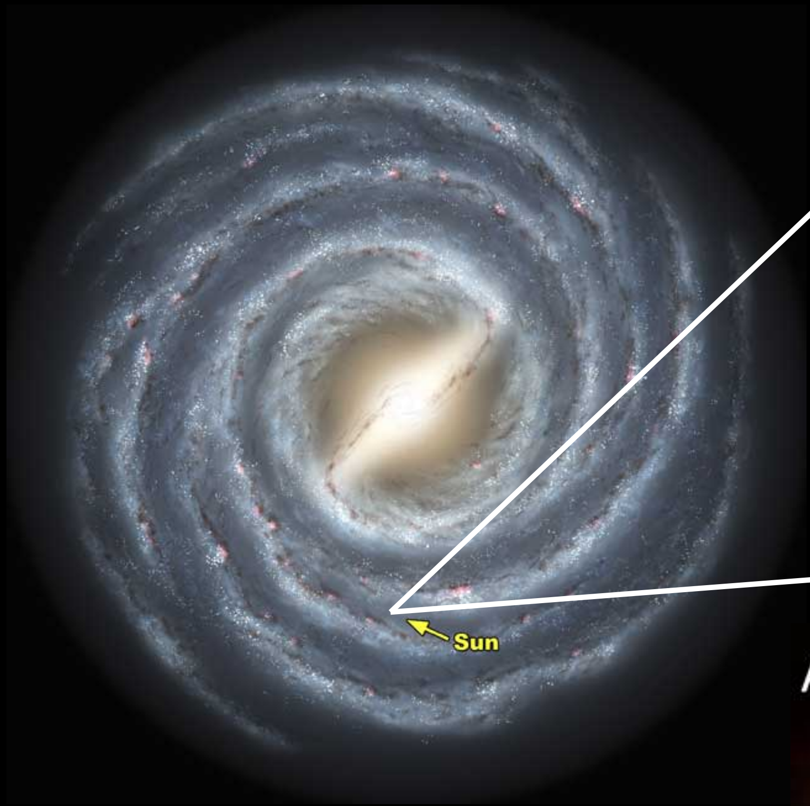
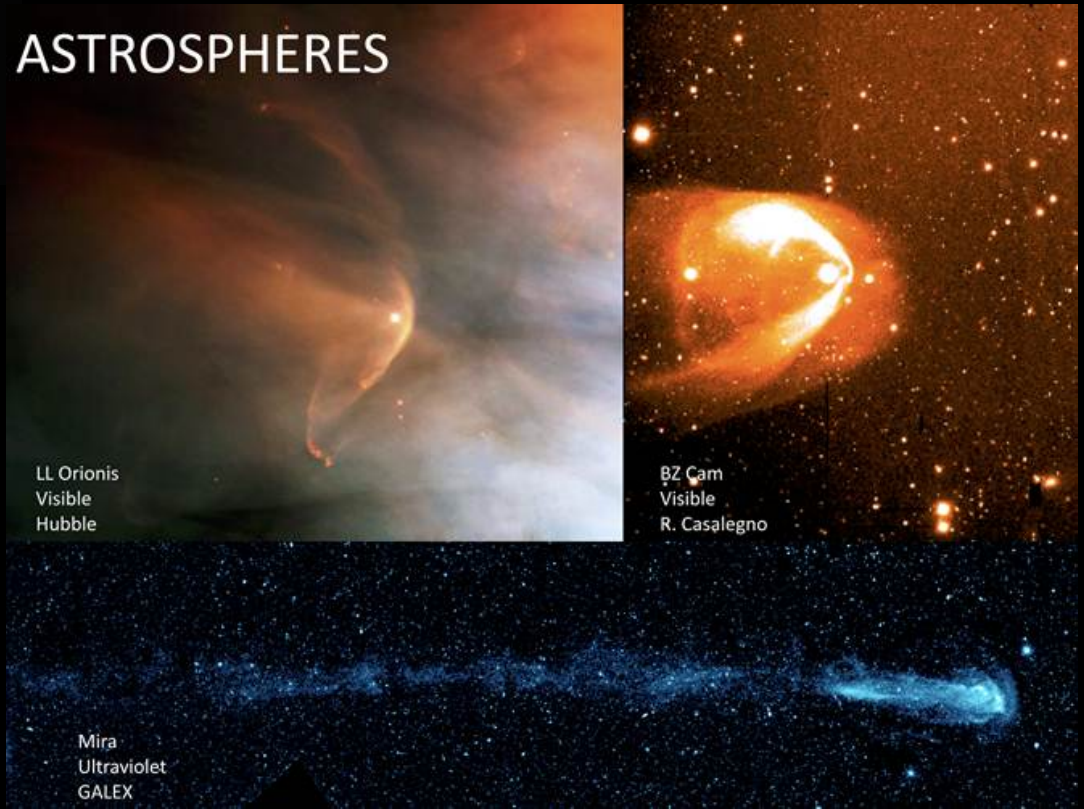
Outline

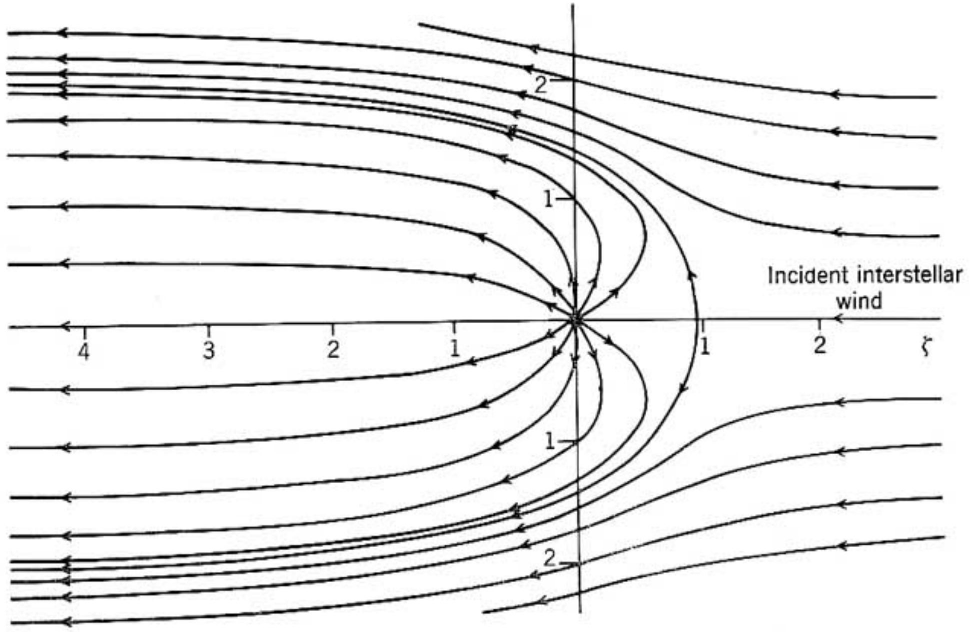
- Lecture 1: Background
  - The heliosphere
  - Cosmic Rays in the heliosphere
  - Record-intensity cosmic rays during the last sunspot minimum
  - Has Voyager 1 entered the interstellar medium?
- Lecture 2: Basic theory of charged-particle transport
  - Equations of motion, large-scale drifts, resonances
  - Restricted motions
  - Diffusion, Convection, Energy Change
  - The Parker transport equation
- Recitation/Problem Sets: Applications





As the Sun moves through its local environment, it carves out a region –the heliosphere – that is analogous to astrospheres seen surrounding other stars

Parker's view of the heliosphere in 1961 – from an analytic formulation. He came up with a scale of **45-90** AU from knowledge of the ram pressure at 1 AU and the estimated interstellar pressure of (1-4) x 10^{-12} erg/cm^2.

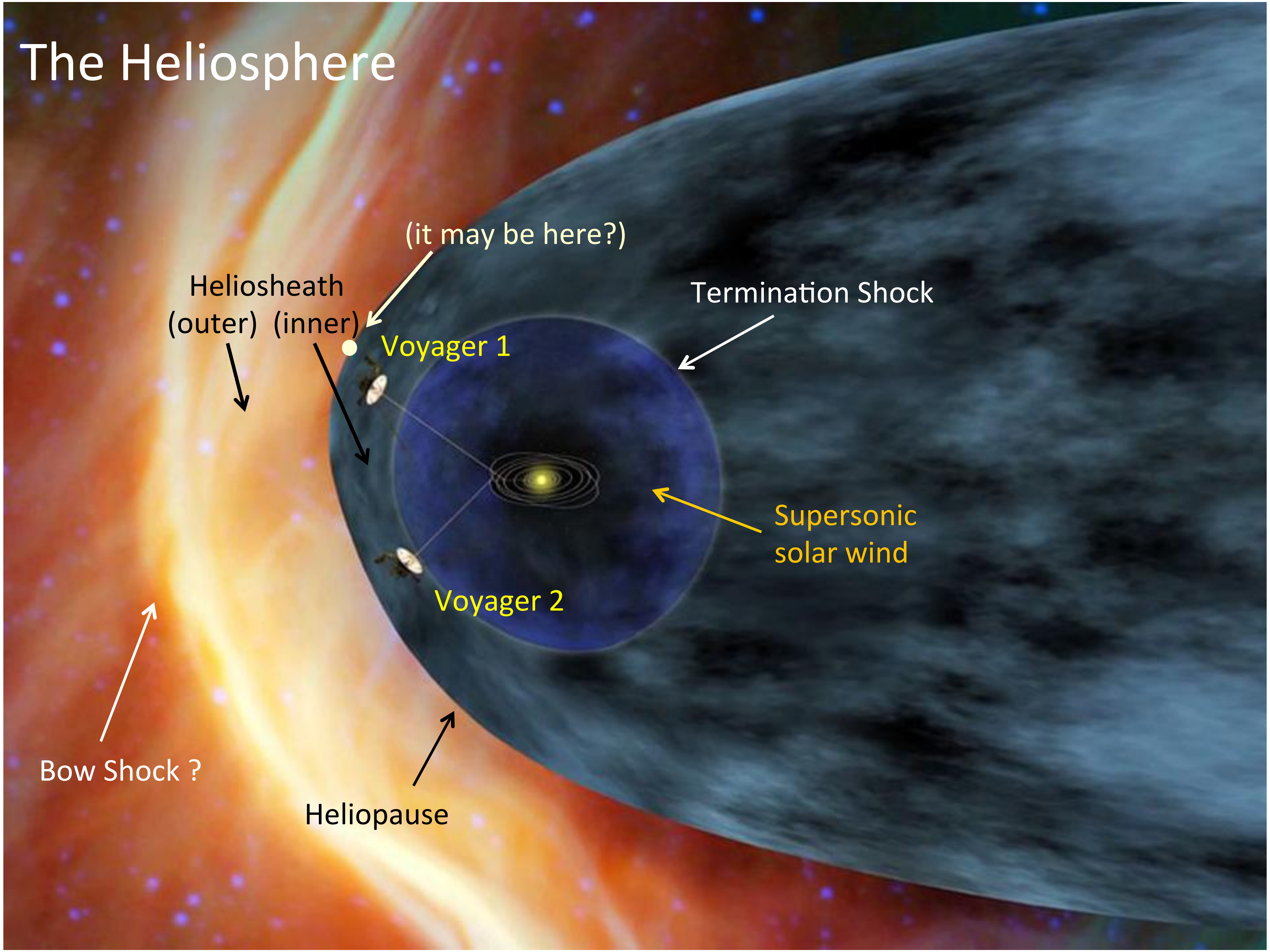


- The solar wind flows *supersonically* and nearly *radially* from the Sun
- Thus, its large-scale structure is determined mainly by the initial and boundary conditions at the Sun.
- The solar wind terminates at the termination shock – where

