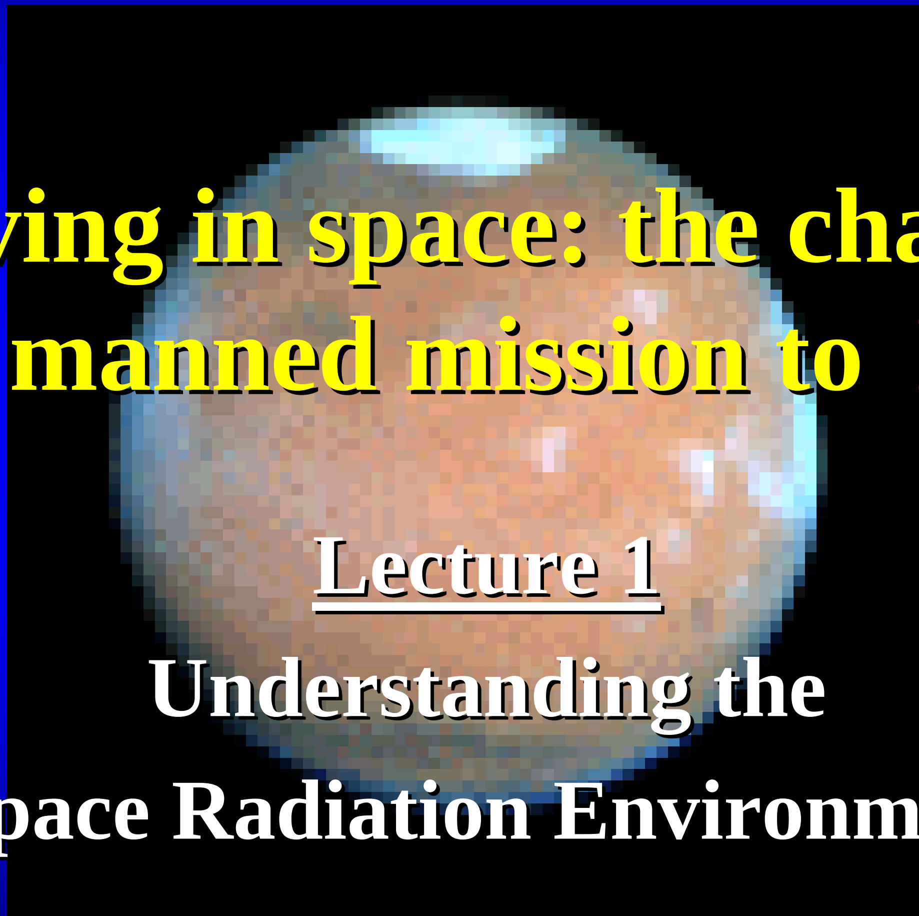


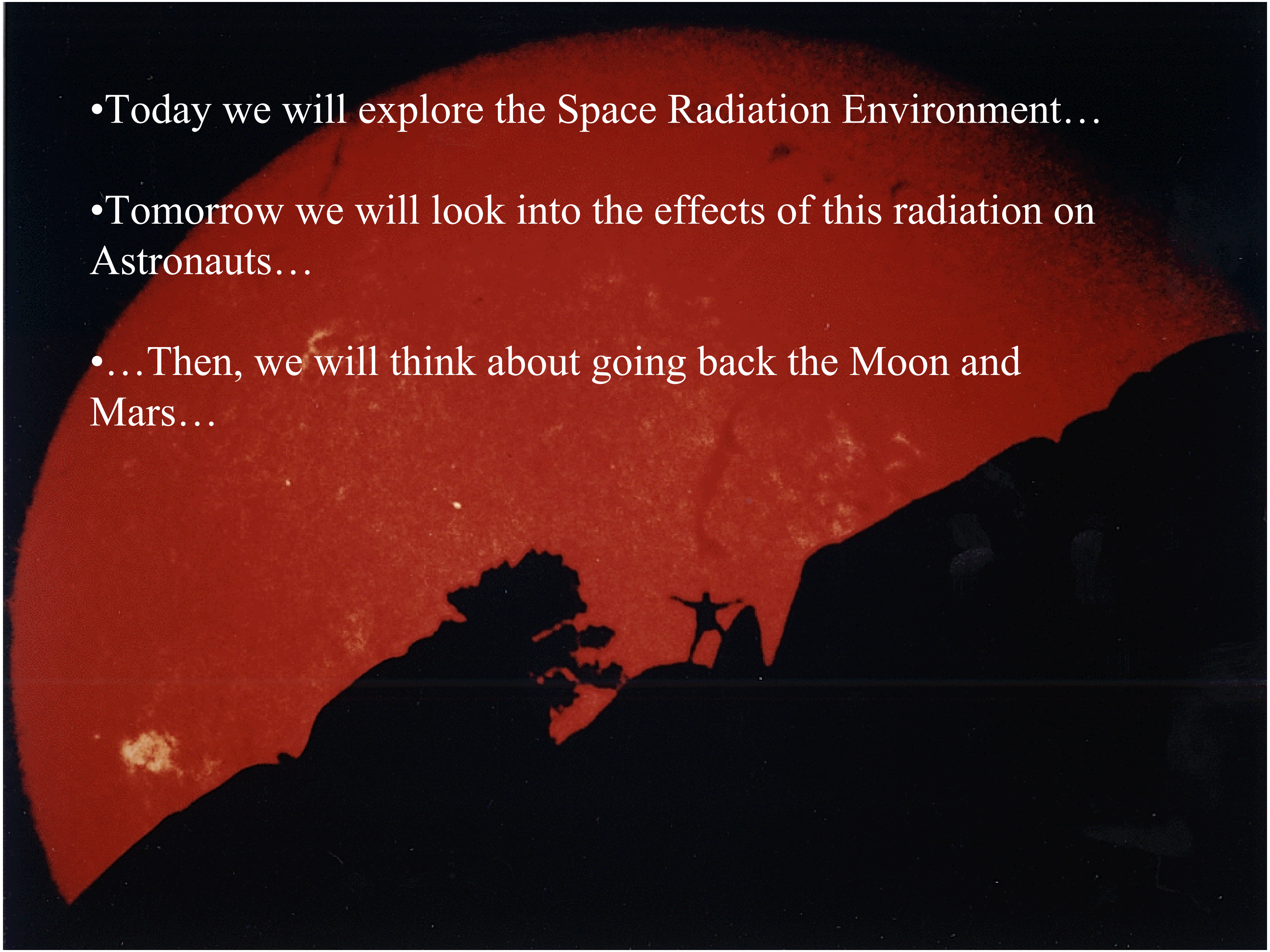
Surviving in space: the challenges of a manned mission to Mars

Lecture 1

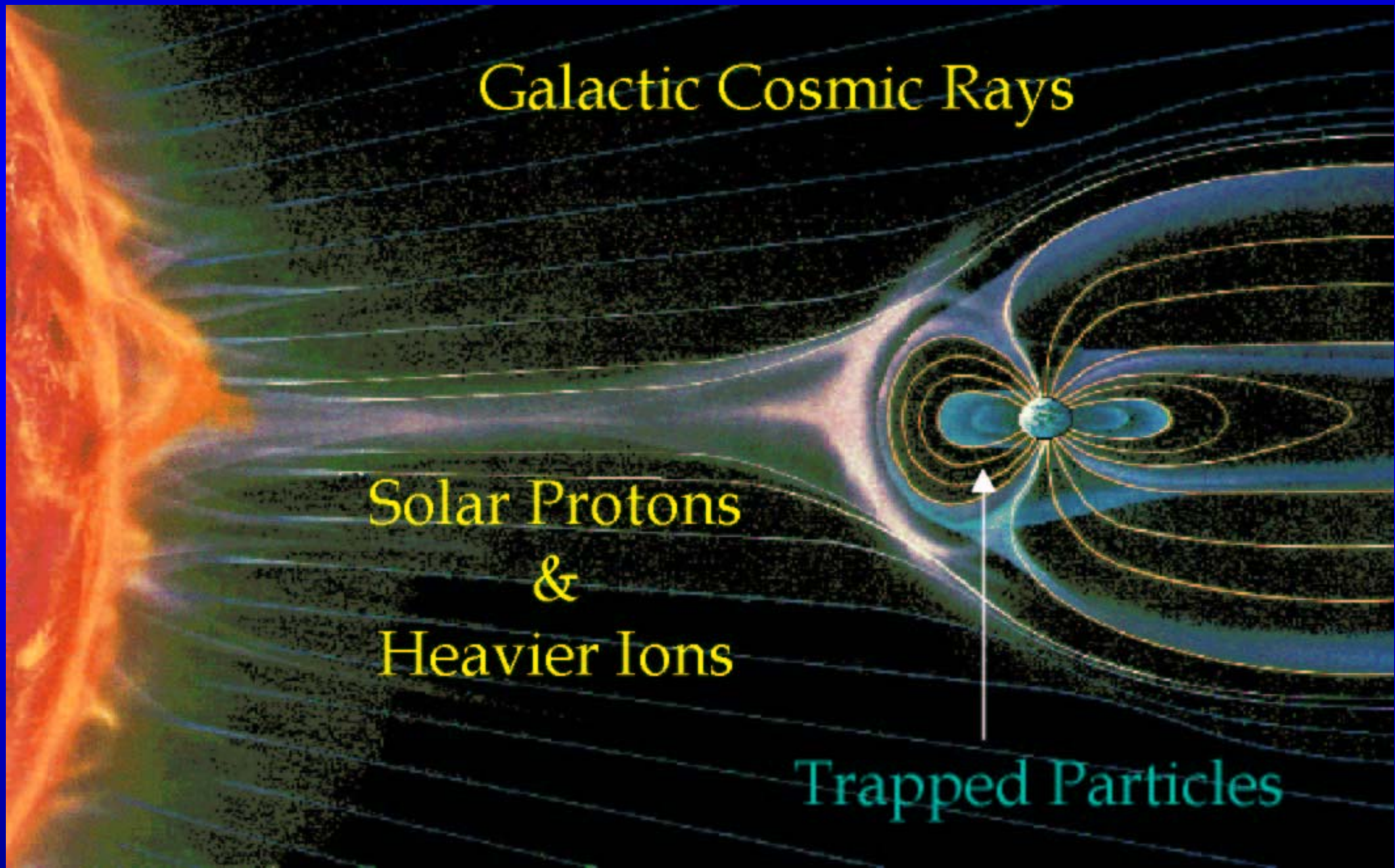
Understanding the Space Radiation Environment

- Ionizing Radiation is Hazardous to Humans
- The more heavily ionizing it is

  the greater the hazard…
- Two general exposure regimes exist:
  - Acute—Risk = Incapacitation & imminent death
  - Chronic—Risk = Stochastic long-term effects
- The Space Radiation Environment is Unique
  - Nothing like it remotely exists on Earth, so…
  - We have no experience in predicting the effects!
- Current policy calls for Astronauts to be treated the same as radiation workers on Earth (e.g. like workers at CERN!!!!)


•Today we will explore the Space Radiation Environment…
•Tomorrow we will look into the effects of this radiation on Astronauts…
•…Then, we will think about going back the Moon and Mars…

Space Radiation Sources



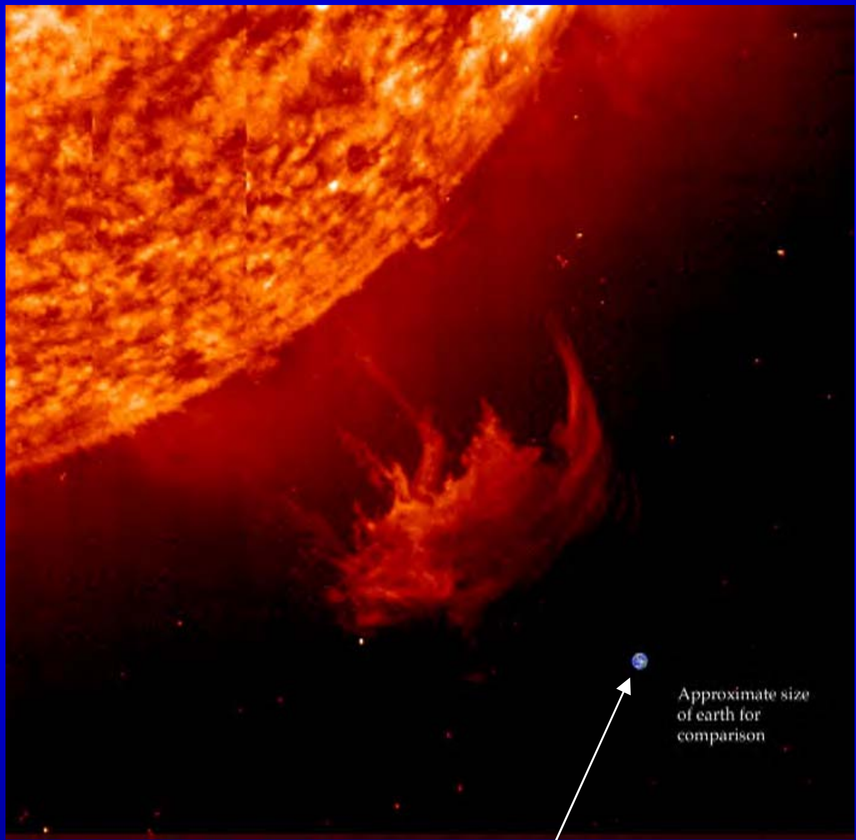
+ Albedos Caused by These Sources

From J. Barth
NASA/GSFC

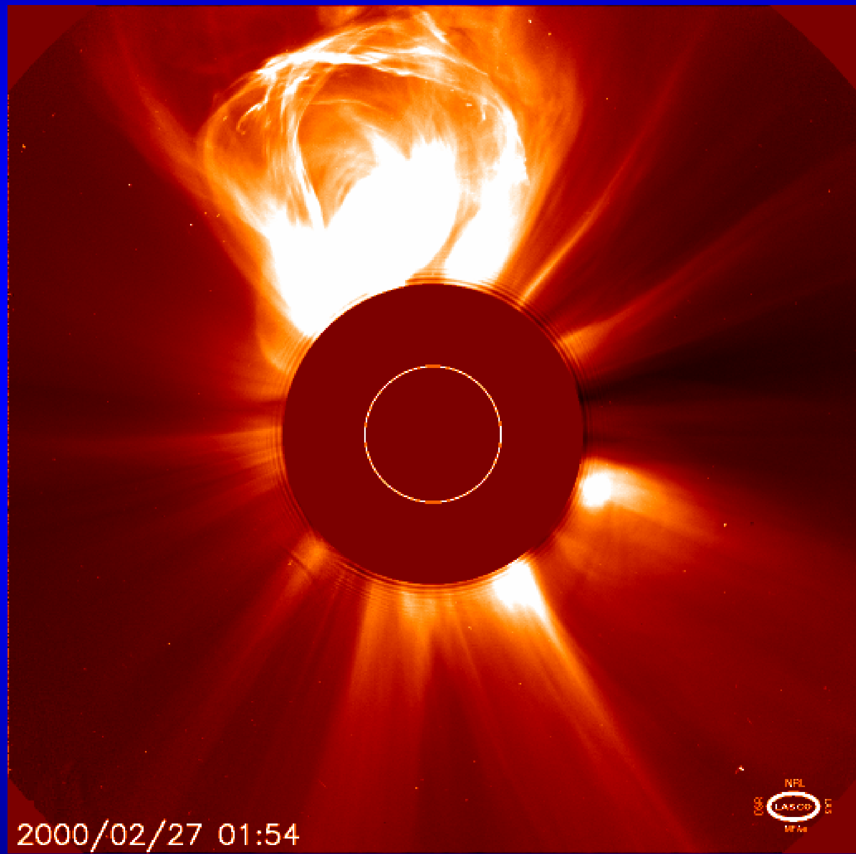
Solar Radiation Sources

- Solar Wind
  - NOT a Radiation Hazard to Astronauts—Can cause metals to become brittle over long times
- Solar X-Rays and γ-Rays
  - Low doses in thinly shielded situations…
- **Solar Particle Events—SPE's**
  - Coronal Mass Ejections—CMEs (& Associated Flares can give rise to Solar Energetic Particles—SEP's)