$$\rho V_w^2 = \rho_0 (r_0/r)^2 V_w^2 = P_{ism}.$$

An instructive analog

The Heliosphere



Why we study the outer heliosphere

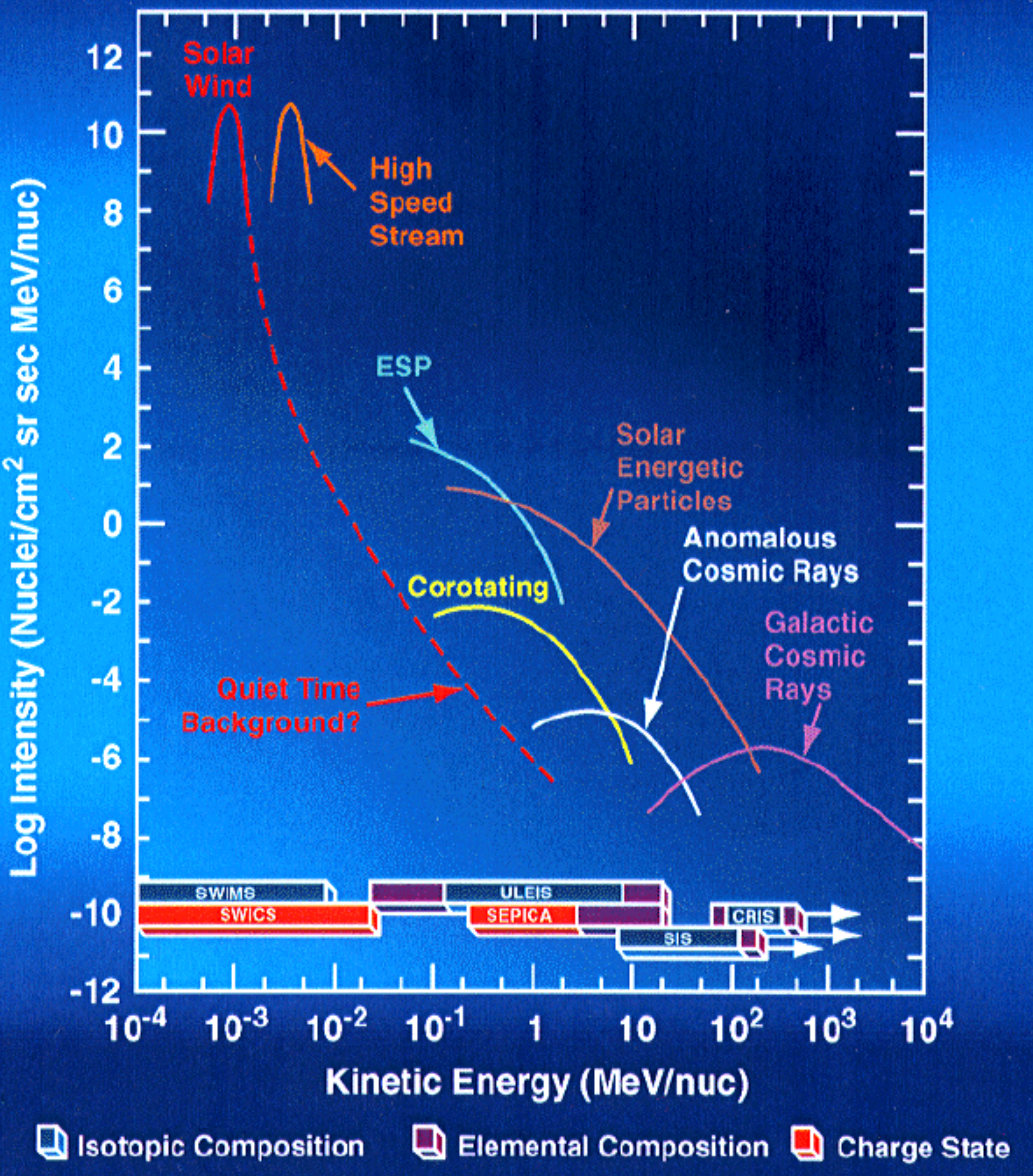
- The heliosphere represents the first of several boundaries shielding Earth from radiation coming outside our solar system – it is important to understand how it does this (especially if we *really* want to send humans to Mars or the moon, or elsewhere)

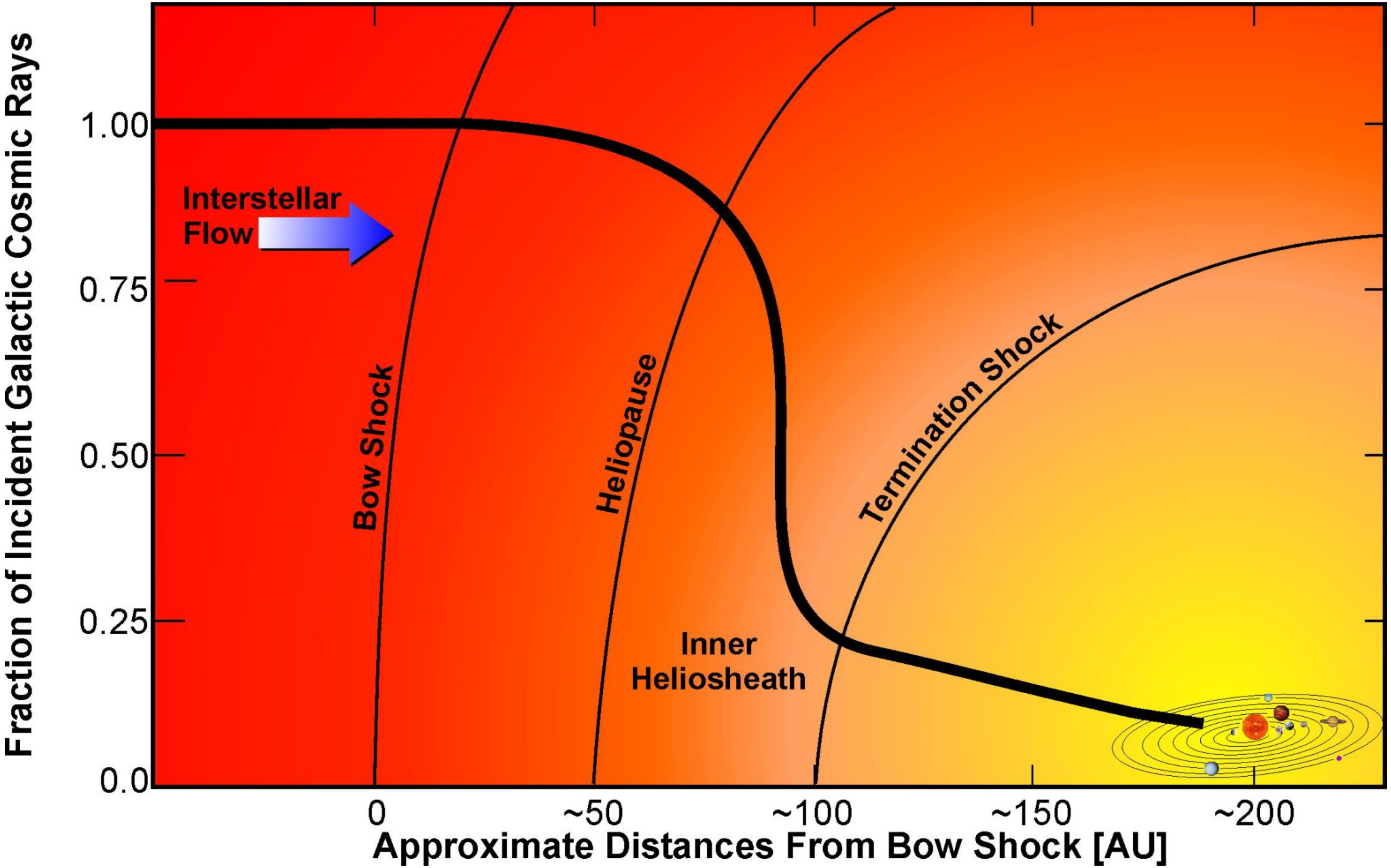
- NASA has several missions aimed at understanding the heliosphere (Voyager, IBEX, ACE, Ulysses, etc.) with rich data sets open for interpretation.

- It is a important laboratory for studying the physics of multi-component plasmas (interstellar neutral atoms, pickup ions, solar wind ions, cosmic rays), and particle acceleration.

- The source of many interesting and puzzling physics problems!

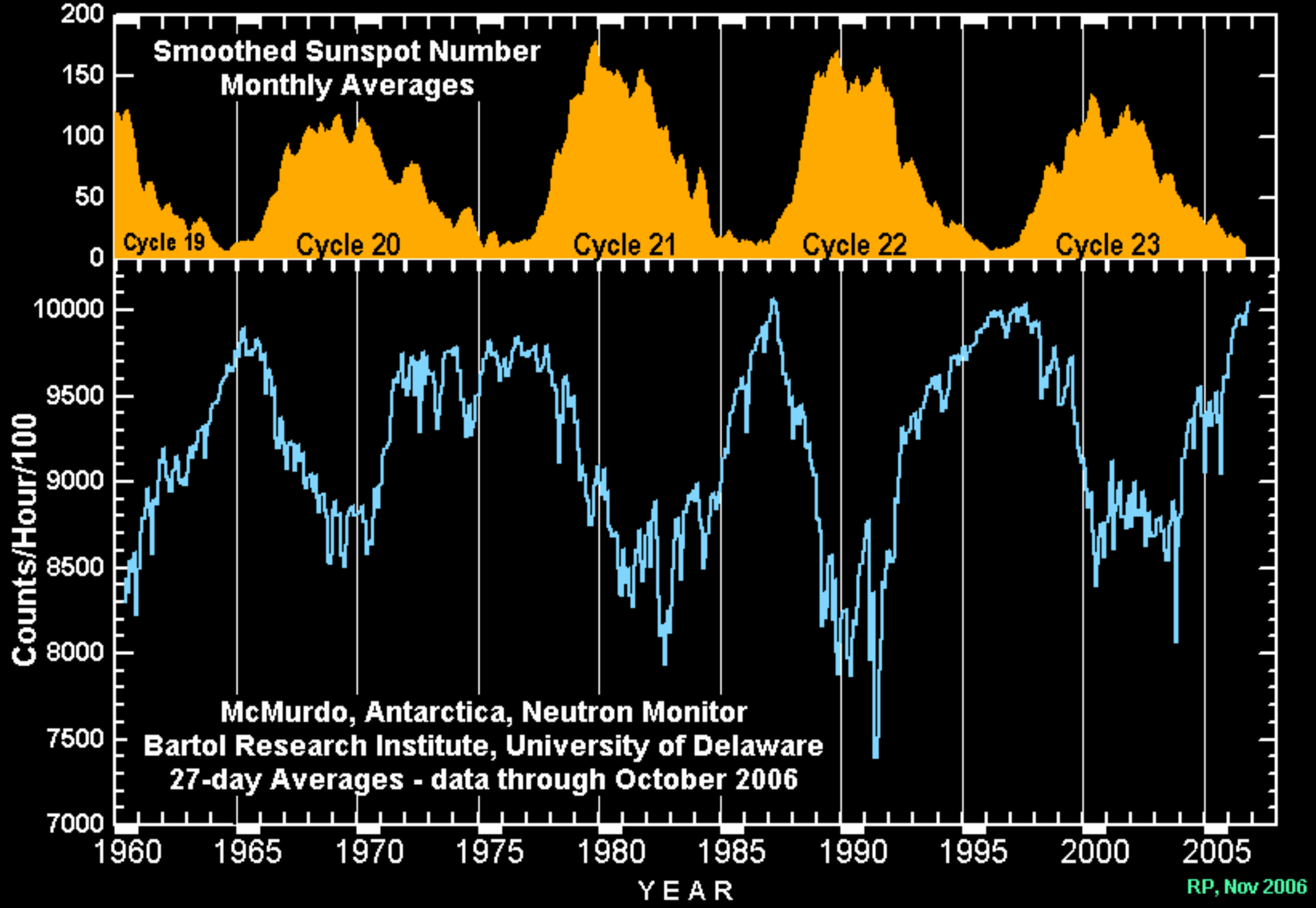
Spectra of Energetic Oxygen Nuclei



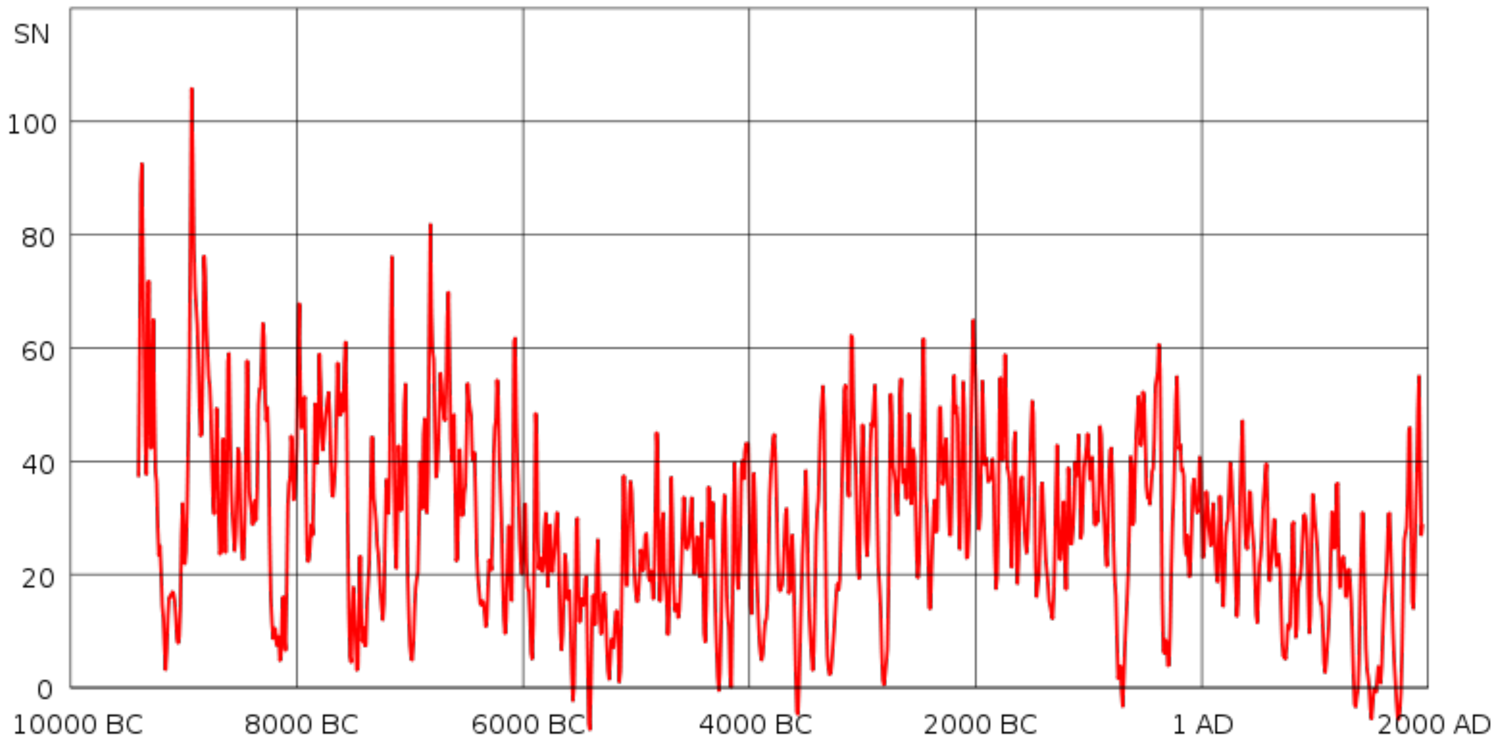


The intensity of galactic cosmic rays (GCRs) reaching 1 AU depends on a number of things, such as the energy of the cosmic rays, and the solar wind and interplanetary magnetic field. GCRs generally have the highest intensity when the Sun is quiet, and lowest when it is active.

Galactic Cosmic Rays and the Solar Cycle



Sunspot number reconstruction from dendrochronology



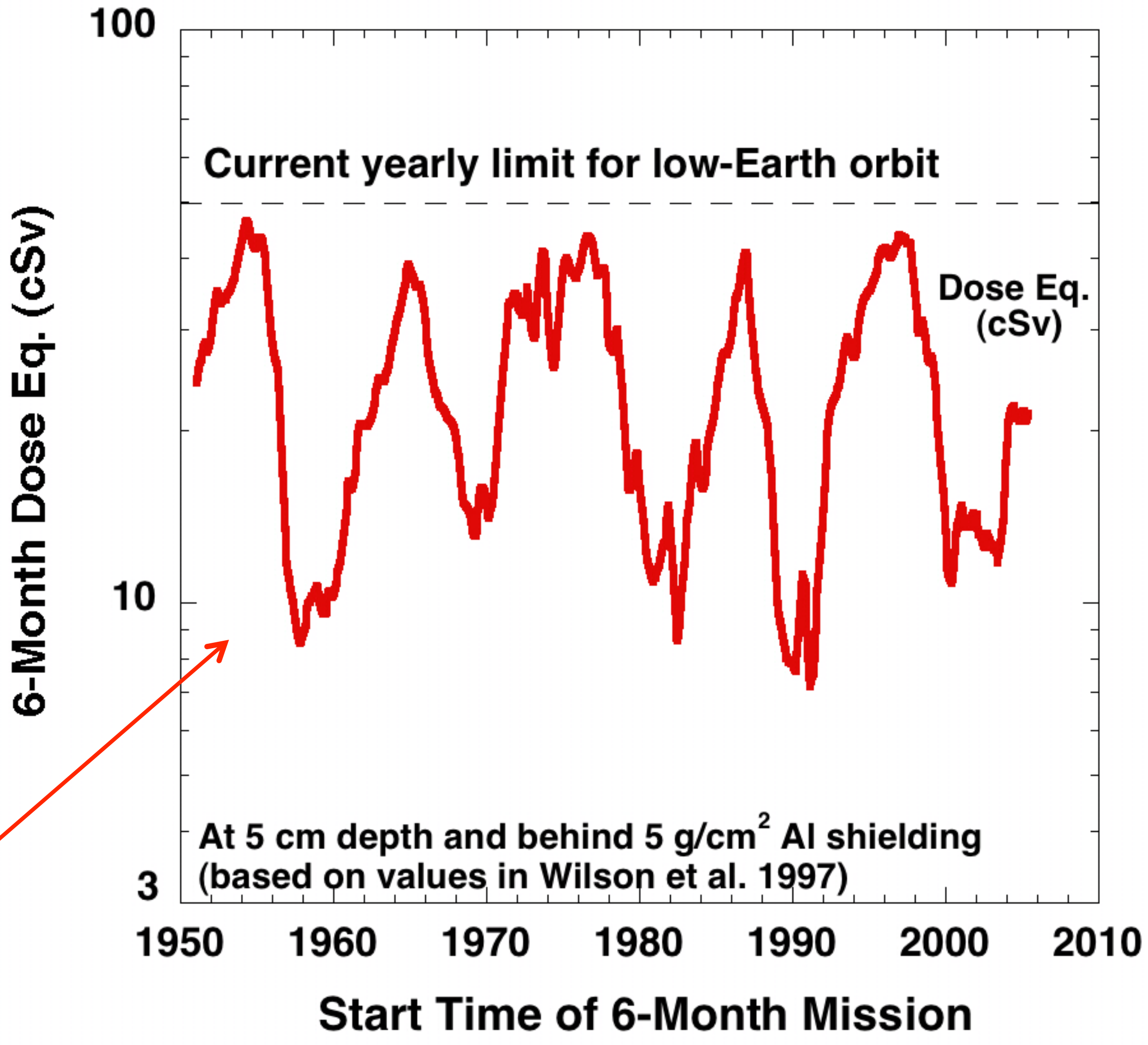
Cosmic rays are used as an indicator of past solar activity through their production of cosmogenic nuclei, such as C-14 and Be-10.

Relating this to solar phenomena requires understanding how the heliosphere modulates cosmic rays