Coronal Mass Ejections—CME's

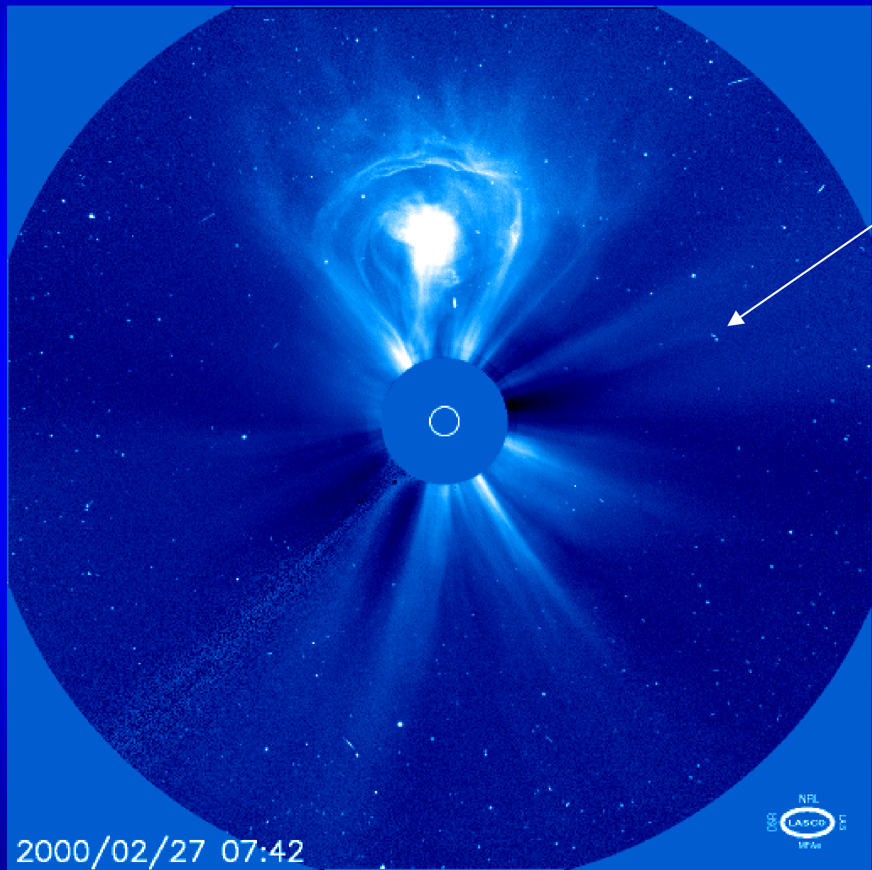


Size of Earth

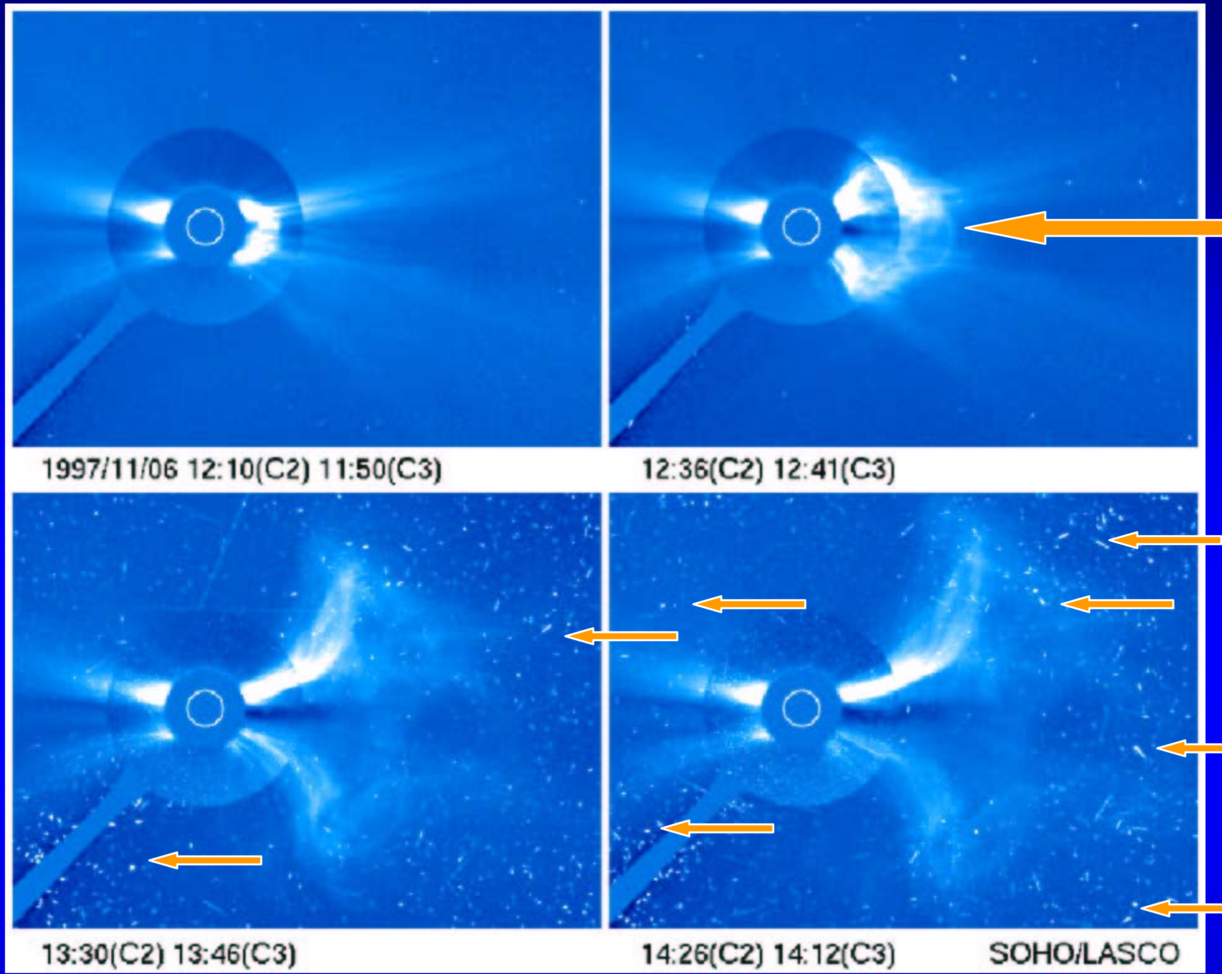


SOHO

SOHO Image (6 Hours Later)



SOHO/LASCO

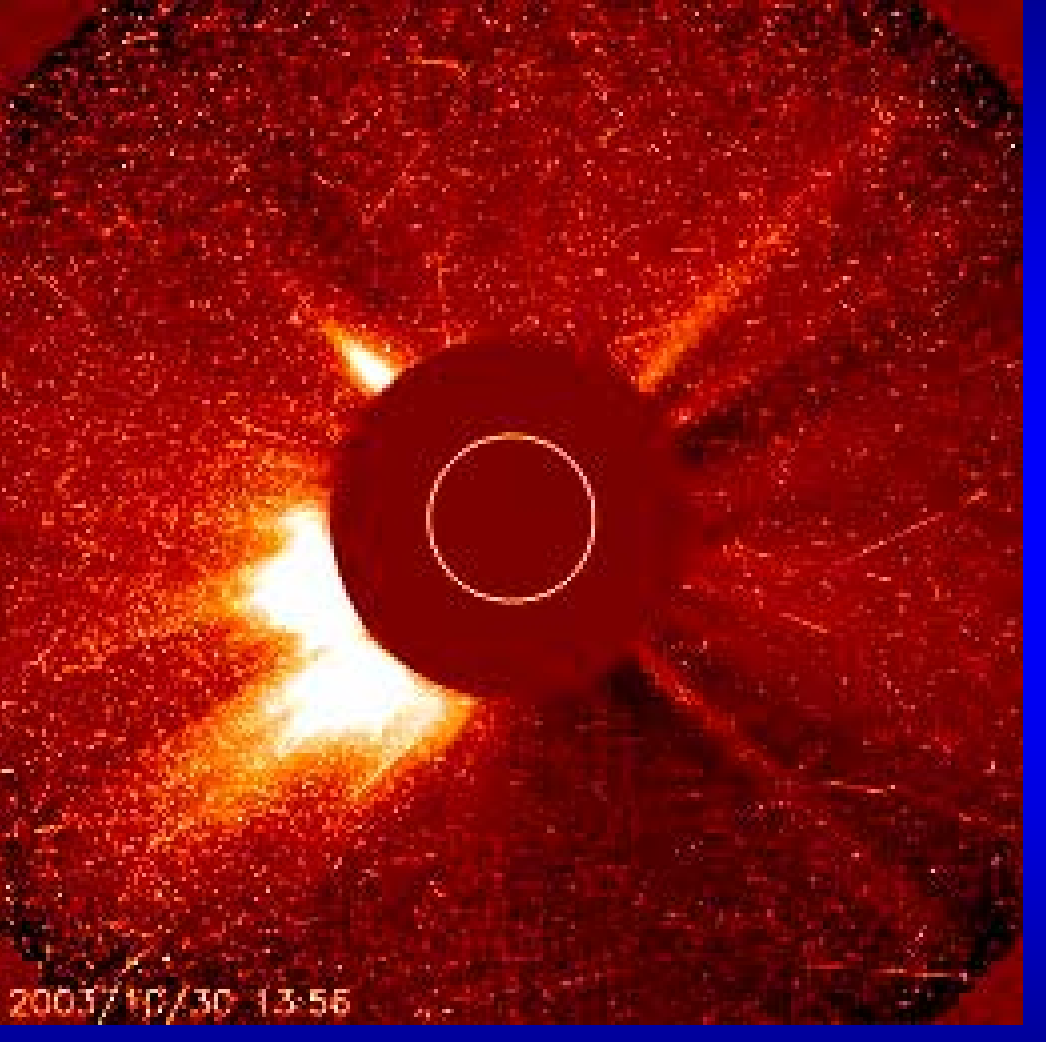


CME

"Snow" = subsequent hits by p & heavier ions on the photo-imaging device due to particles accelerated by the CME…

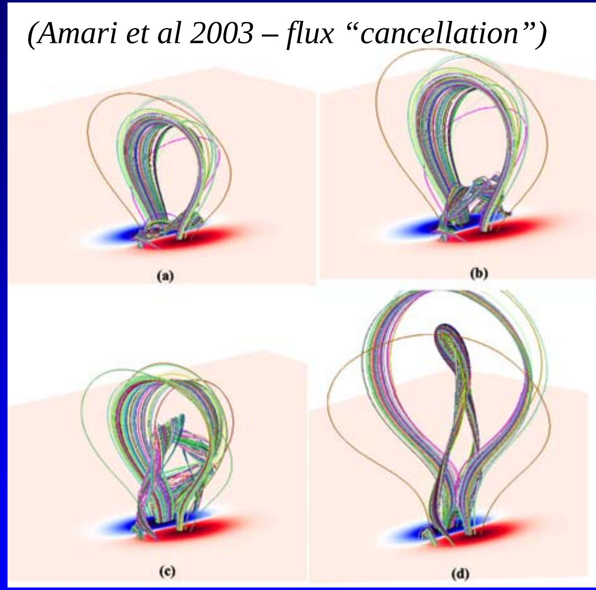
Energetic Solar Particle Events caused by a Coronal Mass Ejection

SOHO/LASCO

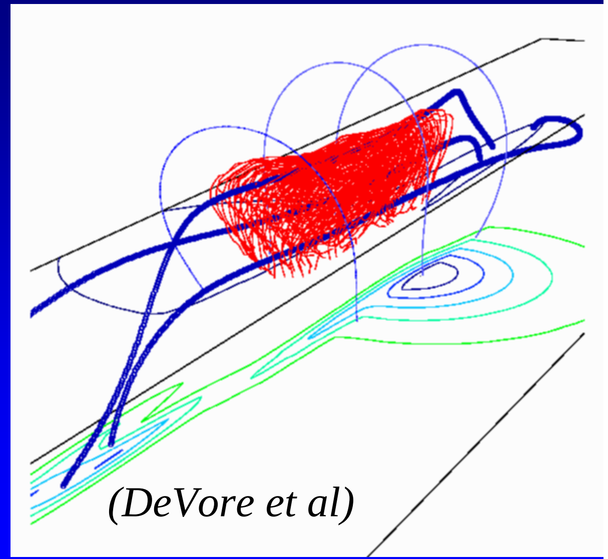

2003/10/30 13:56

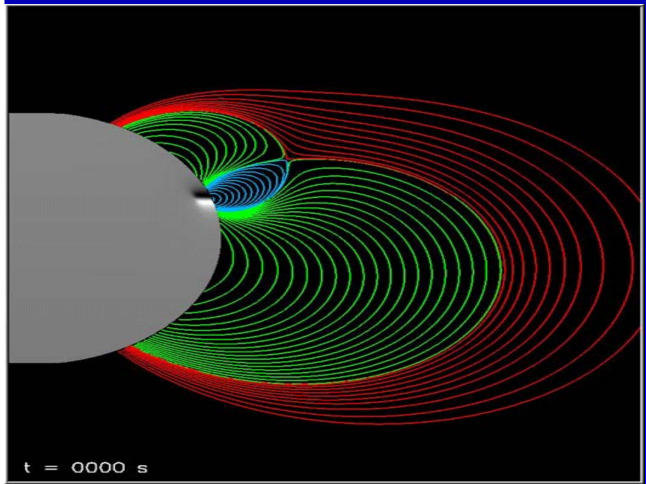
Why do CME's Occur?

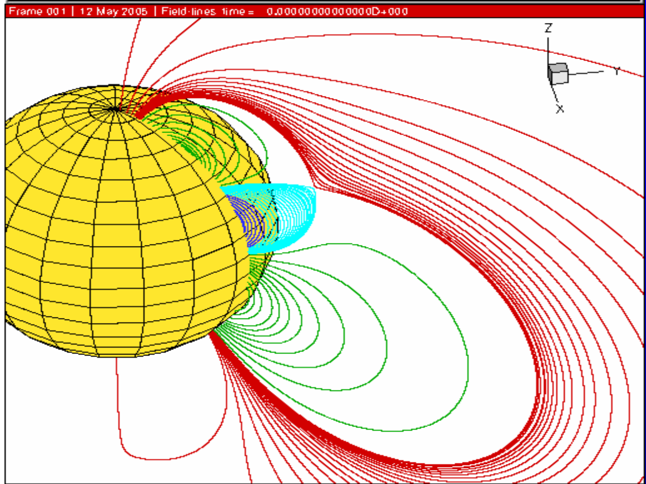
(Courtesy T. Antiochos, NRL)



Twisted Flux Rope Models





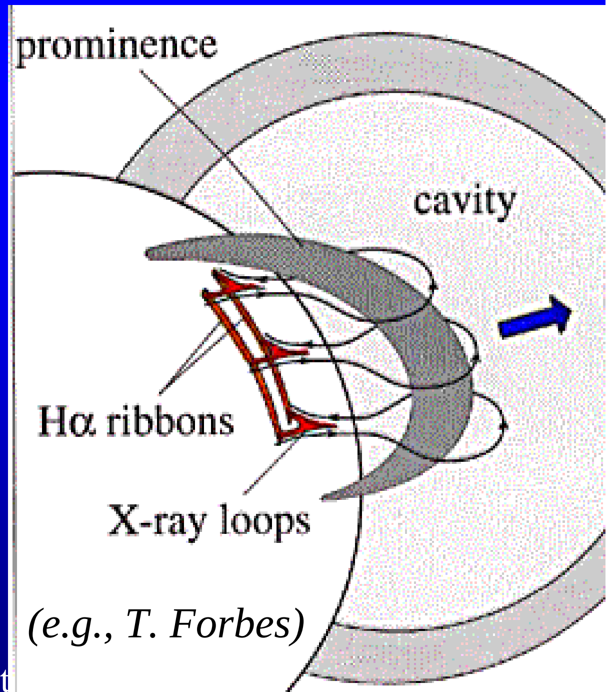


Breakout Model

Reconnection Models

- Multi-polar field & footpoint shear
- Reconnection removes overlying flux
- CME due to run-away expansion, accelerates when flare turns on

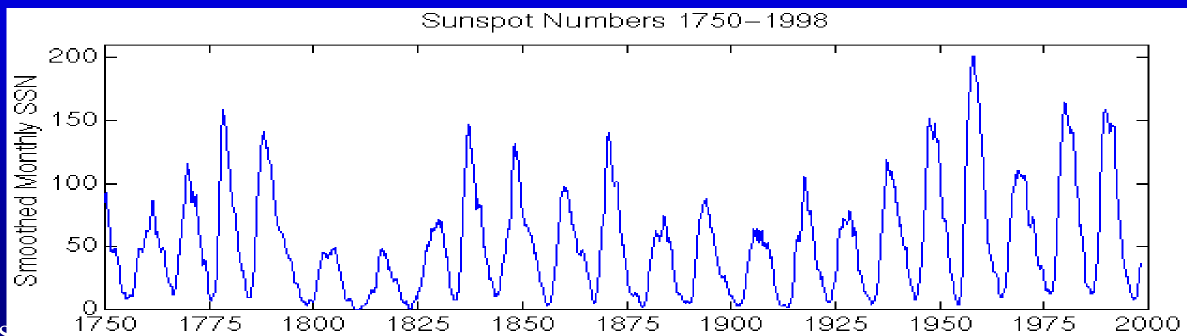
(from Lynch et al)



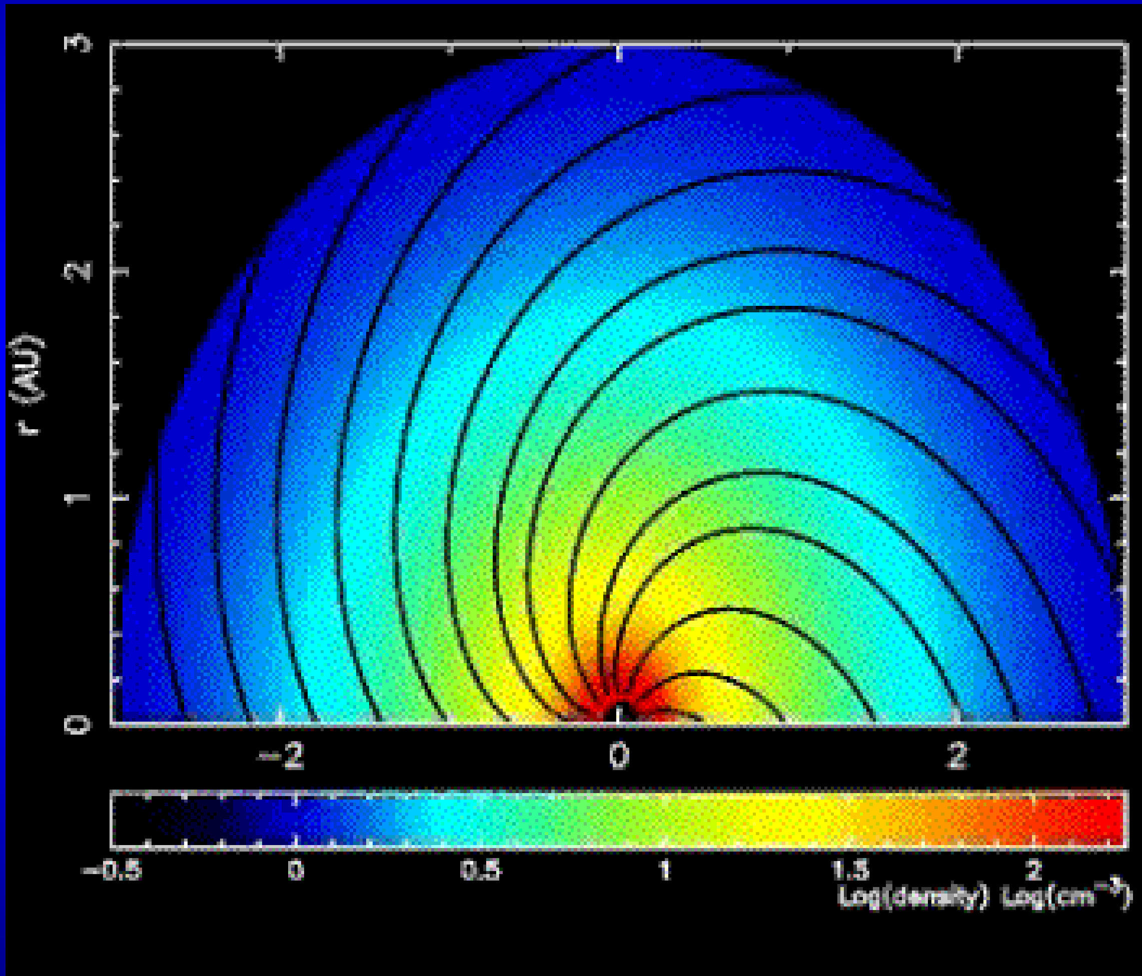
We don't know !