Cosmic Rays pose a significant radiation-threat to astronauts

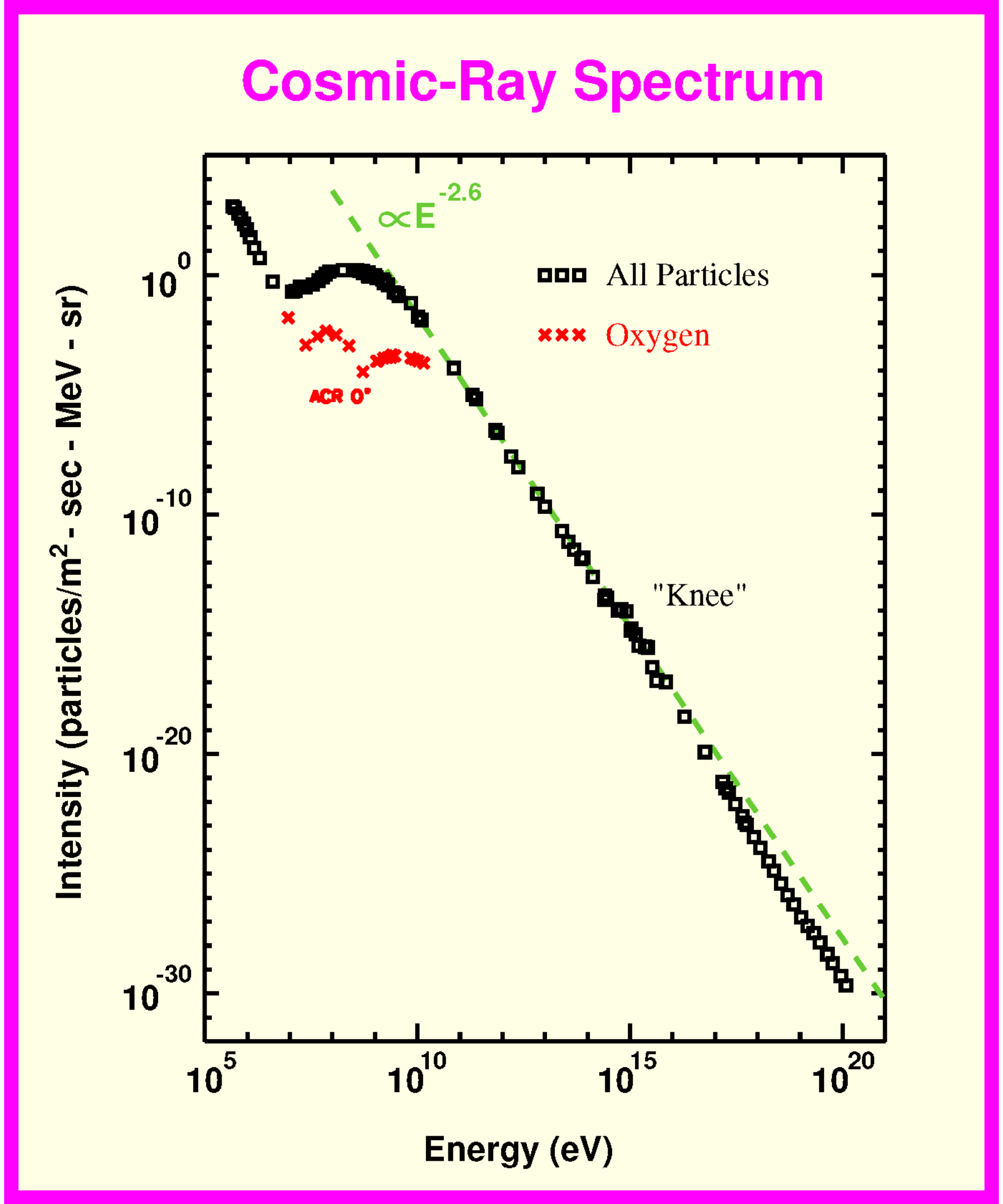
The solar minimum intensity of GCRs for a 20+month mission to Mars (and back again pus time on the planet) is more than 3 times larger than the current yearly limit for astronauts in low-earth orbit.

Equivalent to more than 10,000 chest x-rays!



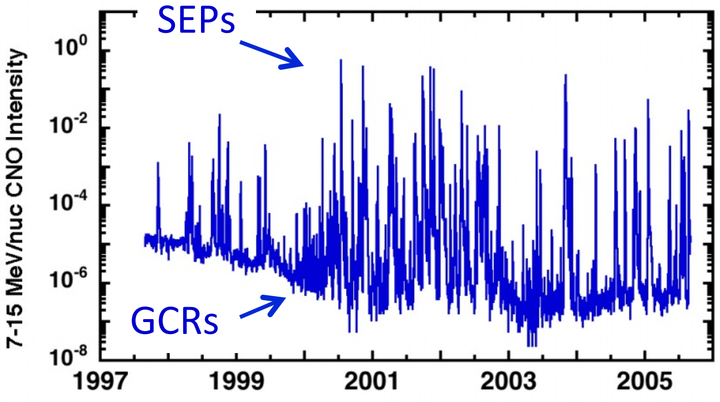
1 AU neutron monitor data converted to radiation dose equivalent

Mewaldt et al. 2006



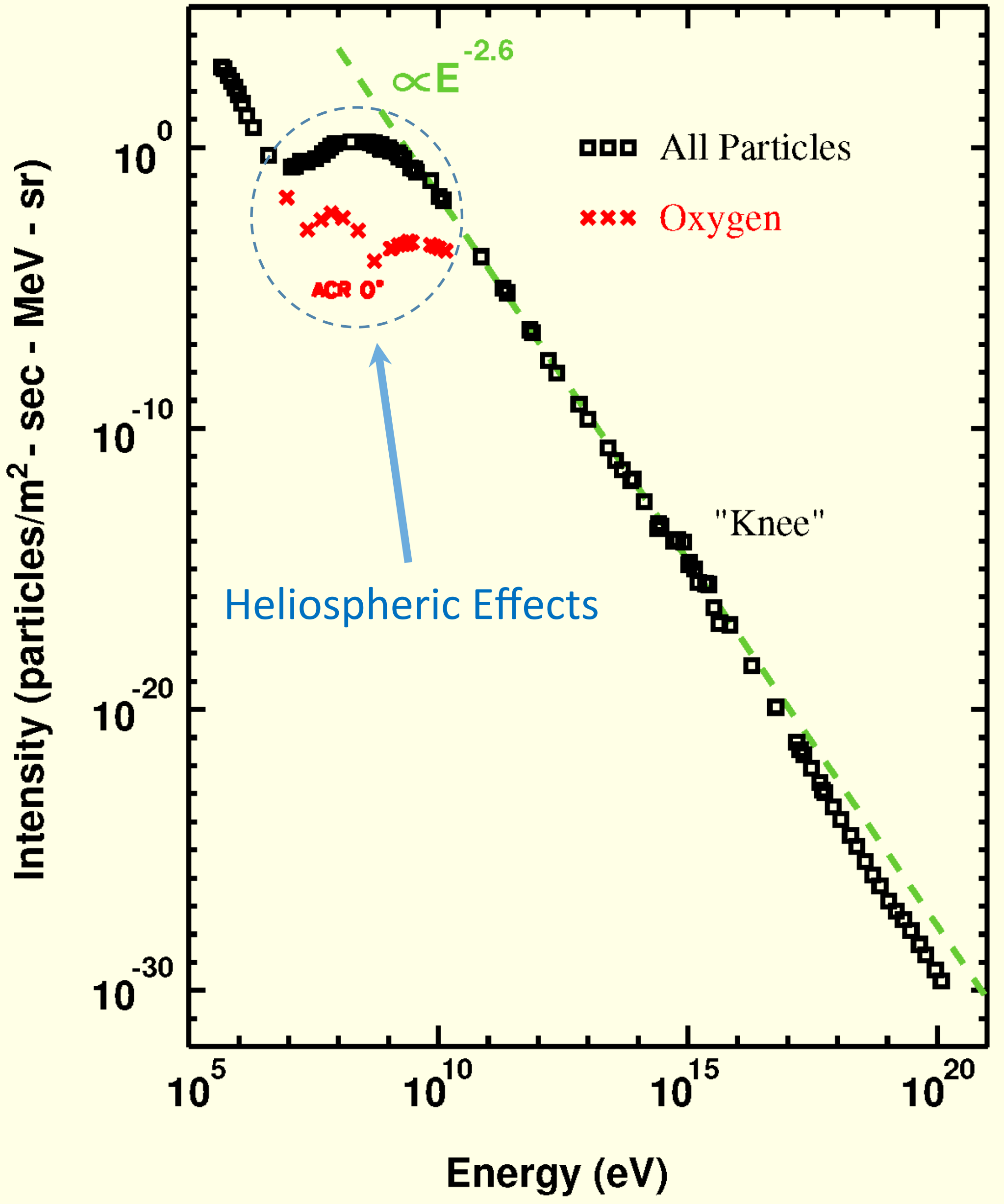
GCRs dominate over other energetic particle species (such as solar-energetic particles) at energies above ~100 MeV/nuc.

At lower energies, solar-energetic particles – which are not predictable – significantly dominate the intensity. Sometimes by factors exceeding a million



Courtesy Dick Mewaldt

Cosmic-Ray Spectrum



The heliosphere has a significant effect on GCRs with energies below about 10 GeV.

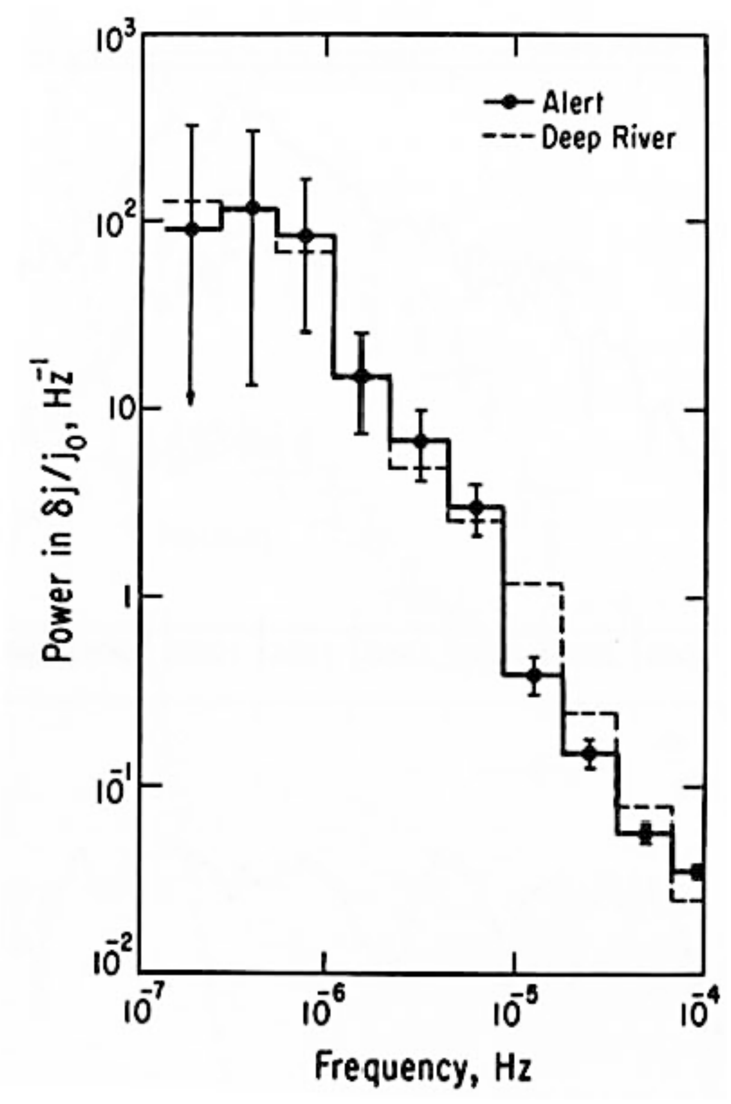
The "modulation" is due to the heliosphere – hence GCRs can also be used as probes of the heliosphere

Anomalous Cosmic Rays (ACRs) are a separate component, that are produced in the heliosphere – they are also important probes

The mechanism of acceleration ACRs will be discussed later in this talk

Cosmic Rays Vary on Many Scales

- Short, irregular fluctuations caused by solar wind and interplanetary magnetic field variations – both from irregular solar effects and co-rotating with the Sun.
- Quasi-periodic 11-year and 22-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.



Owens & Jokipii (1972)

Particle transport in the heliosphere is actually the combination of four physical 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:*** with the flow of the plasma.
- ***Guiding-center drifts:*** Such as gradient and curvature drifts, but also arising from interaction with current sheets in the solar wind
- ***Energy Change:*** caused by expansion/compression of the background fluid.

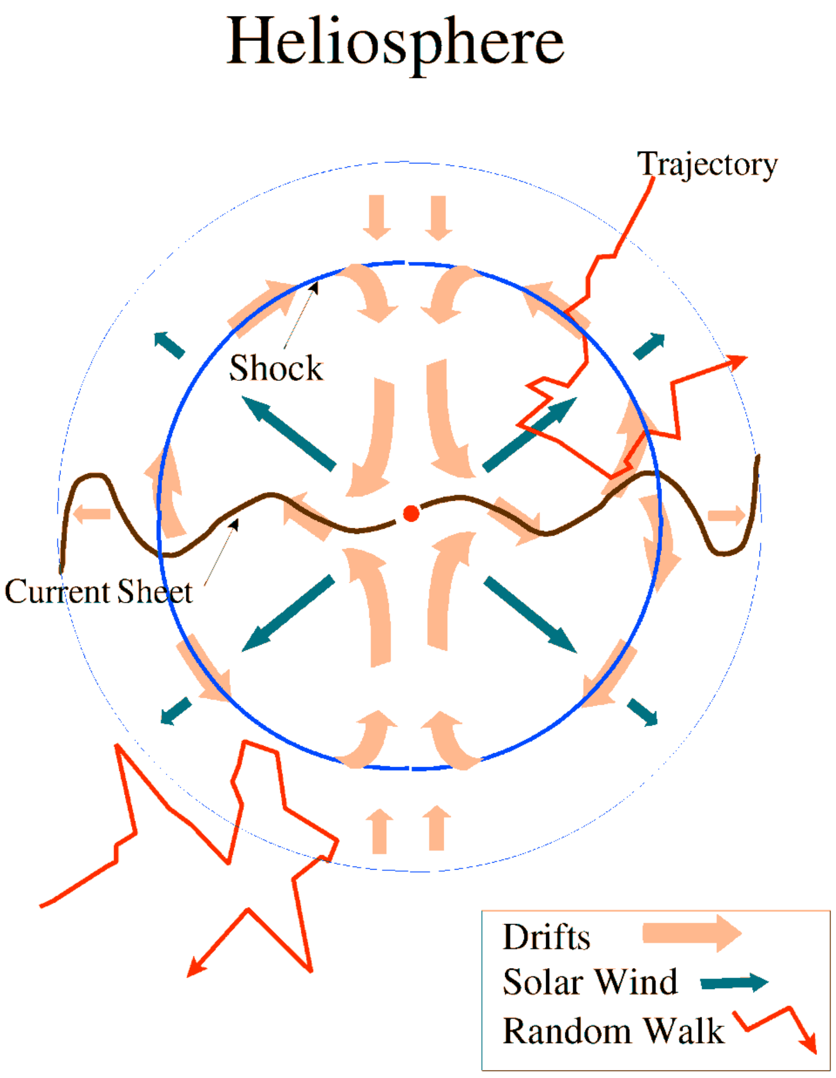
All of these effects play important roles in GCR modulation (it is difficult to isolate the effects – they are all important)

These are combined in Parker's cosmic-ray transport equation, first written down nearly 50 years ago (next lecture).

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

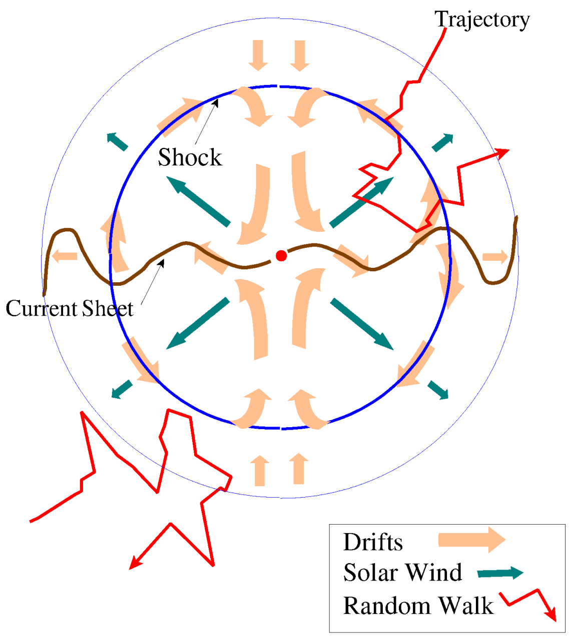
These motions are counteracted by outward convection and the associated cooling by the expansion of the wind.

The drift motions are very significant.



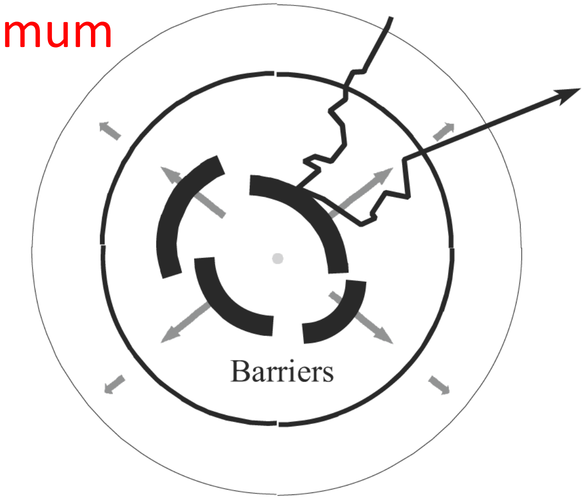
During ***solar minimum***, the interplanetary field is weaker, there is less solar-wind turbulence, and fewer large-scale barriers (e.g. CMEs, shocks and merged interaction regions) and GCRs have easier access to 1 AU – ***higher GCR intensity***

Near sunspot Minimum (A>0)



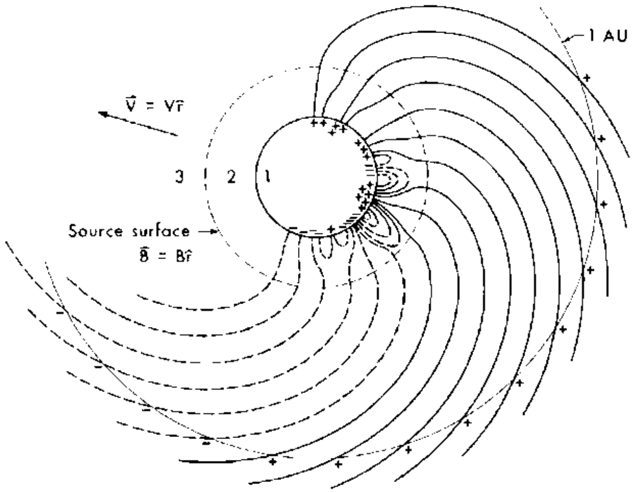
During ***solar maximum***, the interplanetary field is stronger on average, there is more solar-wind turbulence, and numerous large-scale barriers (e.g. CMEs). GCRs have difficulty entering the solar system – ***lower GCR intensity***

Near sunspot Maximum

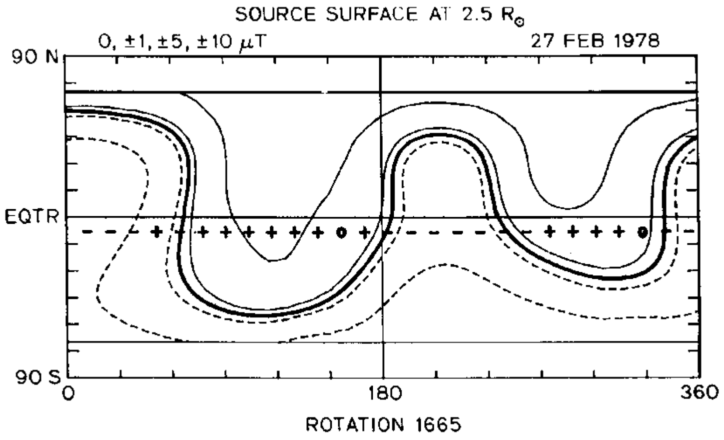


Cosmic Rays are also influenced by the Heliospheric Current Sheet

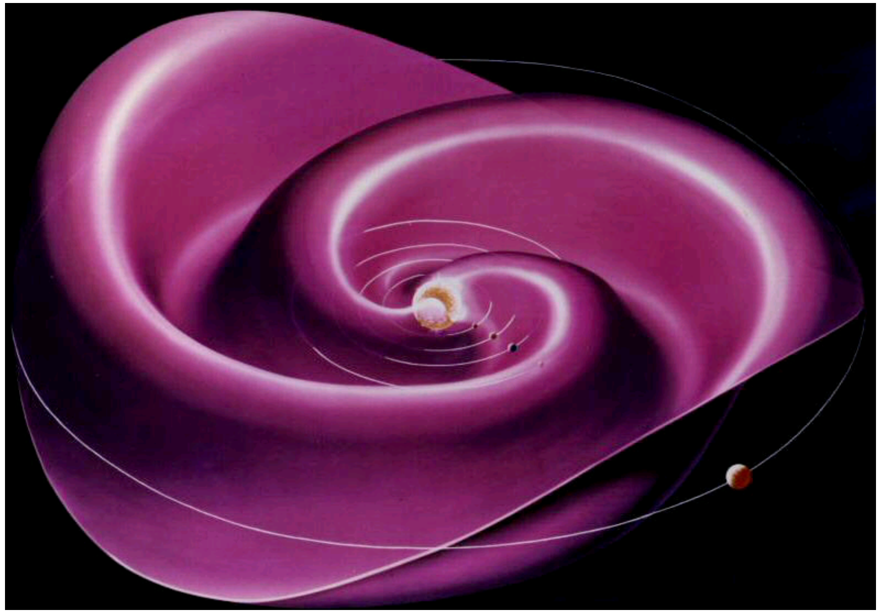
Interplanetary magnetic-field sector structure.



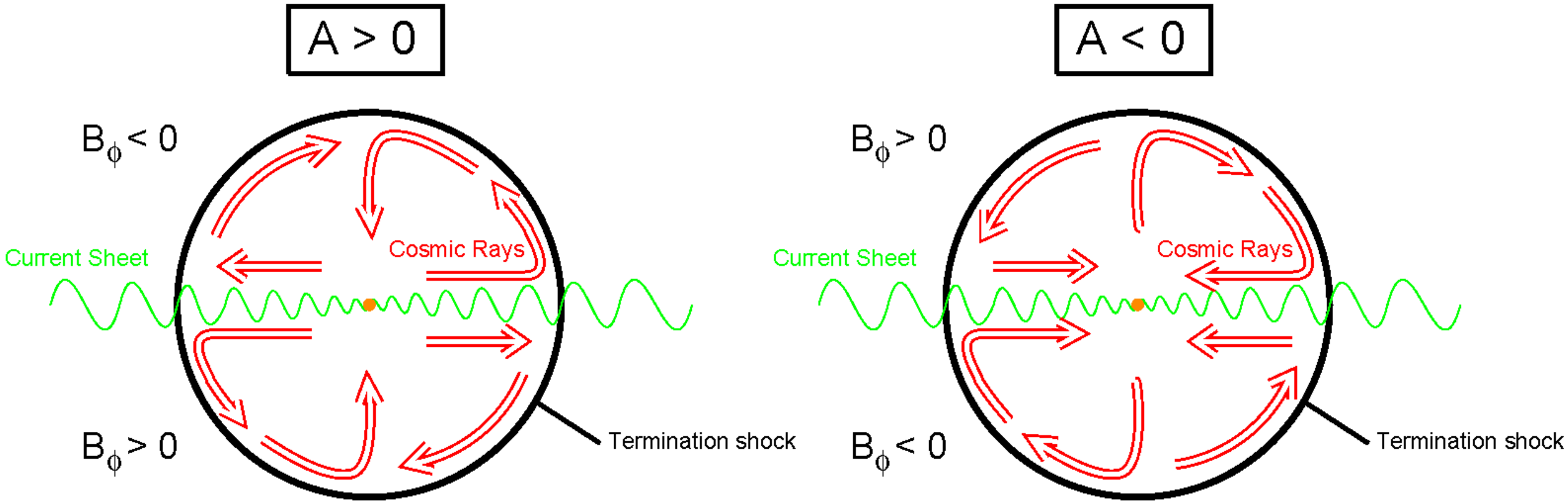
Neutral line at the solar source surface