The Solar Cycle

- The Sun's magnetic field inverts on an approximately 11 year cycle
- It takes 2 successive 11 year cycles return the polarity to the original configuration.
- The effects seen during each cycle differ from "positive" to "negative" cycles
- ALL SOLAR ACTIVITY FOLLOWS THE SOLAR CYCLE (Sunspots, Flares, CME's, Solar Wind Fluence, etc.)

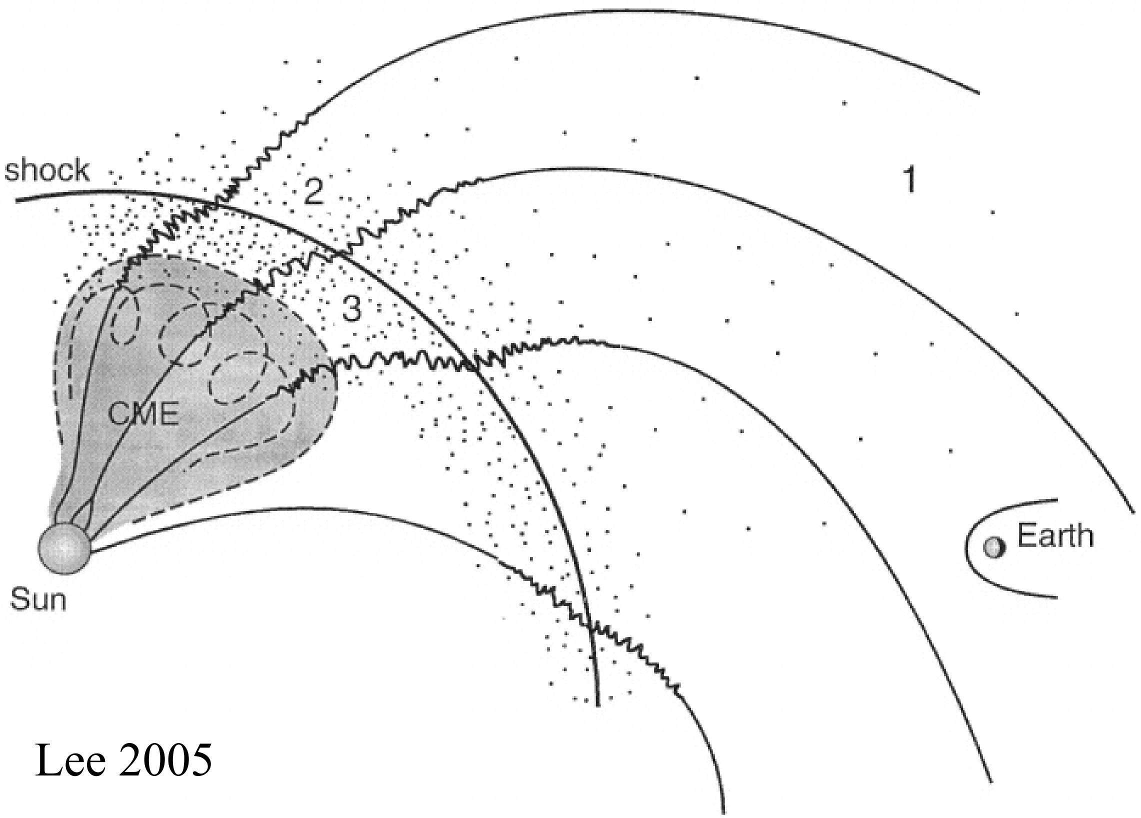


Simulation of CME Shock



Courtesy
G.P. Zank

Characteristics Depend on Longitude of the Event with respect to Earth



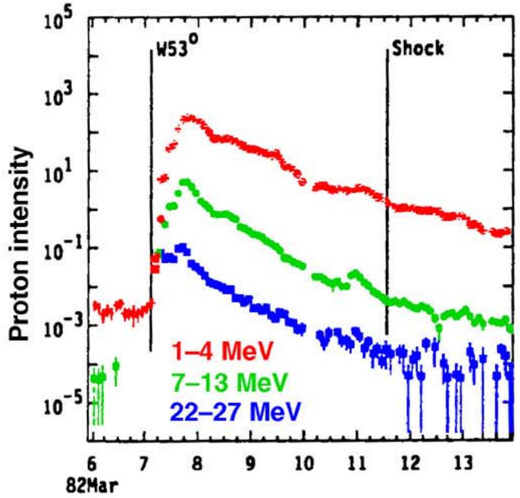
Lee 2005

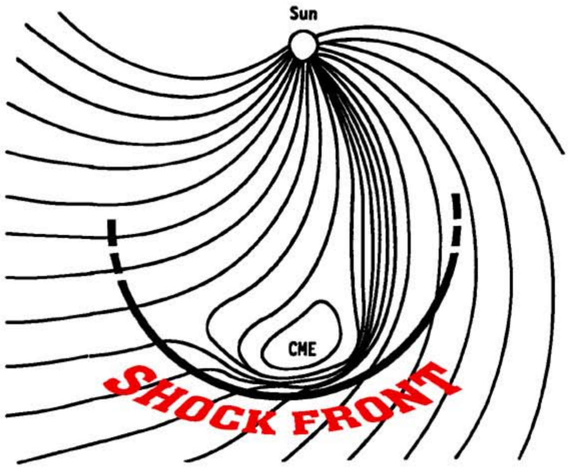
- Rise time-Faster the farther west the event is with respect to Earth.
- Compostion ratios
- Spectral Hardness
- Intensity

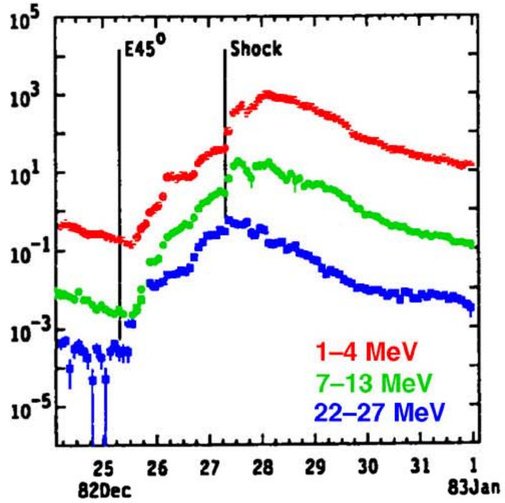
From C. Cohen

Intensity profiles

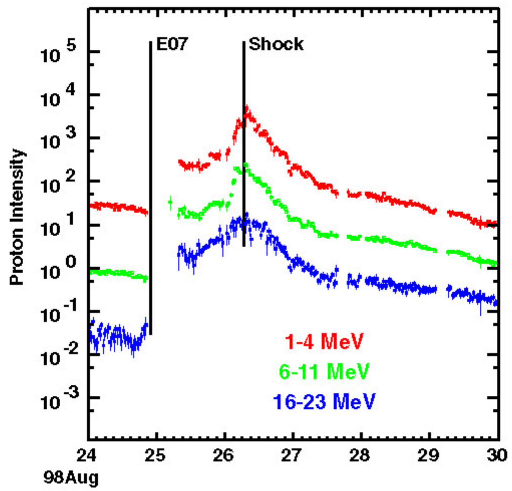
after Cane et al. (1988); Reames et al. (1996).





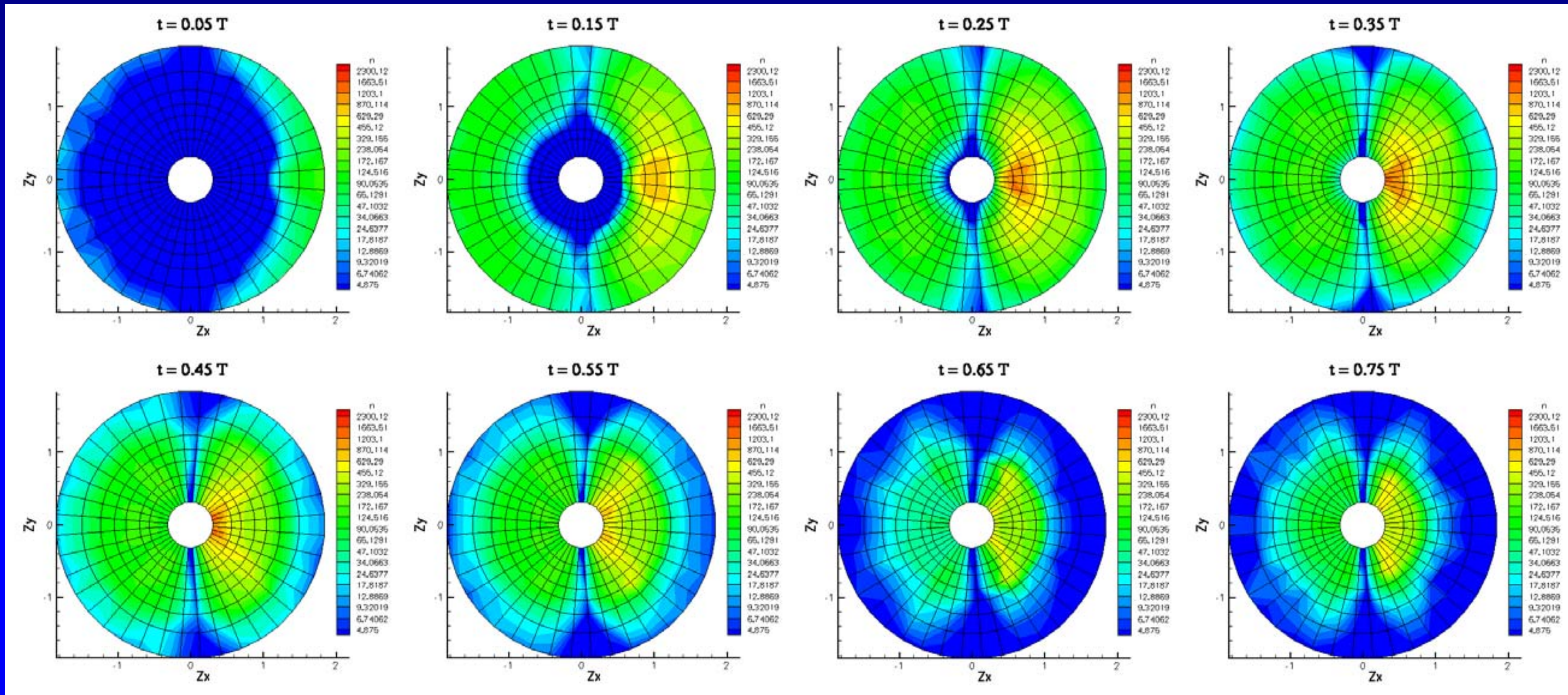


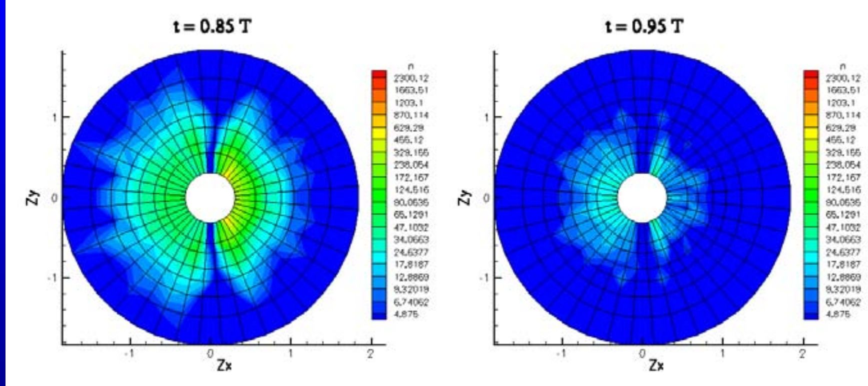
Only the fastest CMEs (~1-2 %) drive shocks which make high-energy particles.



Courtesy G.P. Zank

Phase space evolution – time sequence





At t=0.85 T, we can see clearly that there are more backward propagating particles than forward ones between 20<K<30 MeV.

At t=0.95 T, it is more pronounced for K~10 MeV.

Solar Particle Event Intensity

Figure D.2. Time Course of a Solar Particle Event

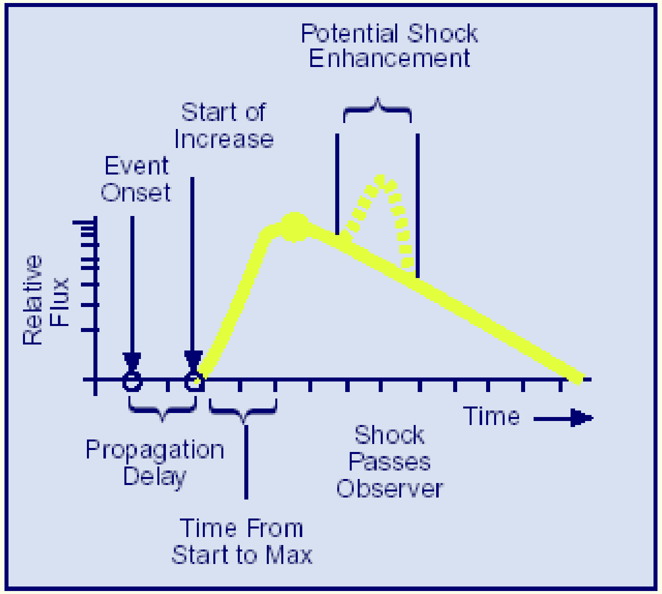
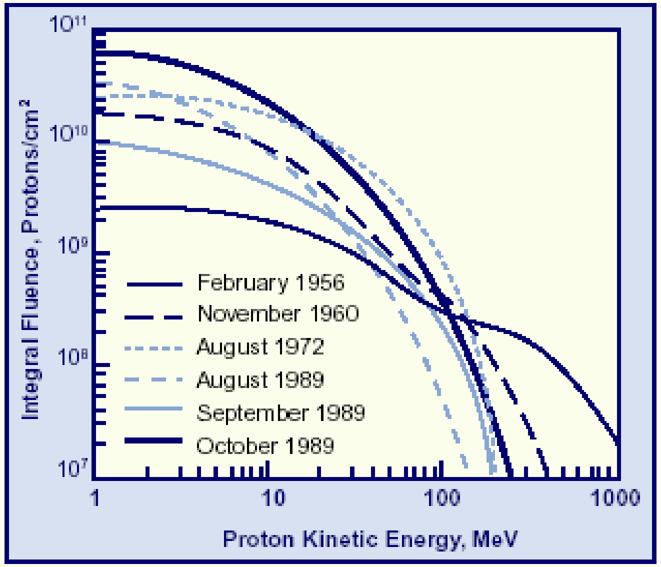


Figure D.3. Distribution in Energy of Proton Fluxes for Major Past SPE's (Free Space)