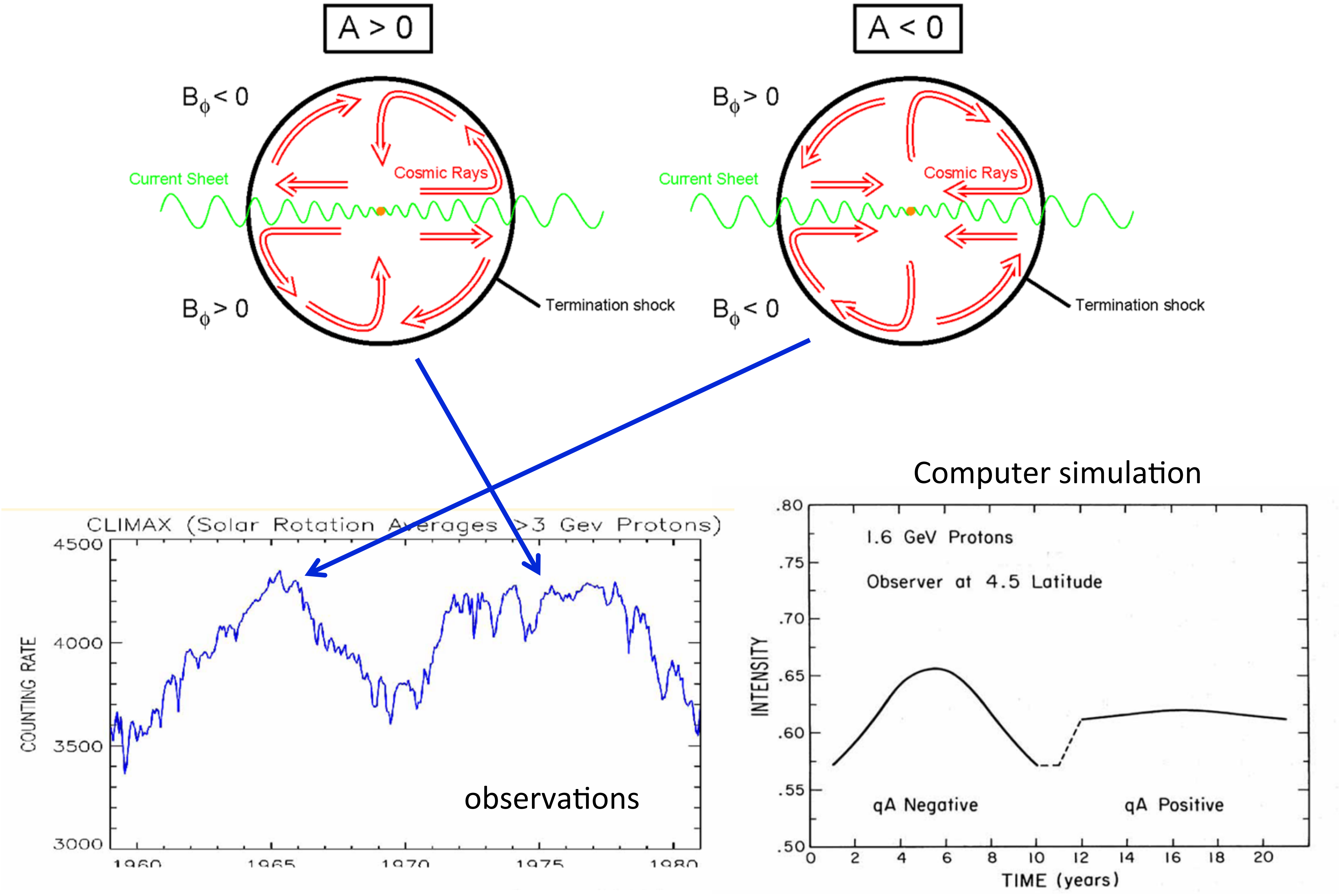


Heliospheric current sheet →



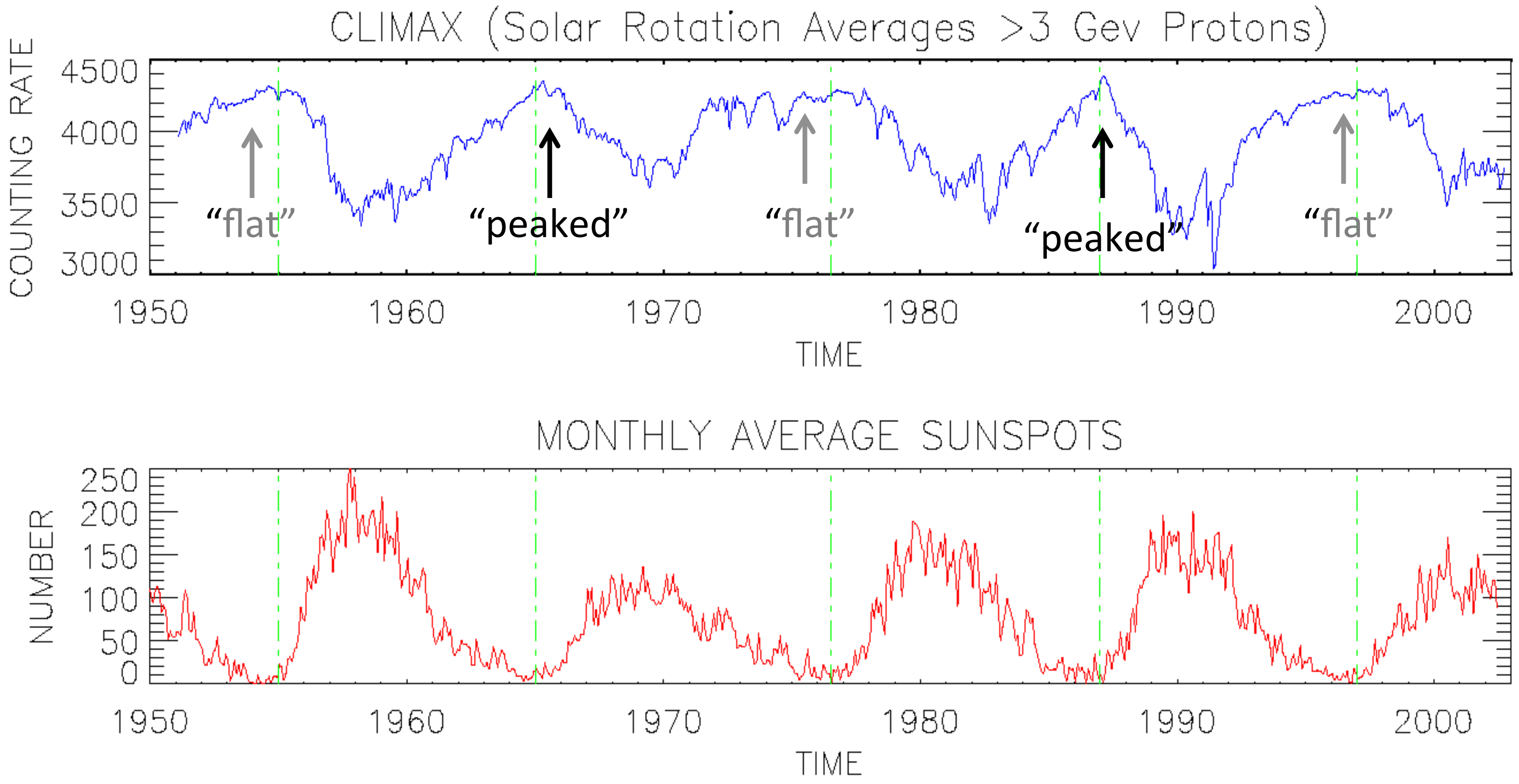
- The sense of the particle drift changes from one sunspot cycle to the next.
- For A>0, GCRs enter inward over the poles and out along the heliospheric current sheet.
- For A<0, GCRs come inward along heliospheric current sheet, out toward the poles.





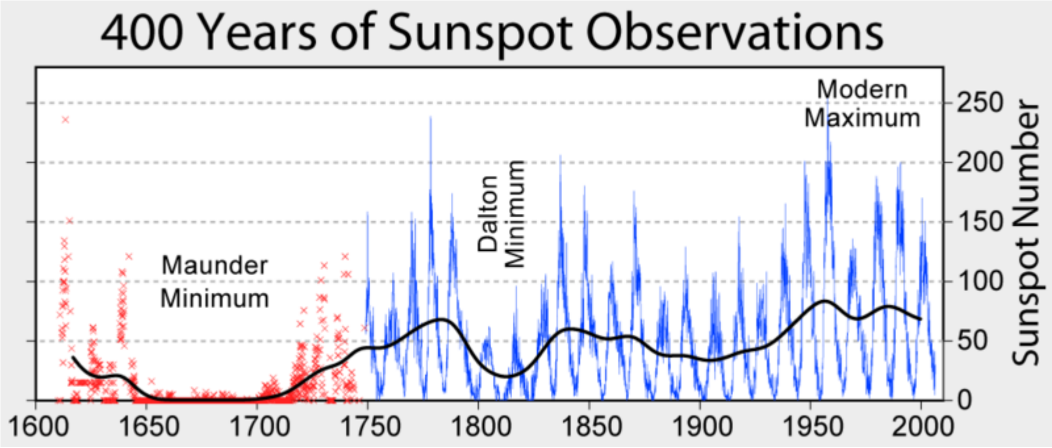
Jokipii & Thomas, 1981

The 22-year cosmic-ray cycle

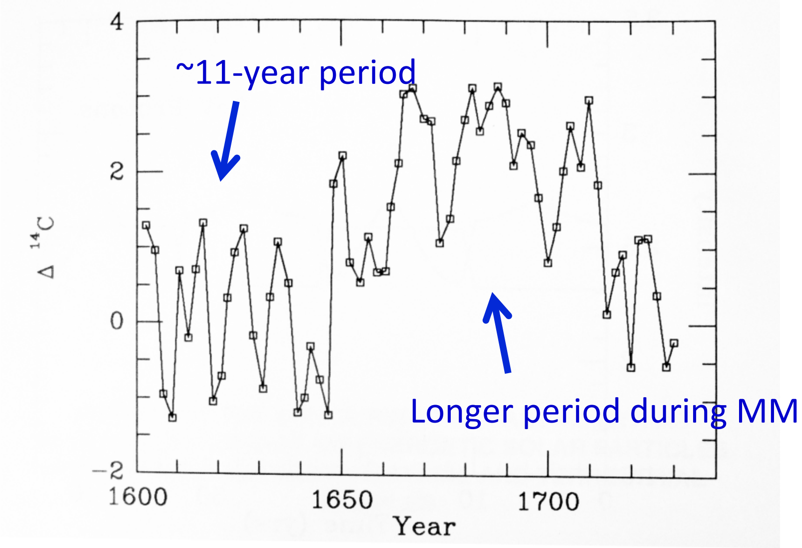


Cosmic Rays during the Maunder Minimum

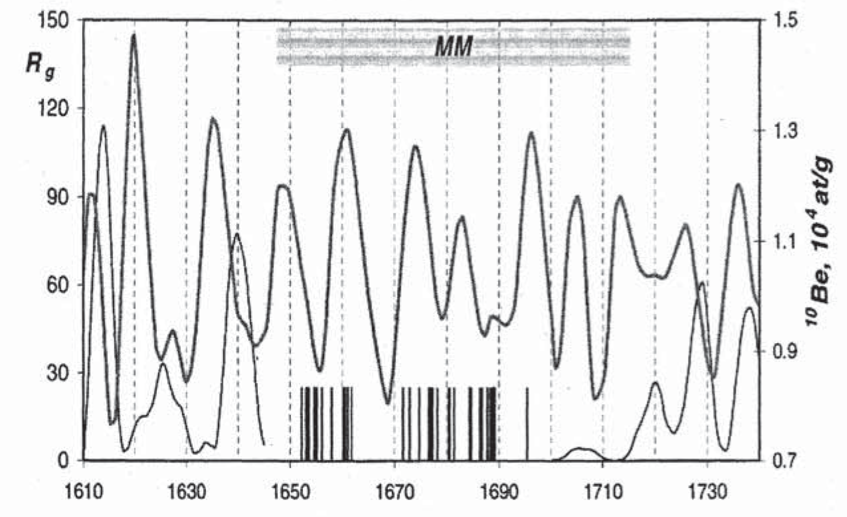
- The Maunder Minimum is the name given to the period spanning roughly the years 1645 to 1715, when sunspots were exceedingly rare.
- The cosmic rays could only be measured by proxy.



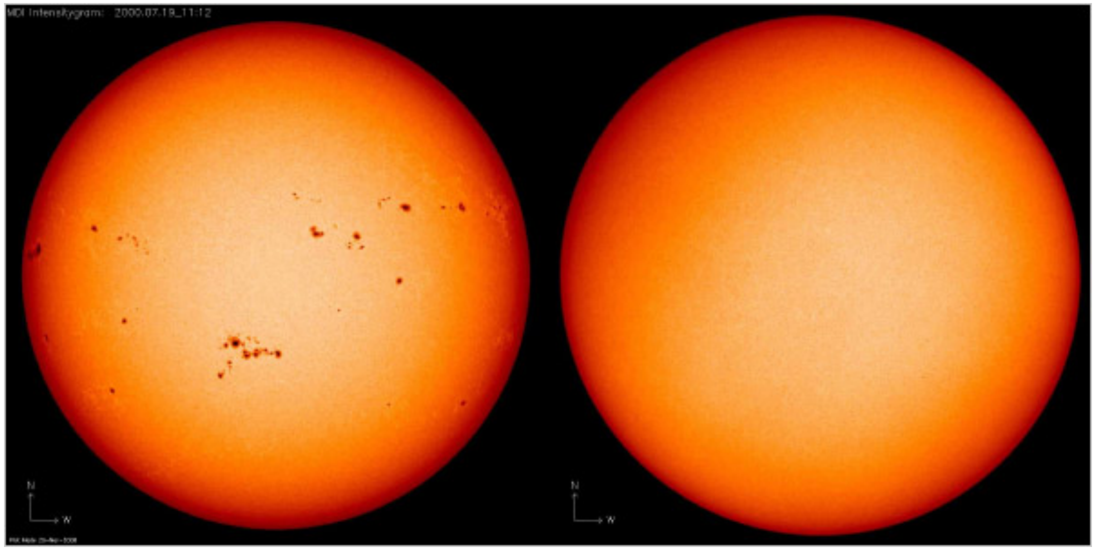
Changes in ^{14}C (Kocharov, 1987)

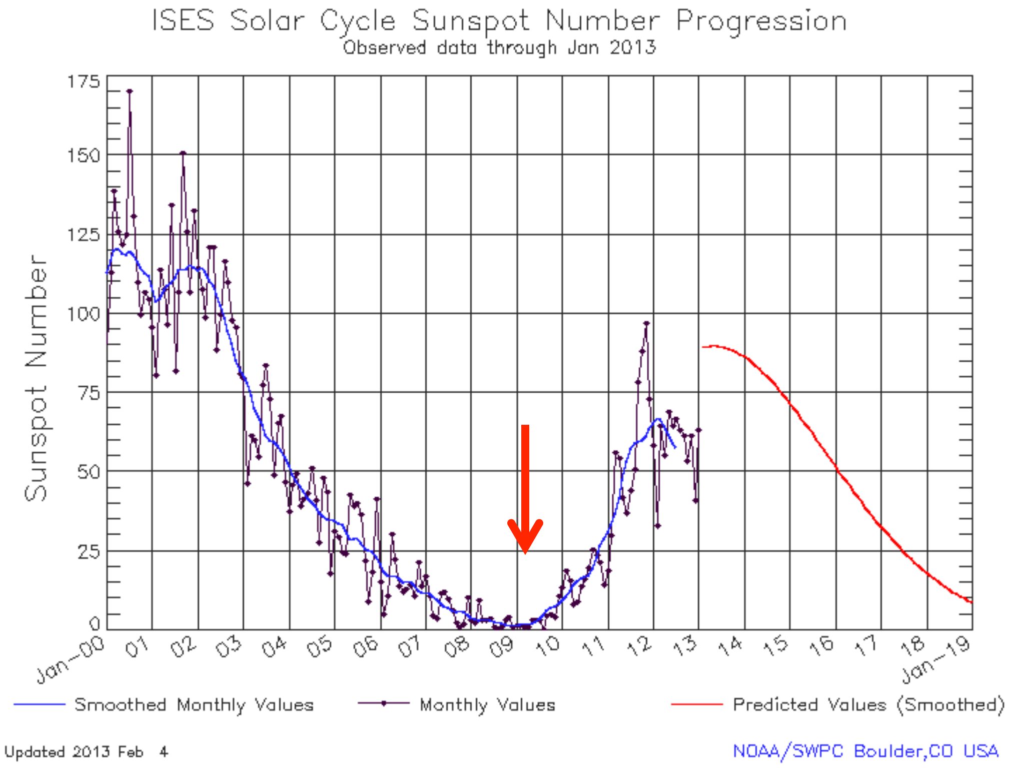


^{10}Be (Usoskin et al., 2001)



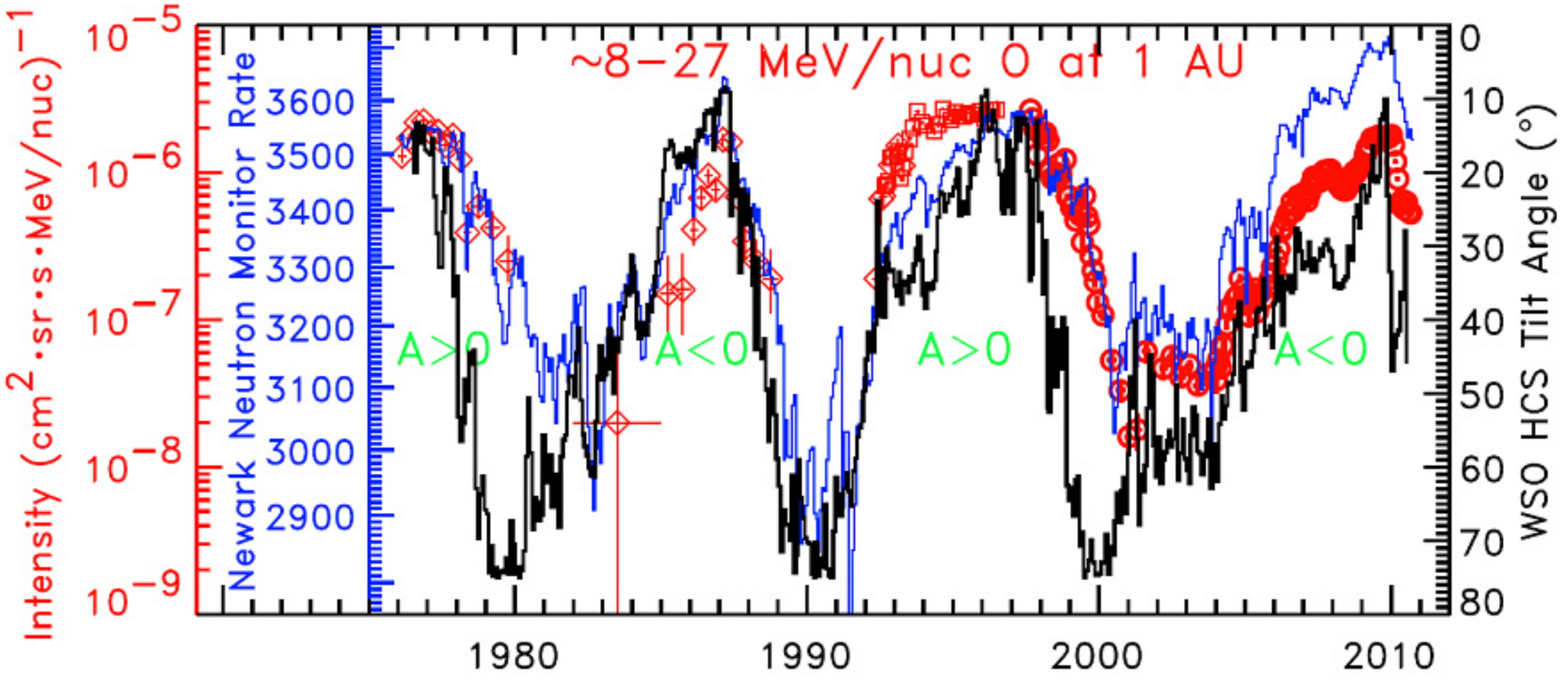
The Sunspot Minimum Between Solar Cycles 23/24 was particularly long lived and “deep” (very few sunspots)