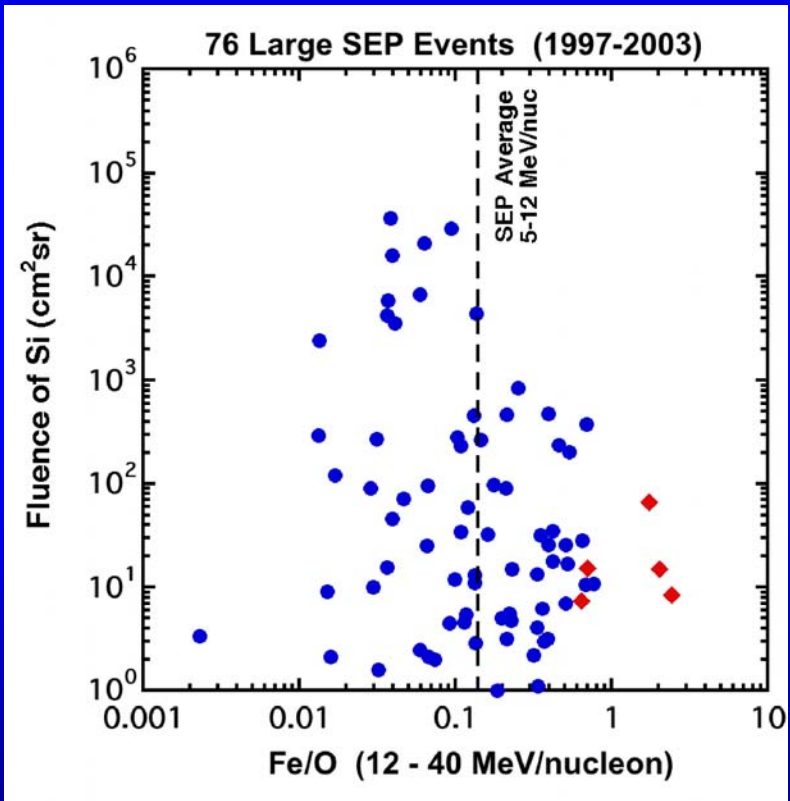


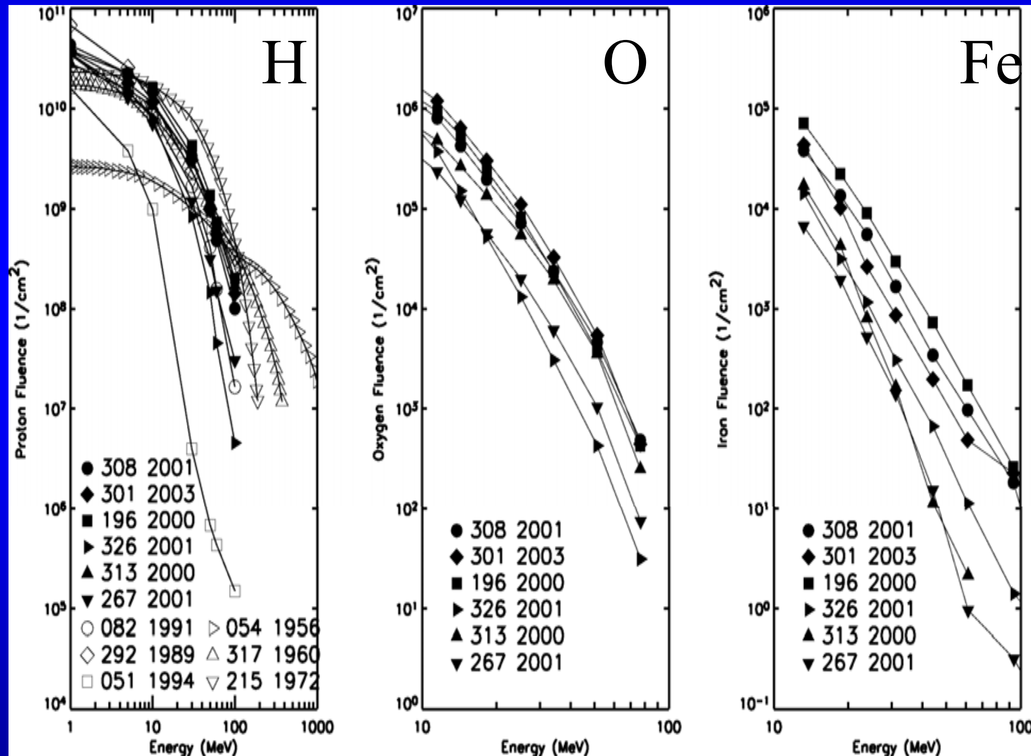
Most events are protons only, some show significant ^{3}He and ^{4}He & a few contain heavy ions. The hardest events have fluxes out to ~ 1 GeV/A…

From NASA 1996 Strategic Program Plan

Characteristics - Composition *Variability*

- mostly protons
- heavy ions still important not predictable from proton measurements

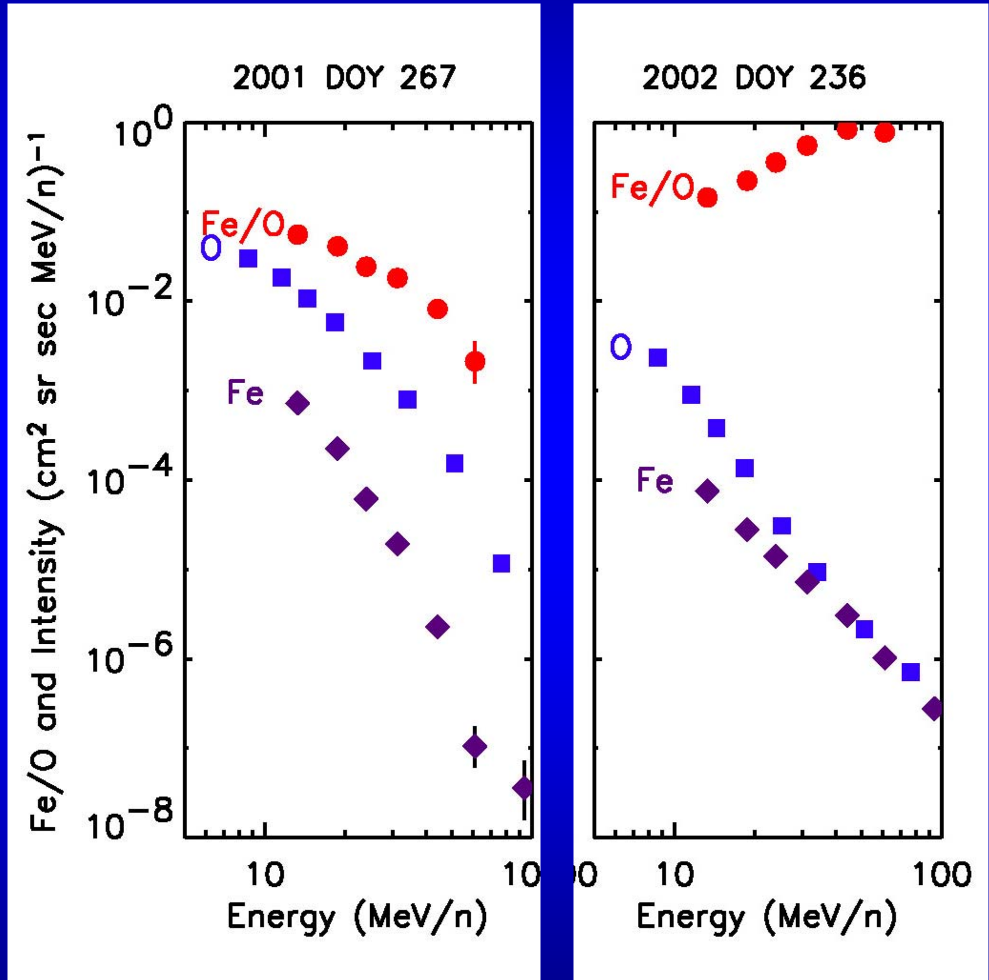




From C. Cohen

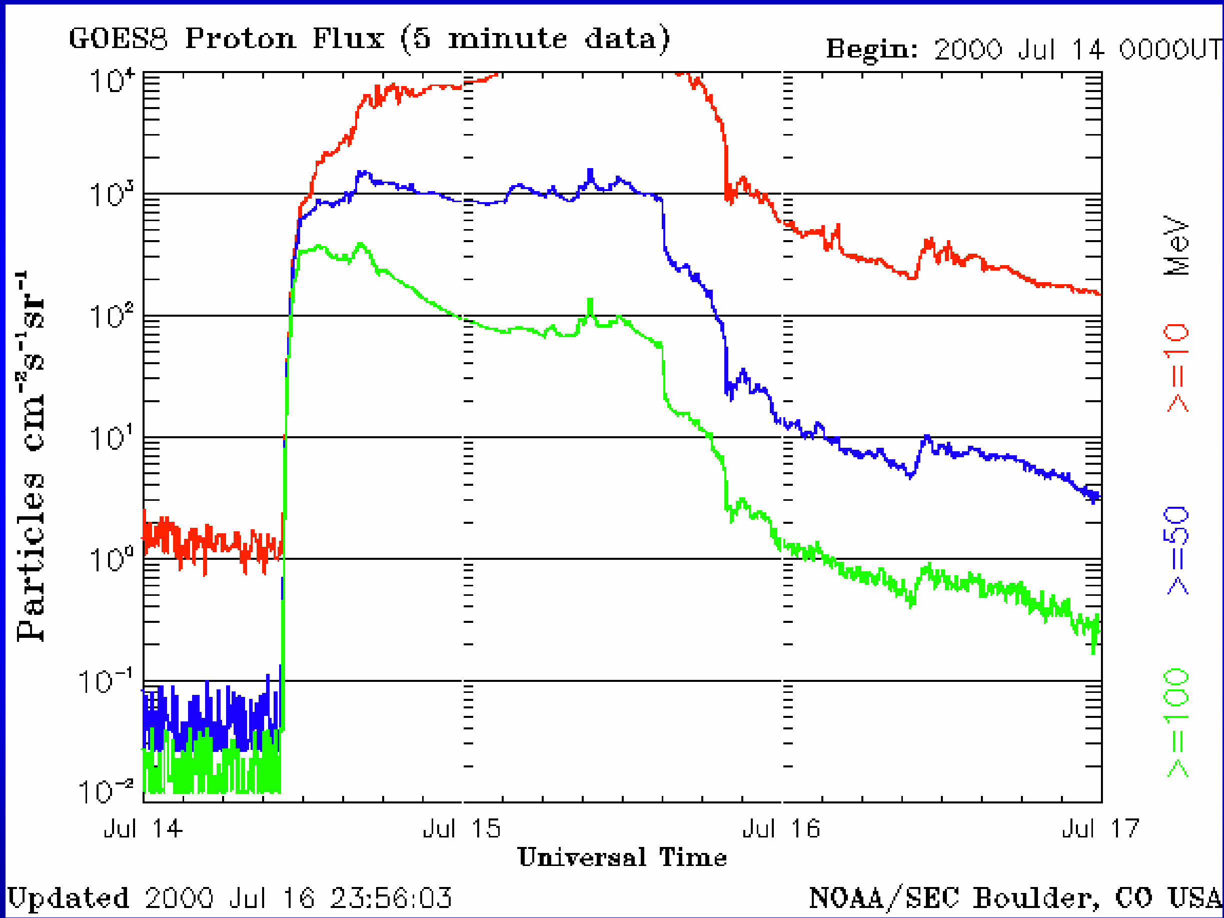
SEP Composition Variability

- mostly protons
- heavy ions still important
  - not predictable from proton measurements
  - very variable
  - dependent on energy



From C. Cohen

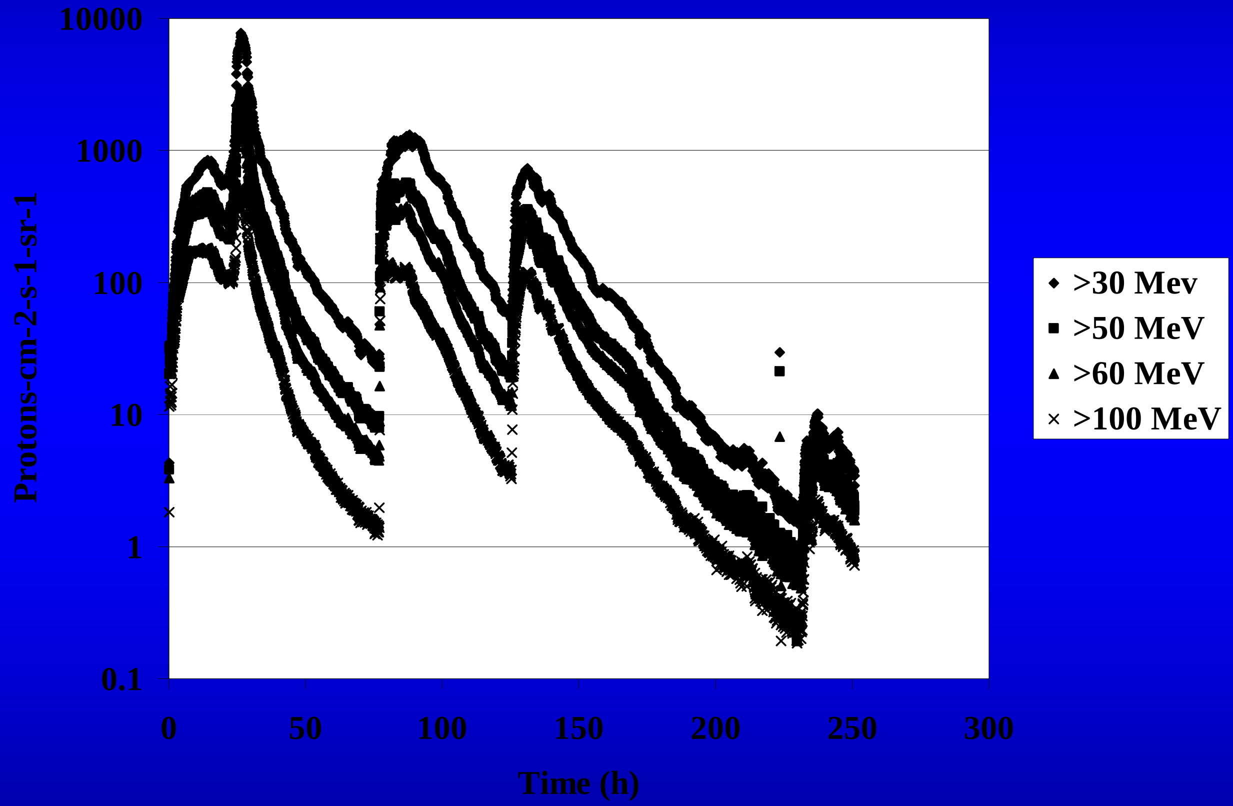
"Bastille Day" 2000 SPE



NOAA GOES 8

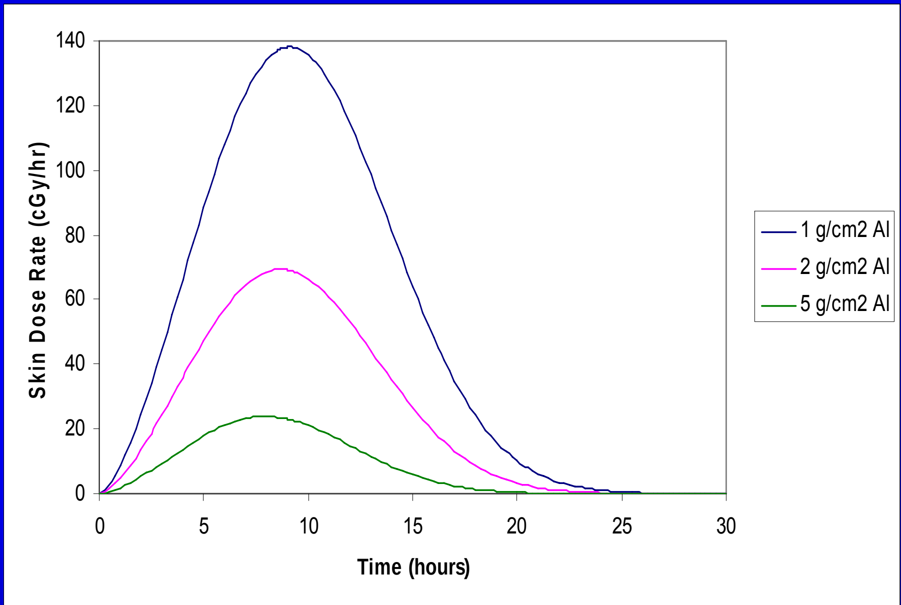
Estimating the "Worst Case" Event

Start with this October 1989 SPE…



Courtesy of L. Townsend, US NCRP

Assume Hardness of the August 1972 Event

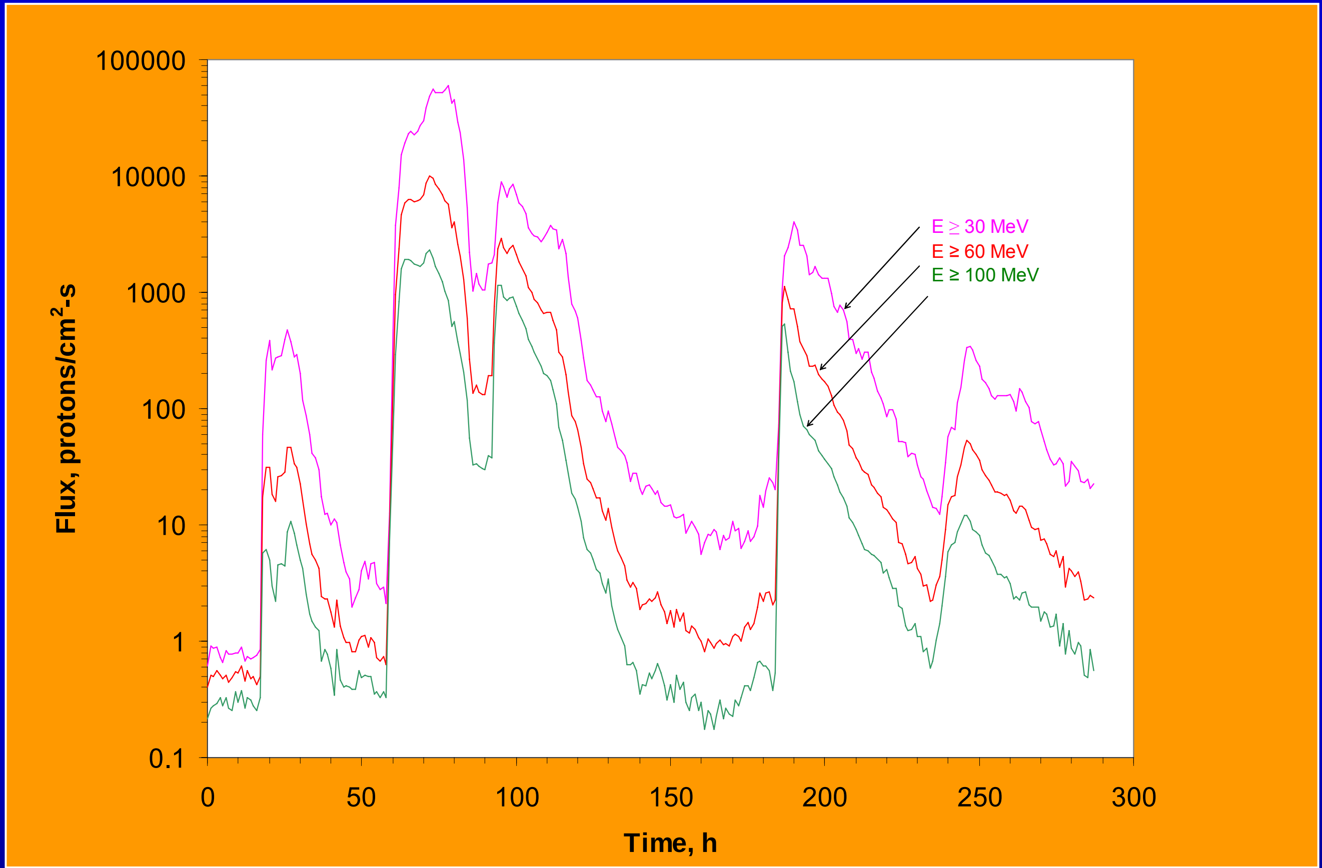


Shielding	Effective Dose (cSv)	Avg. BFO Dose Eq. (cSv)	% Diff.
1 g/cm^2 Al	337.5	111.0	203.9%
2 g/cm^2 Al	200.2	91.3	119.3%
5 g/cm^2 Al	88.5	56.3	57.3%
10 g/cm^2 Al	40.2	30.5	31.7%

Effective "Skin Dose" Behind Shielding

Courtesy of L. Townsend, US NCRP

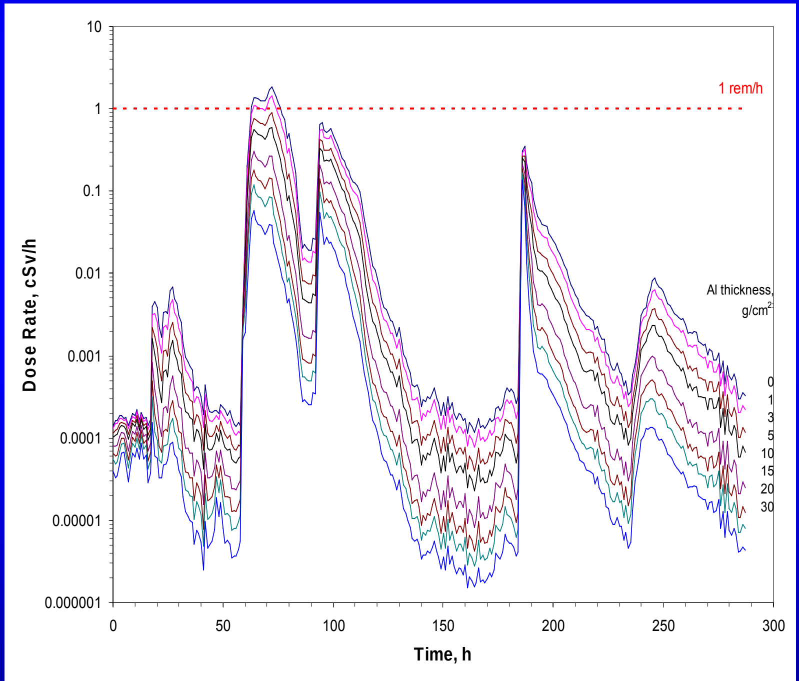
Compare with Oct. 26 - Nov. 6, 2003 SPE



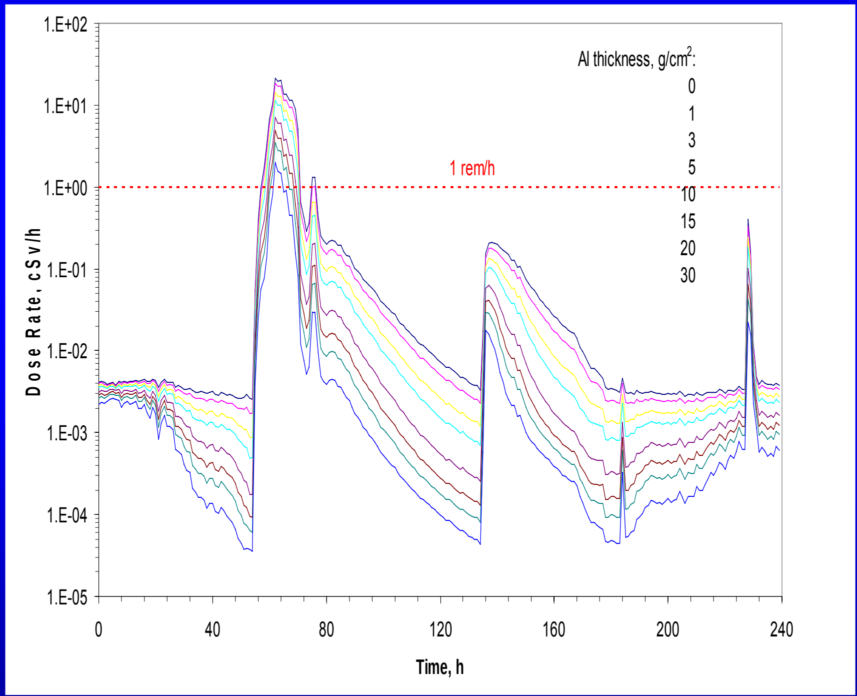
Courtesy of Kim, Cucinotta & Wilson

2003 v. 1972 SPE Dose Rates

2003

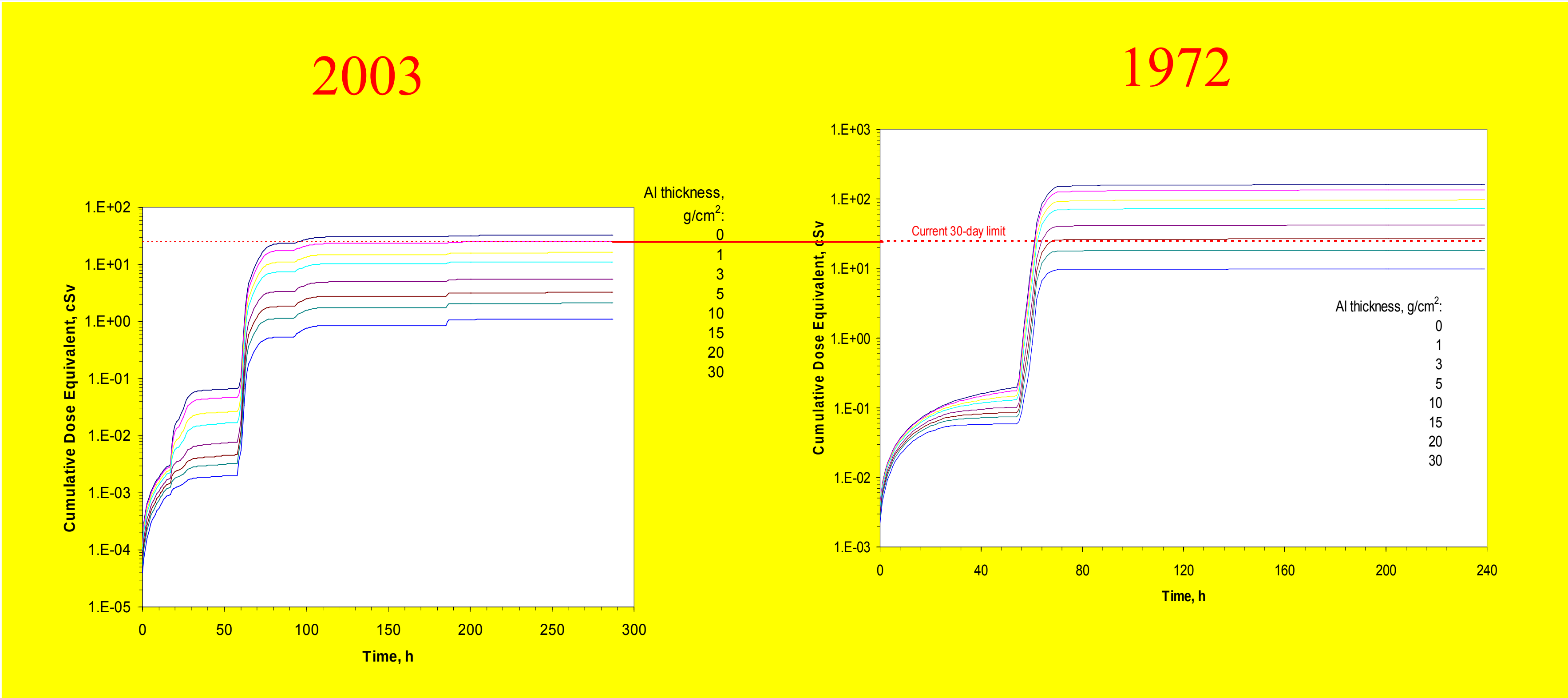


1972



Courtesy of Kim, Cucinotta & Wilson

Cummulative Dose Equivalents Behind Aluminum Shielding



Courtesy of Kim, Cucinotta & Wilson

Fold in Antarctic Icecap Data…

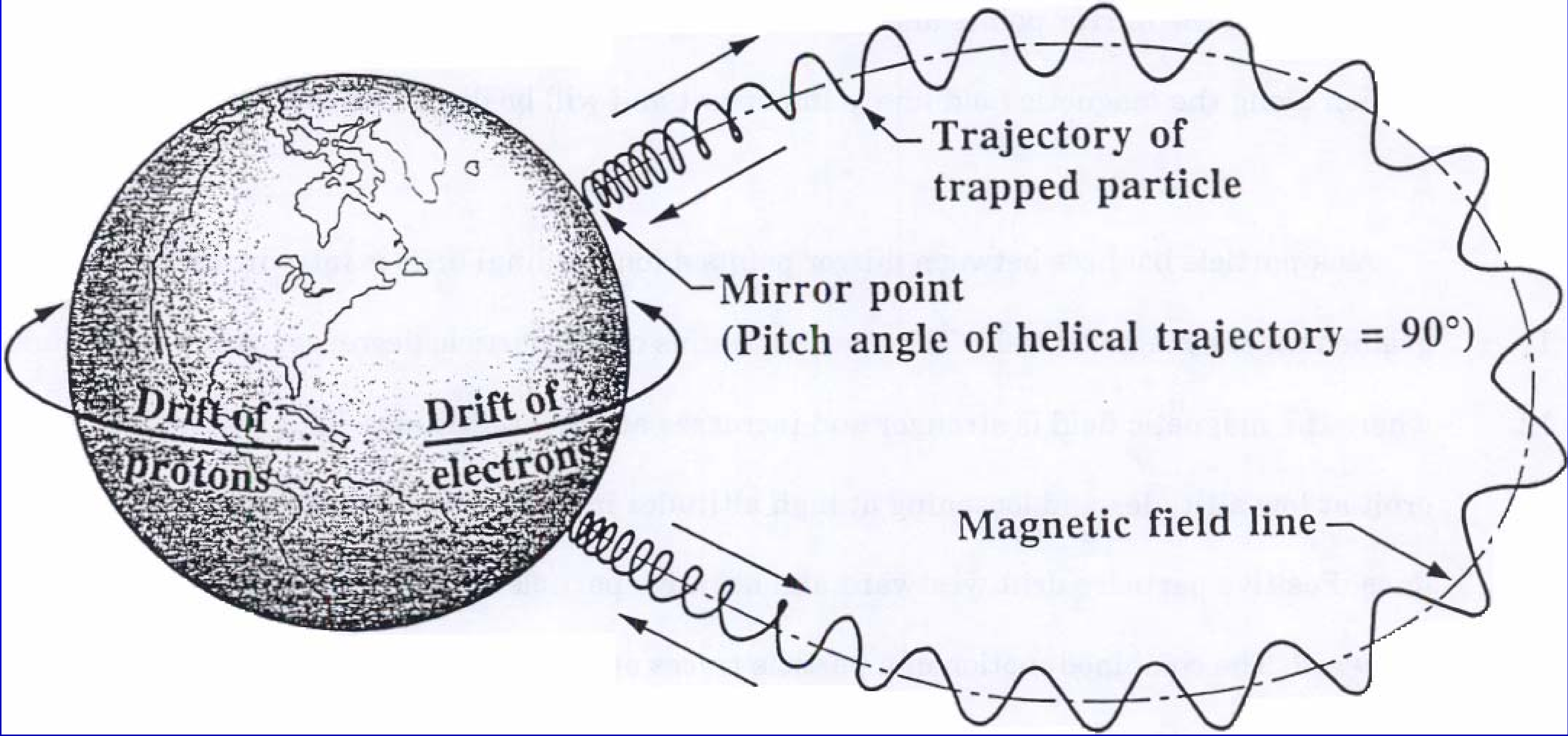
- **Ice core data from the Antarctic indicate that the largest event in past ~ 500 years was probably the Carrington Flare of 1859**
  - **fluence ~ 20× larger than Aug 72**
  - **spectrum energy dependence unavailable, assume hard spectrum**

Courtesy of L. Townsend, US NCRP

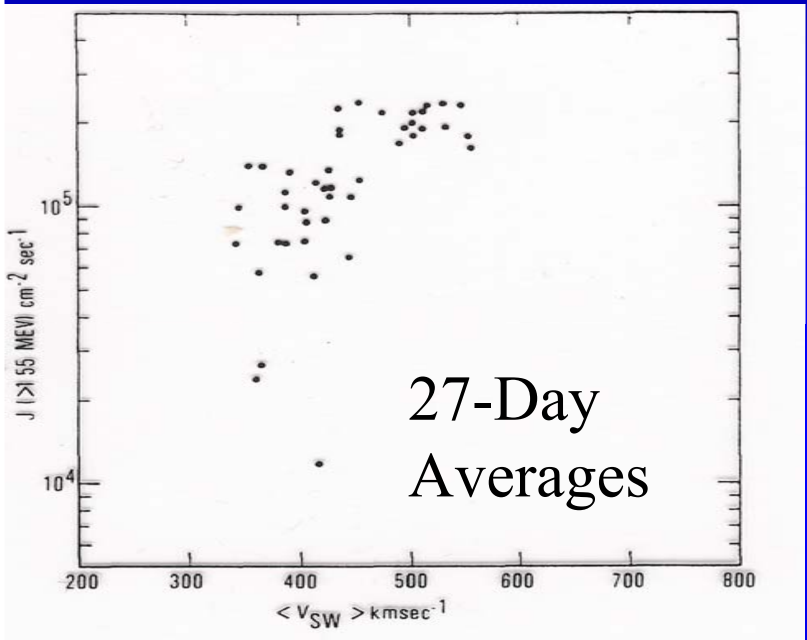
Forcasting CME's & SPE's

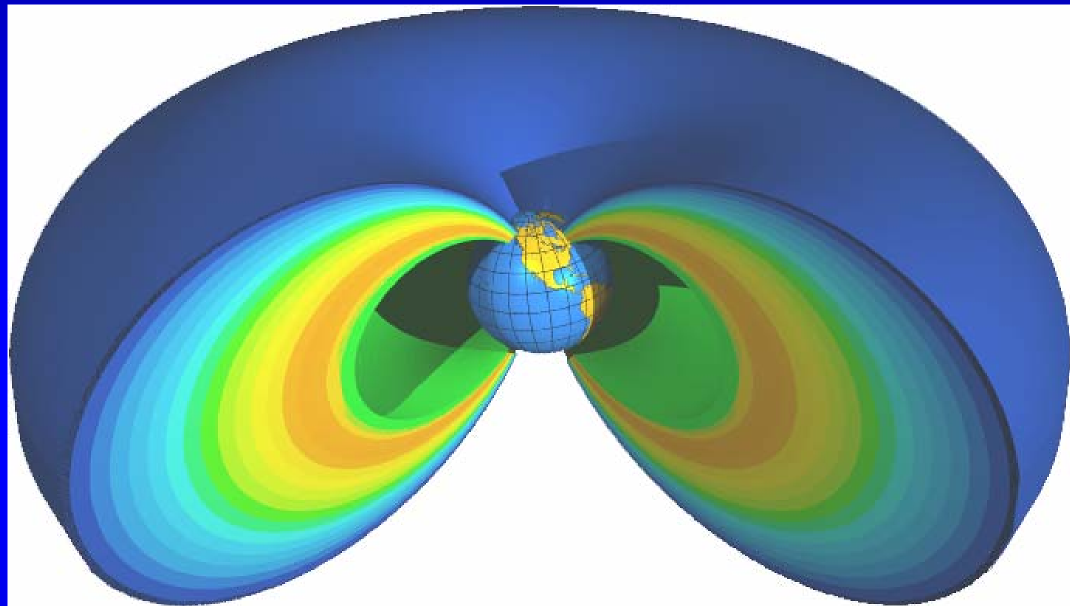
- We cannot (reliably) forecast CME's in advance
- We cannot forecast which CME's will have SEPs
- We cannot give reliable "all clear" forcasts.
- CMEs clearly pose an acute dose threat in lightly shielded exposures
- "Now Forecasting" is a possibility by a few hours
- SPE's may be an example of "Self-Organized Criticality" from non-linear theory…