Cosmic rays seen during this period were unusual

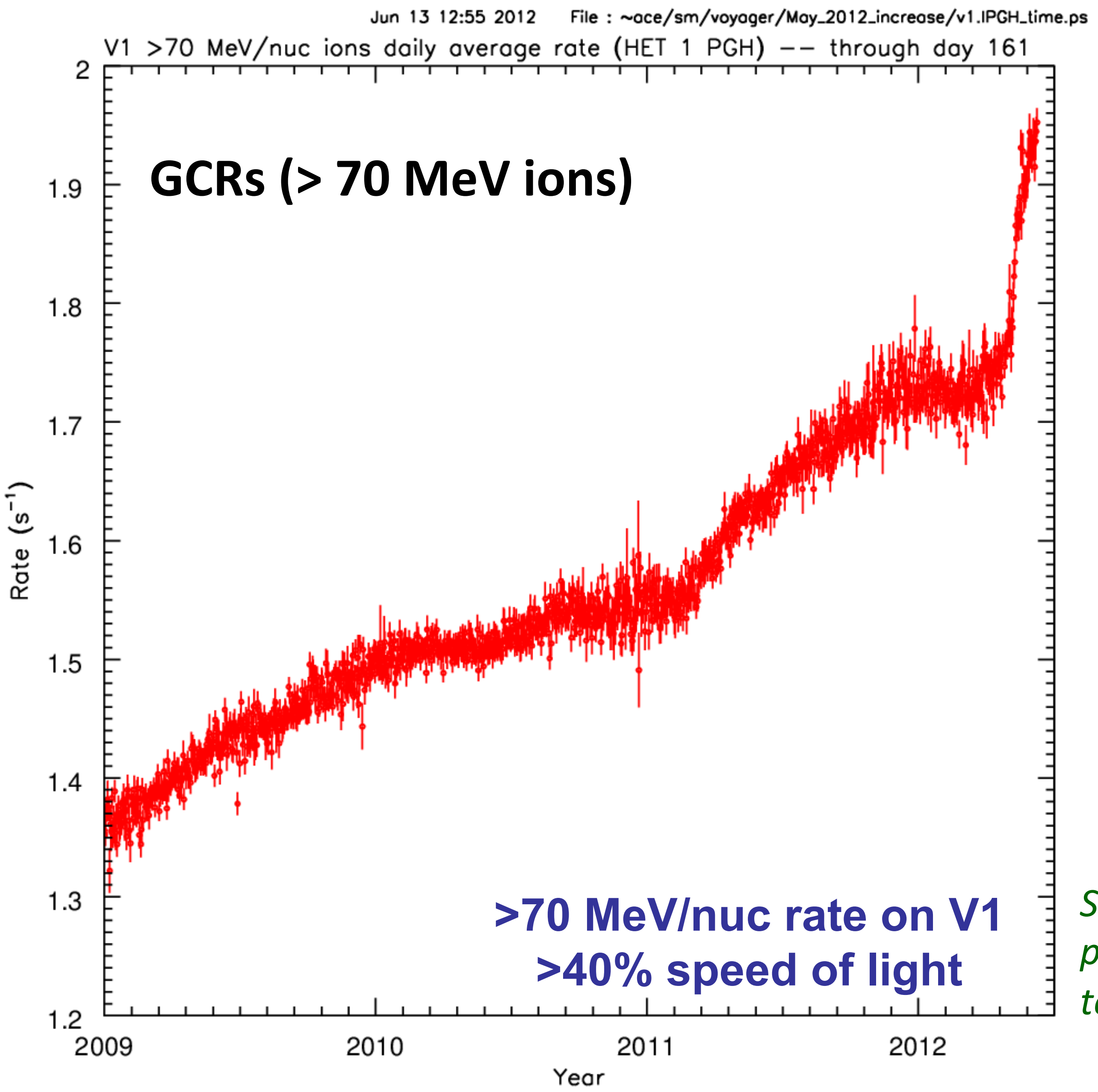
- The GCR intensity was the highest ever during the space era.
- The heliospheric current sheet was not particularly "flat" except for a very short time right at the peak of the GCR/ACR intensity
- The unusually high intensity is almost certainly the result of a weaker solar wind and interplanetary magnetic field that was observed during the last sunspot minimum
- ACRs (shown as red symbols) can also be understood … but that is a different story



A topic of Recent Interest:

Has Voyager 1 entered the interstellar medium?

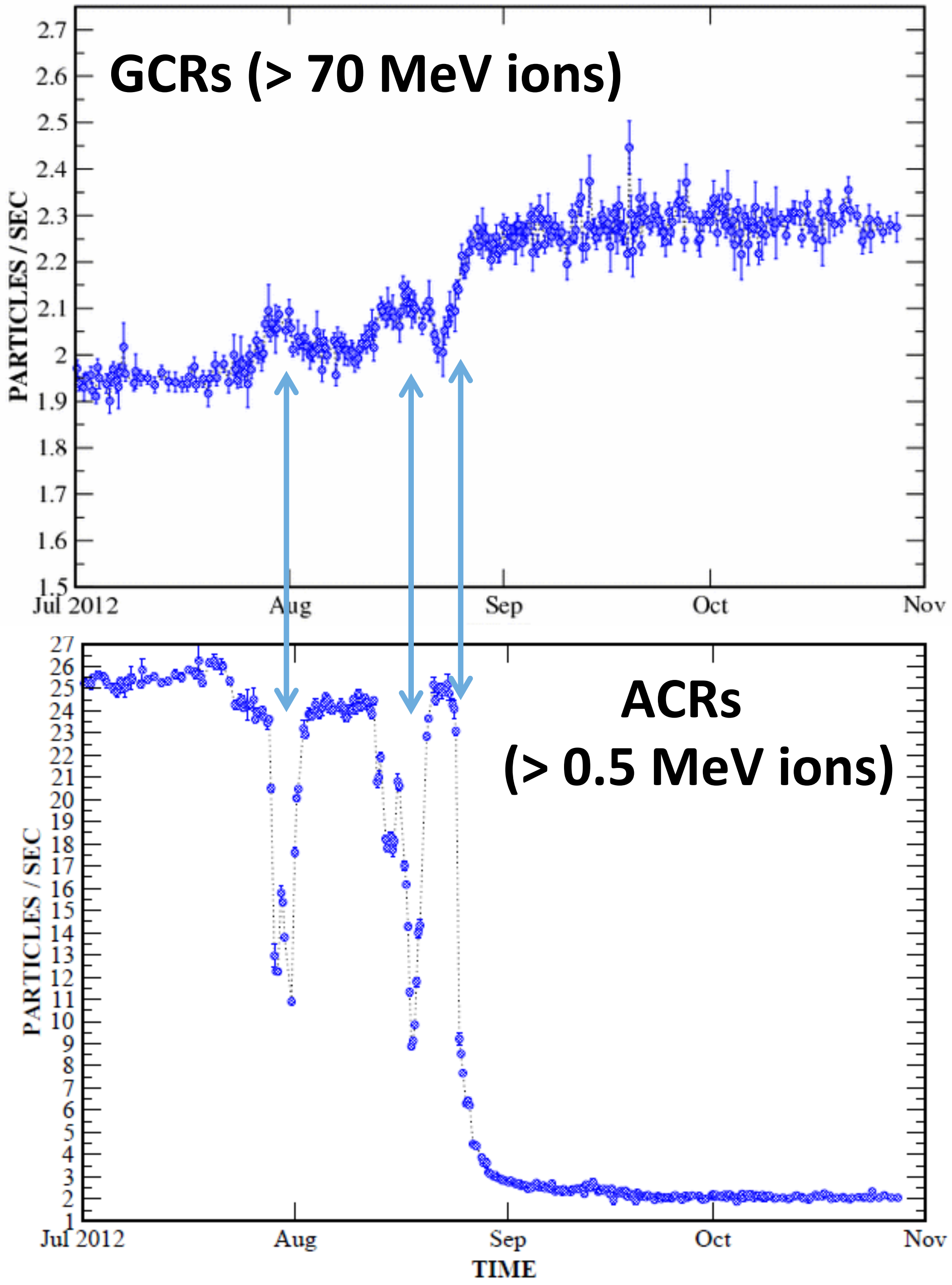
Rate of Cosmic Rays Diffusing in from Galaxy



Rate increased 9% per year over last 3 years

In May 2012 the rate increased 5% in one week and 9% in a month

Slide from E.C. Stone's presentation at Voyager team meeting, Dec. 2012

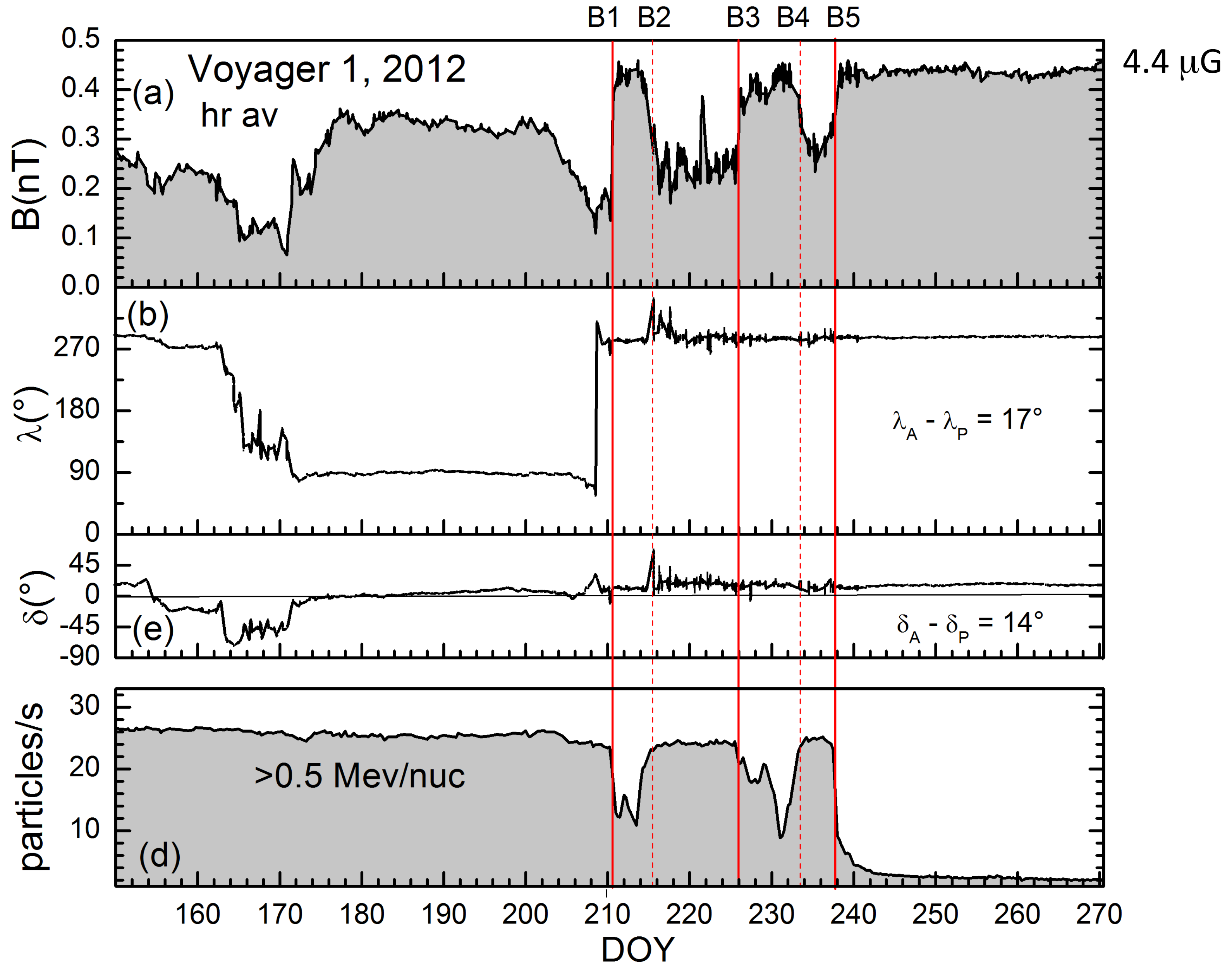


Cosmic rays from outside increased at the same time as ions from inside escaped

Is Voyager 1 in interstellar space,
or is there a new region inside that is connected to interstellar space outside?

voyager.gsfc.nasa.gov

Slide from E.C. Stone's presentation at Voyager team meeting, Dec. 2012



Slide from Len Burlaga's presentation at Voyager team meeting, Dec. 2012

Where do we stand on this?

- The Voyager science held a press conference at AGU and announced Voyager had entered a new region of space – not necessarily the interstellar medium.

- Why didn't the magnetic field change direction?

  This is the big question!

  (ideas anyone?)