Trapped Radiation
"VAN ALLEN BELT" Particles



Inner and Outer Belts

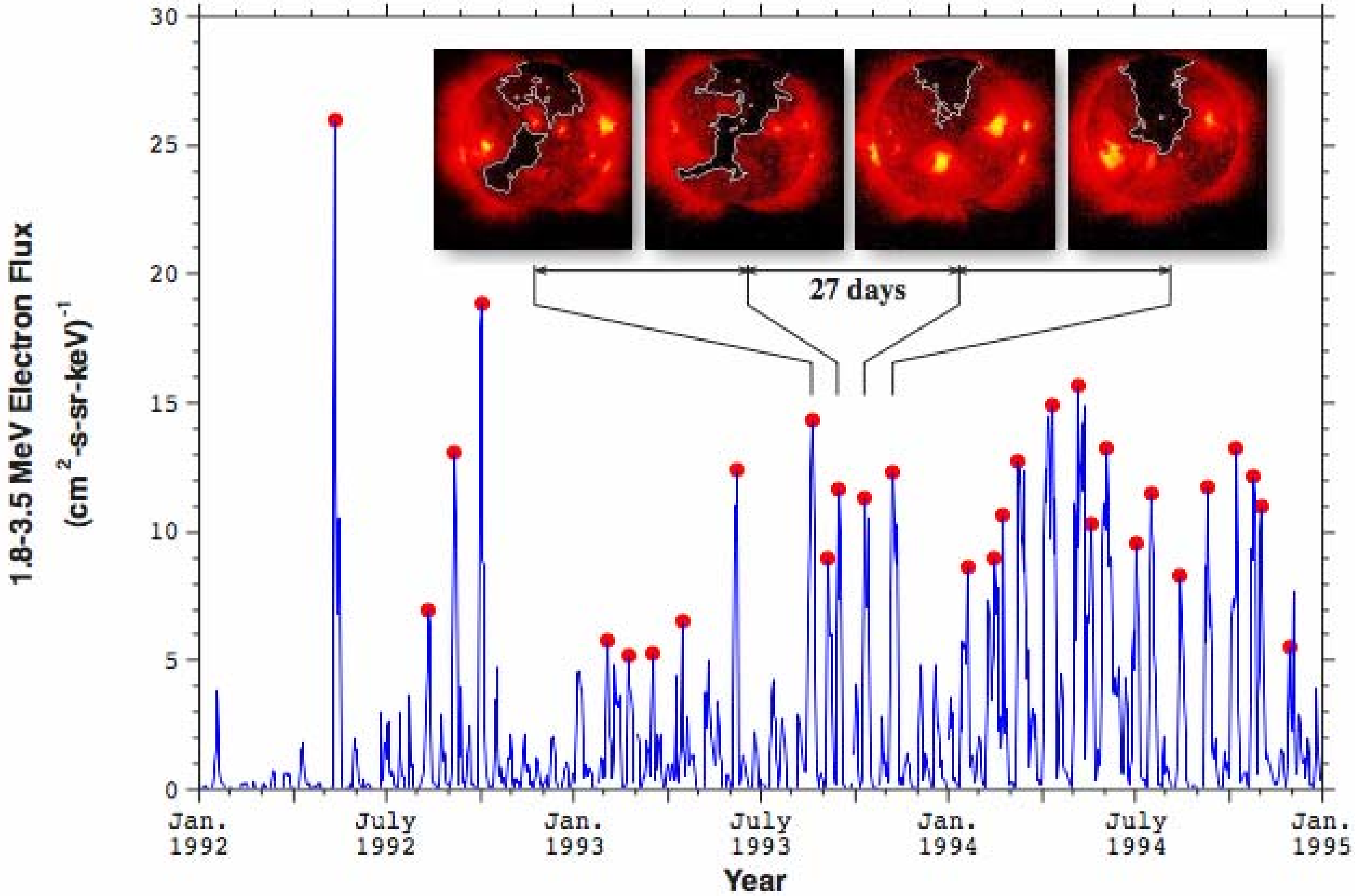




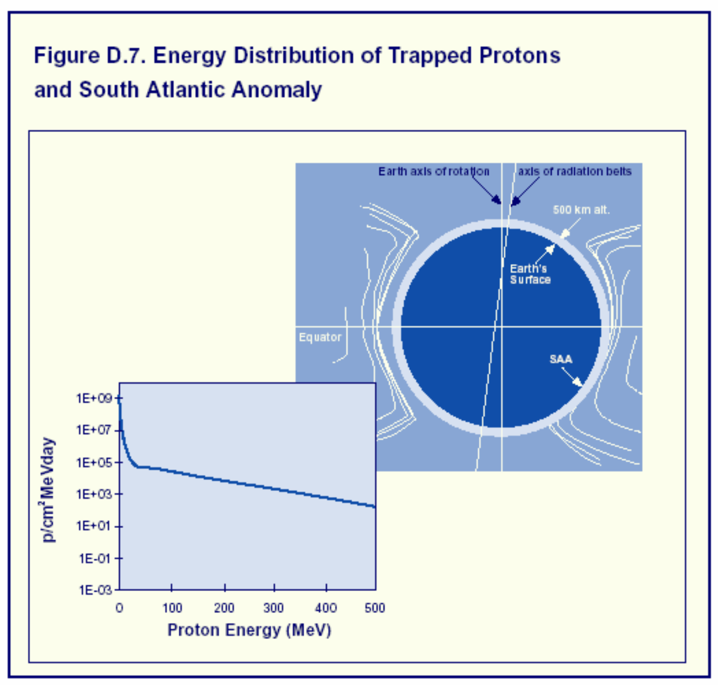
- Outer Belt electrons filled by Solar Wind—Sensitive to SW Velocity
- Inner Belt protons due to albedo neutron decay.
- South Atlantic Anomaly provides a significant exposure in LEO

From G. Reeves

Relativistic Electron Events 1992-1995

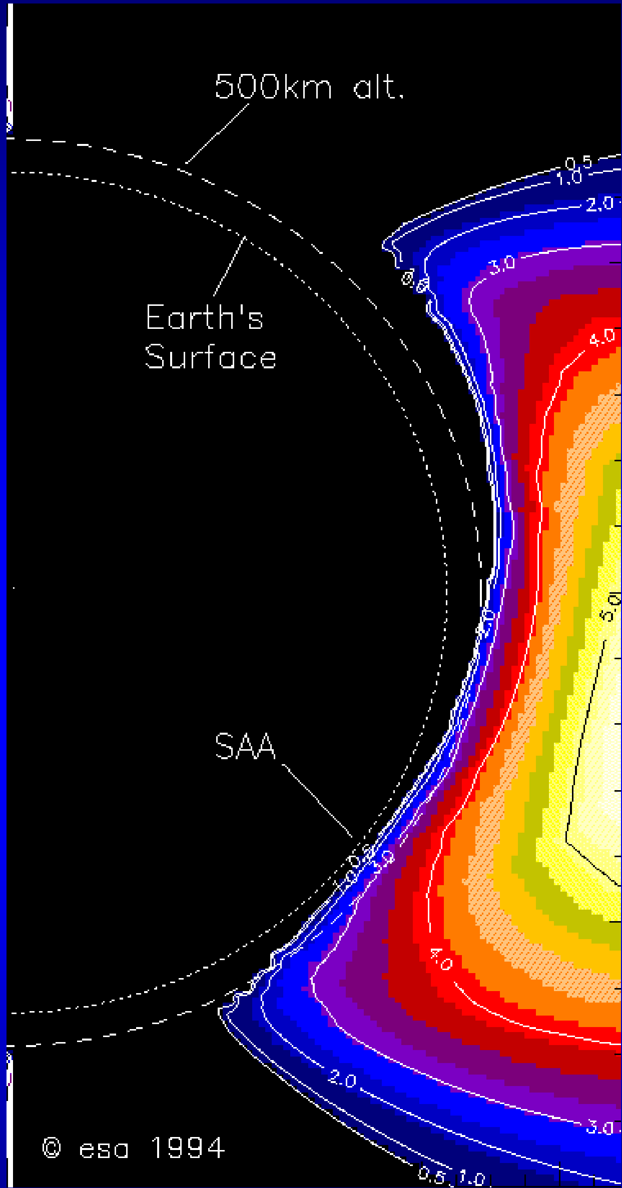


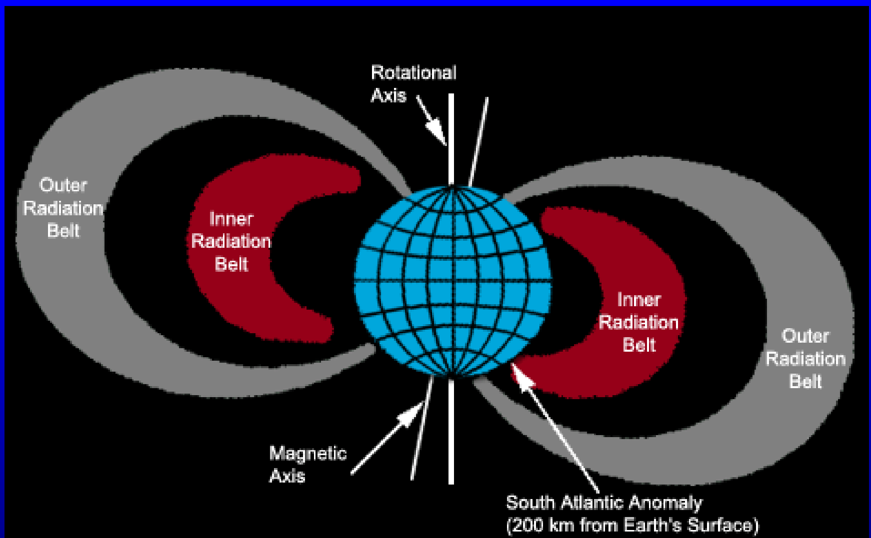
Reeves GRL 1998



South Atlantic Anomaly

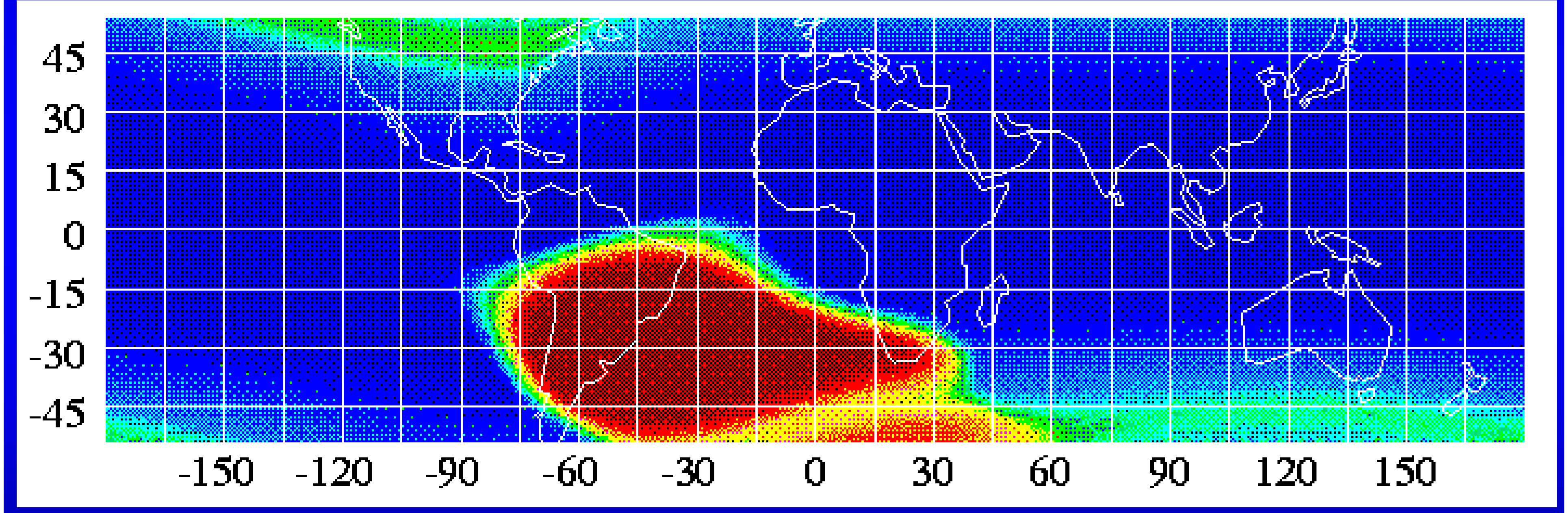
[SAA]





From NASA SPP

Fluence Contours in the SAA



Inner and Outer Belts

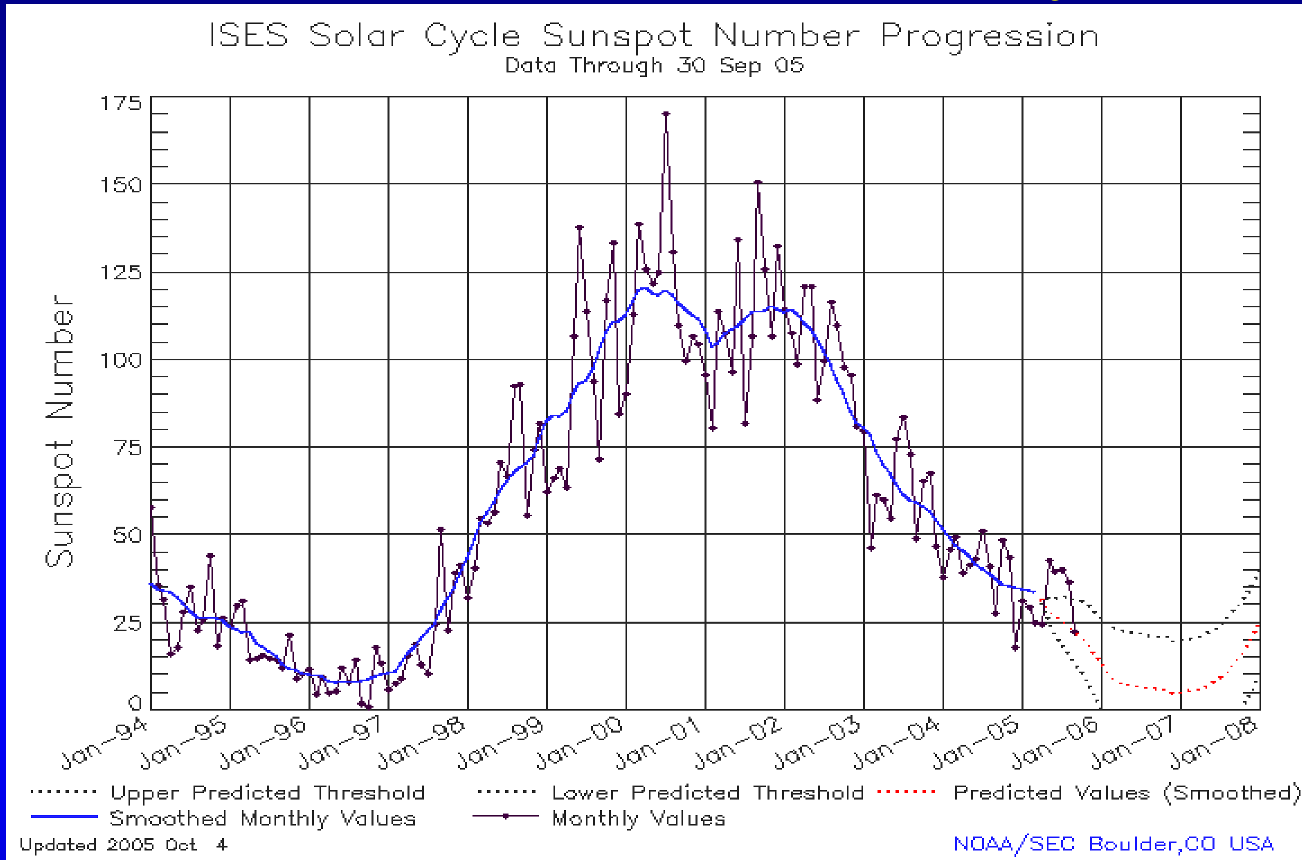
- **Inner Belt**
  - mainly protons; energies up to ~500 MeV
  - 400 MeV peak ~1.3 R_E
  - 4 MeV ~2.0 R_E
- **Outer Belt**
  - mainly electrons; energies > several MeV
  - Large variations (2-4 orders of magnitude) over periods of hours to days
- Rapid transits through belts limit doses to crews

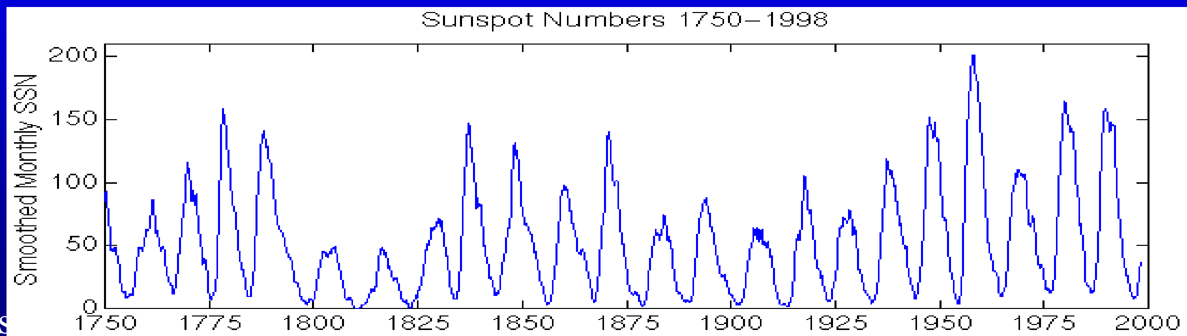
LEO DOSES

- GCR dominates at low altitudes
- SAA protons dominate at higher altitudes
- About half and half at ~ 400 km altitude
- Shuttle flights (28.5-62º; 220-615 km)
  - crew doses : 0.02 – 3.2 cGy
- MIR (51.6º; ~ 400 km)
  - crew doses: 2.3 – 8.2 cGy
- ISS (51.6º; ~ 400 km)
  - crew doses: ~ 5 cGy (solar max)

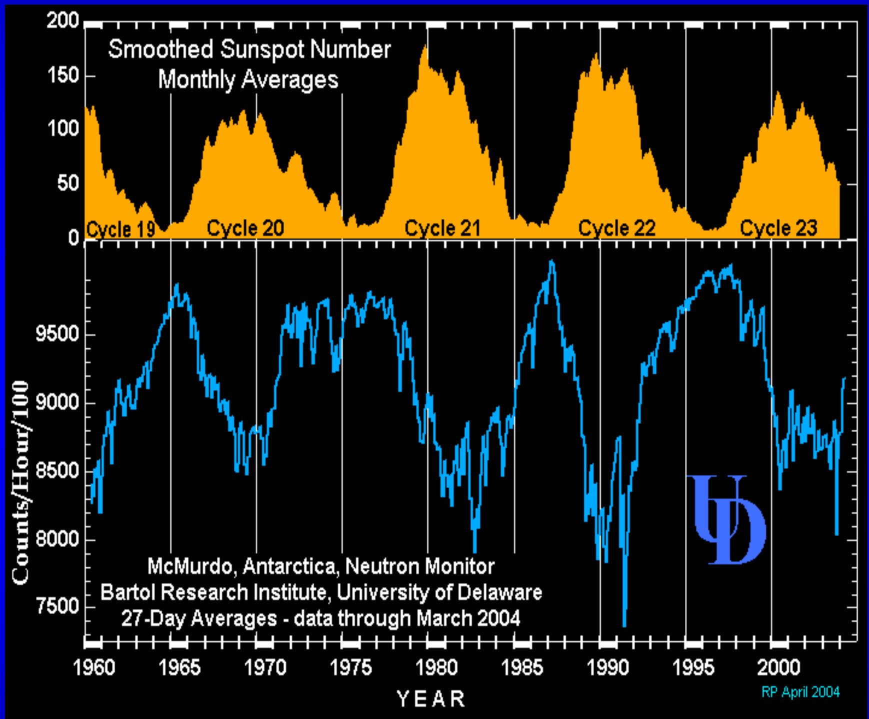
Courtesy of L. Townsend, US NCRP

GCR & The Solar Cycle

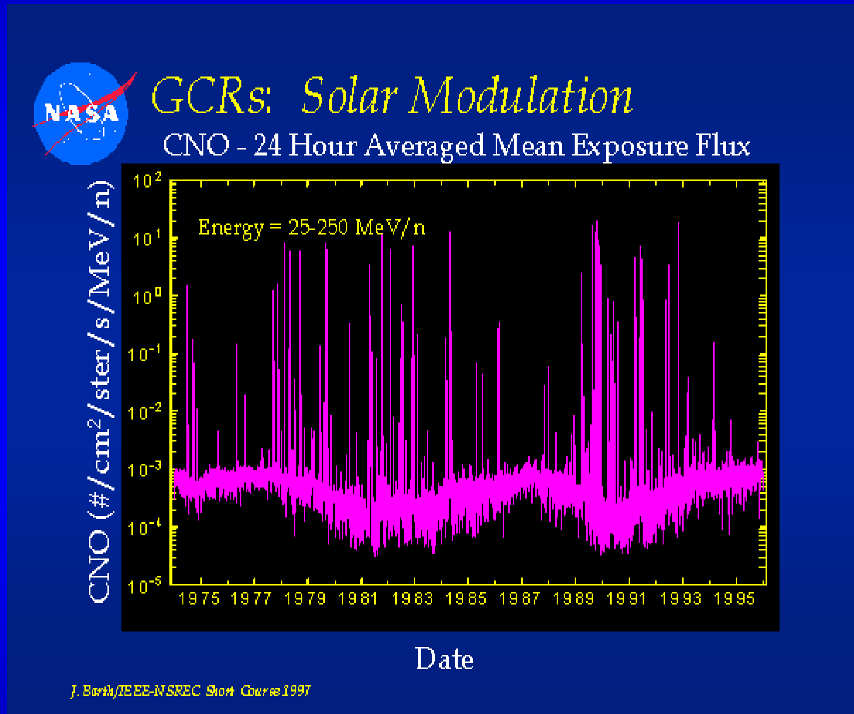




Modulation

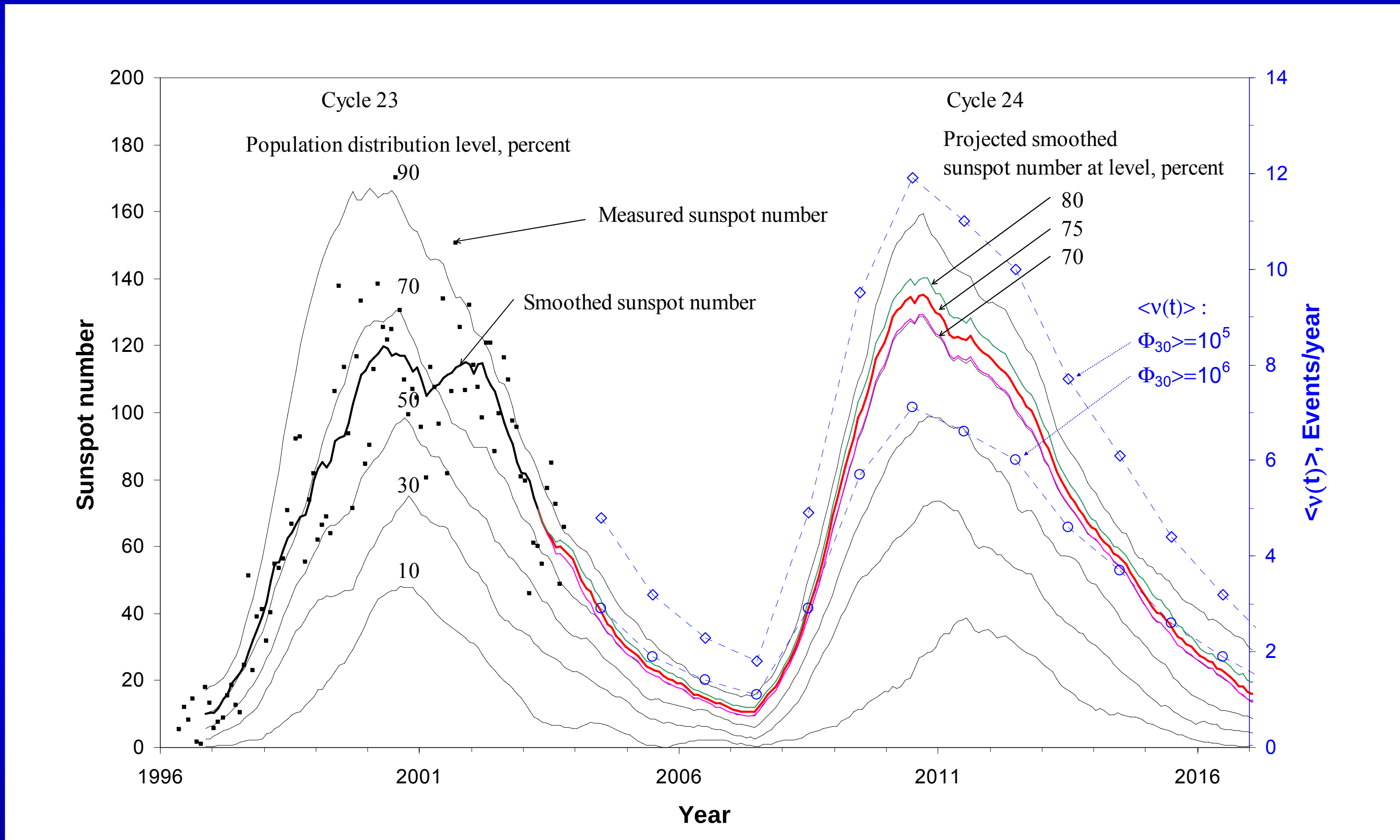


Versus Sunspot Number
[From Bartol]



CNO—24 Hour Averages
[NASA—J. Barth]

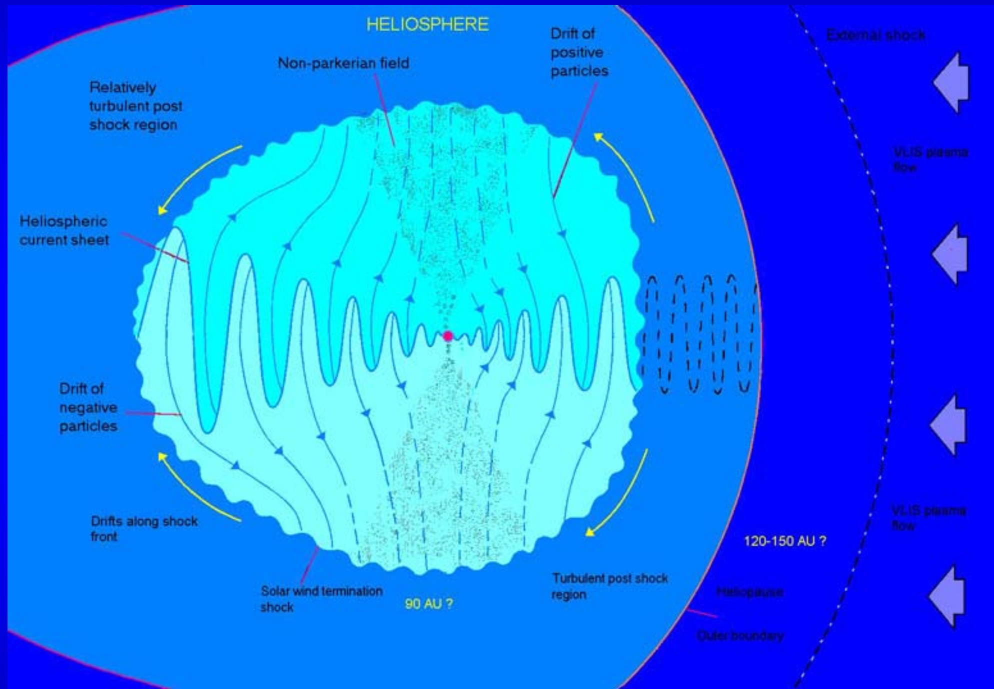
Predicting Solar Activity Based on Past Observations



Courtesy of Kim, Cucinotta & Wilson

Solar Modulation—Prior Work

- Parker (1965)
- Badhwar-O'Neill (1990)
- Fisk (1996)
- Kota & Jokipii (1999-2000)
- "CalTech" (2001)
- No *ab initio* model exists…



Solar Modulation

- The combined influence of the magnetic fields and the Solar Wind environment within the Solar *Heliosphere* causes the Local Interstellar Spectrum (LIS) of Galactic Cosmic Rays (GCR) to be changed when viewed at some point well within the *Heliosphere*.
- We do NOT know the LIS *a priori*, although CR source and galactic propagation models have been used to predict it…
- The effects are separately rigidity, charge and mass dependent, so the influence is species dependent…

Cosmic Ray Transport Equation

$$\underbrace{\nabla \bullet VU}_{convection} - \underbrace{\tfrac{1}{3}\nabla \bullet V \frac{\partial}{\partial T}(\alpha T U)}_{Adibatic \quad cooling} + \underbrace{V_D \bullet \nabla U}_{Drifts} = \underbrace{\nabla \bullet \kappa \bullet \nabla U}_{Diffusion}$$

- (Diffusion) Particles diffuse through irregularities and turbulence in solar wind and imbedded magnetic fields.
- This is essentially a 1-D Approximation (Even if the 1-D is Radial…)

Transport Equation (cont.)

- (Convection) Irregularities are convected outward at solar wind speed. Generally causes an energy loss as an inverse function of r (Radial distance from the Sun…)
- (Adiabatic Cooling) Scattering tends to make particles isotropic in frame of solar wind, leading to adiabatic cooling in expanding solar wind.
- (Drifts) Drifts are due to gradients and curvature of magnetic field lines.

Transport in Practice

- Normally solve spherically symmetric equation
- Need inputs of the radius of heliosphere (from Voyager), solar wind speed (normally assumed constant), local interstellar spectrum of CR's (either assumed or from galactic transport models.) One generally does this backwards. (i.e. Iterate the LIS to give the best fit to the 1-AU data)

Transport in Practice (cont.)

- Ideally, elements of diffusion tensor and drift velocities would be derived from detailed knowledge of interplanetary magnetic field. In practice, simple forms for terms assumed, overall normalization of coefficients derived by fitting observed cosmic ray spectra.
- In the end, the best one can say is that the form is suggested by physics, but NOT the details…

To "Predict" GCR Spectra…

- Heavily Approximate the Description:

$$\mu(r,R) = \mu_0(R)\exp\left\{-\int_r \left[V(r')/D(r',R)\right]dr'\right\}$$

$$\mu(r,R) = \mu_0(R)\exp\left\{-V_0\left(r_0^{1-s} - r^{1-s}\right)/\left[(1-s)D_0(R)\right]\right\}$$

Where μ is ion density

V_0 is solar wind speed (assumed constant at 400 km/s)

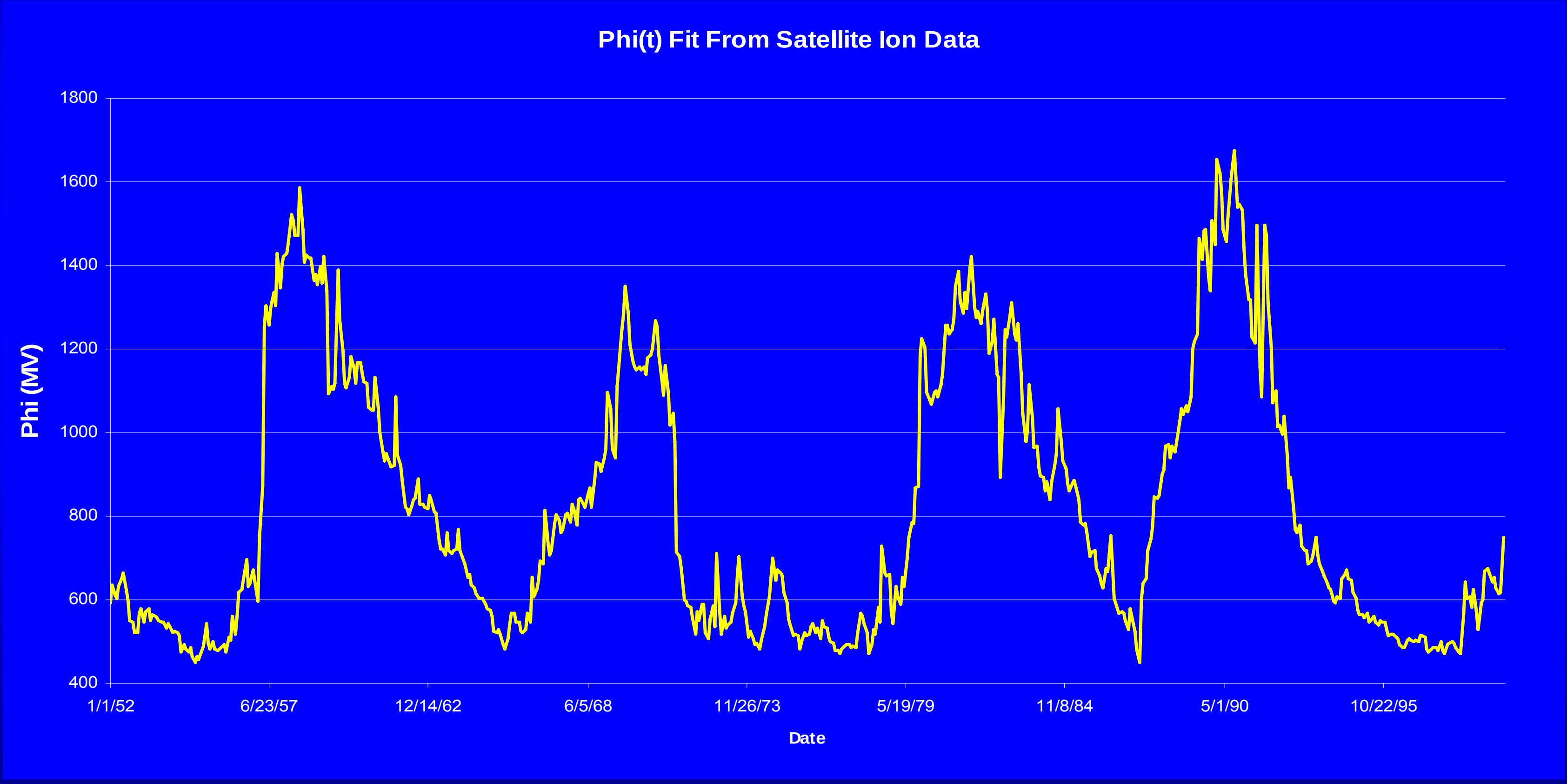
$D_0(R)$ is a constant diffusion coefficient at 1 AU assumed a function of rigidity which varies as $D_0(R)r^s$

s is a fitting parameter varying from ~ 0 to 2

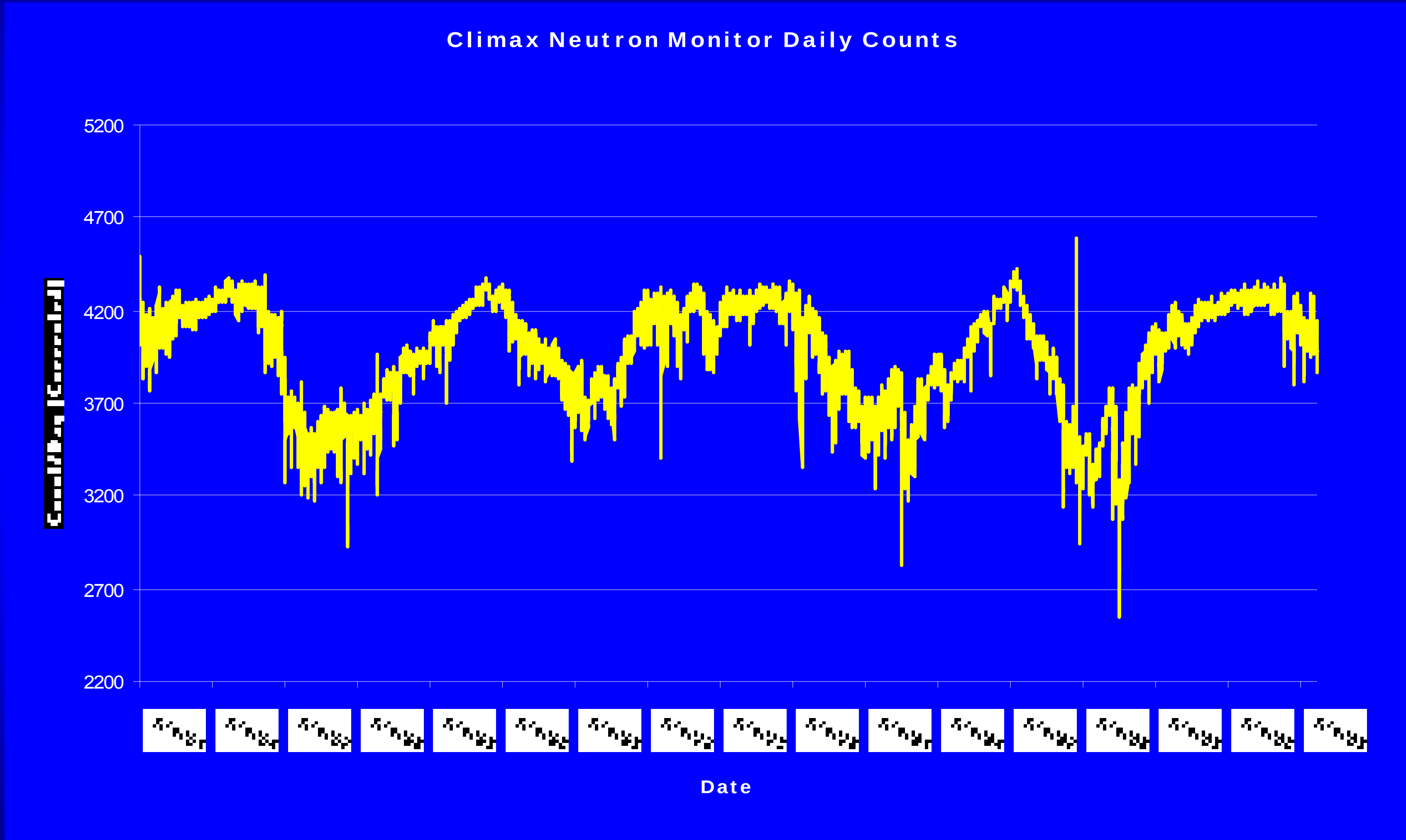
r_0 is the size of the modulation cavity (50-100 AU)

Prediction Continued…

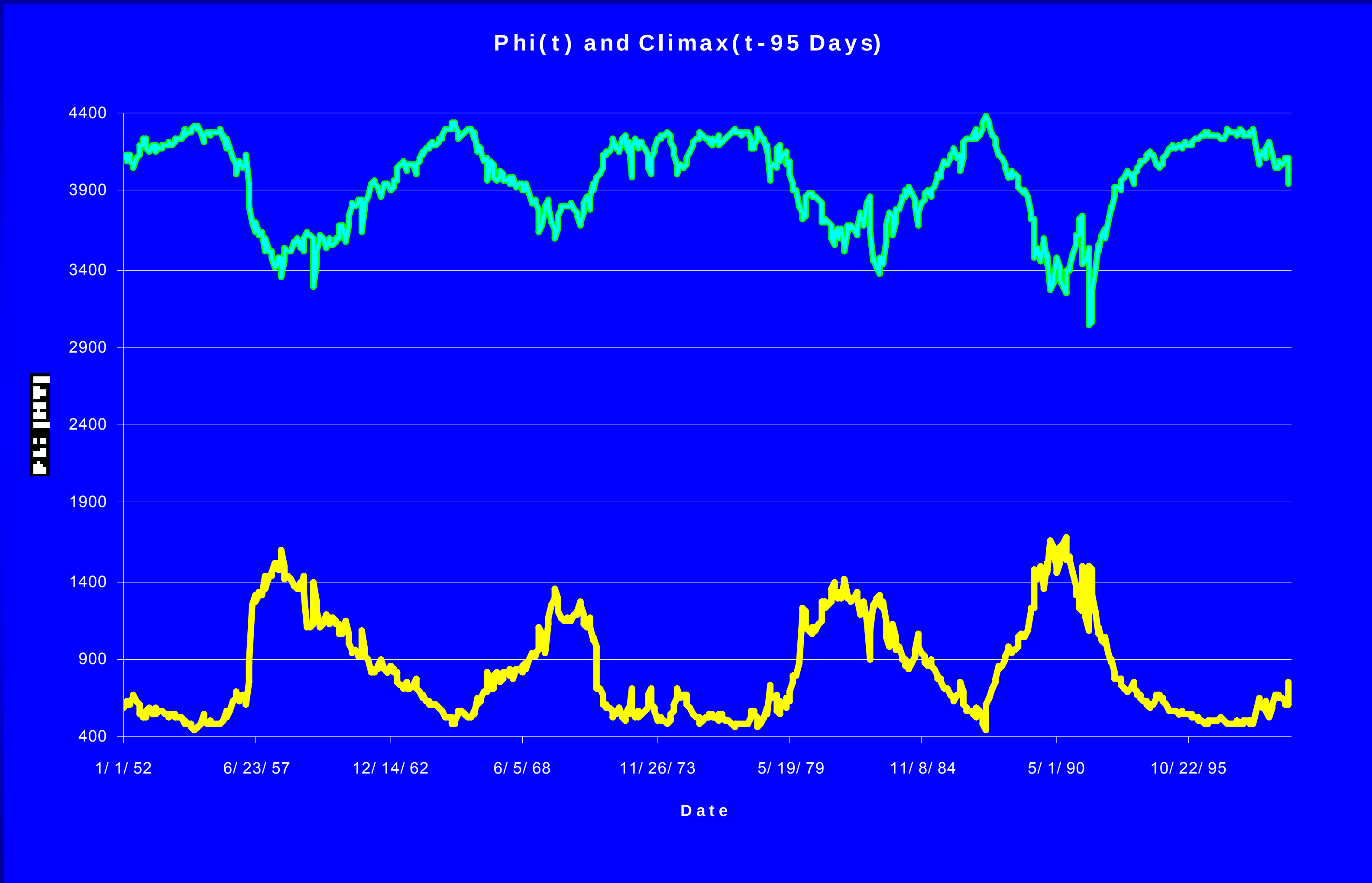
– Φ (integrand first expression) from χ^2 fitting species fluence satellite data



Neutron Monitor Data



Together


Phi(t) and Climax(t-95 Days)
4400
3900
3400
2900
2400
1900
1400
900
400
1/1/52
6/23/57
12/14/62
6/5/68
11/26/73
5/19/79
11/8/84
5/1/90
10/22/95
Date

Fitting

- Scatter Plot Phi(t) vs. Climax(t-t')
  - Three Populations
  - Correspond to Helio-Magnetic Field Polarity

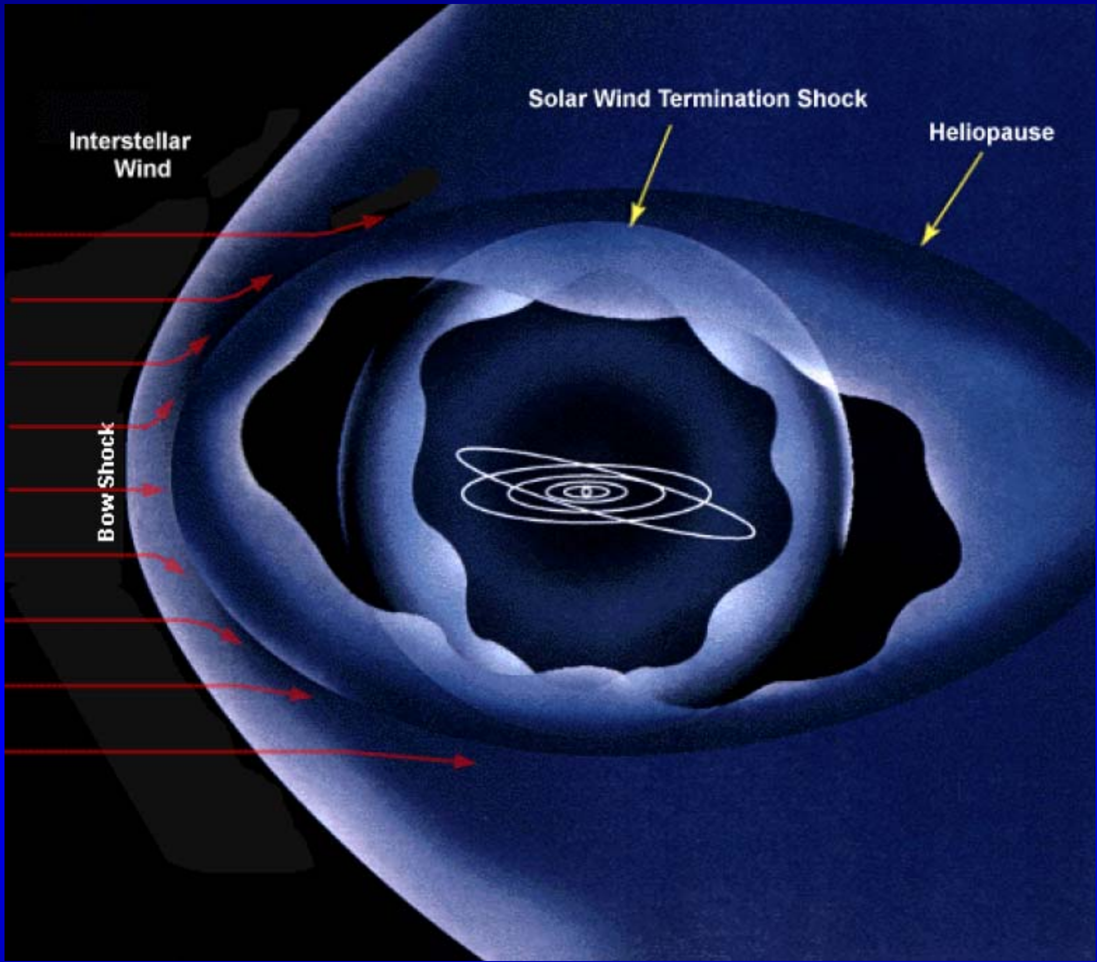
  χ^2 minimized by t'=95 days

$$\Phi_{POS} = -.8124 * C + 3957.89$$

$$\Phi_{NEG} = -.8563 * C + 4202.76$$

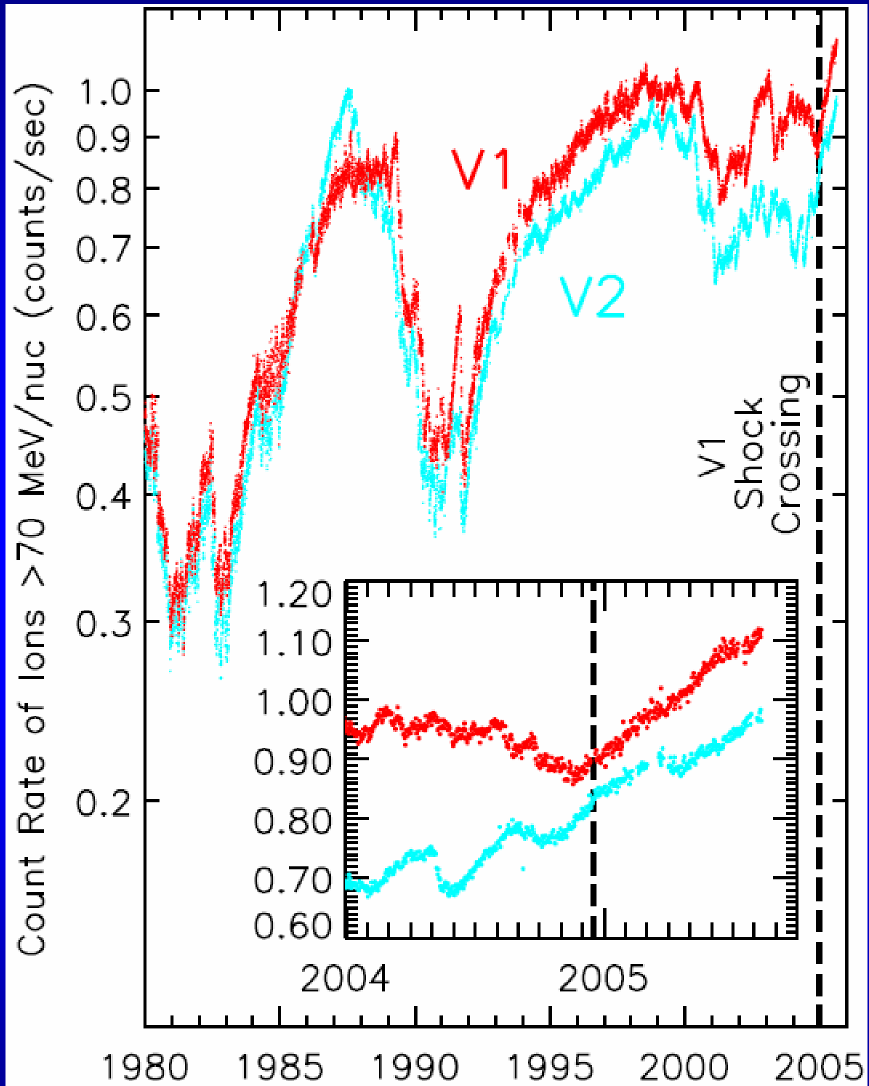
$$\Phi_{REV} = -.9528 * C + 4772.86$$

NO MECHANISM SUGGESTED



Now that the Voyagers are going beyond the solar wind's termination shock it is becoming clear that not all of the GCR modulation occurs inside this boundary as was once thought.

Usoskin

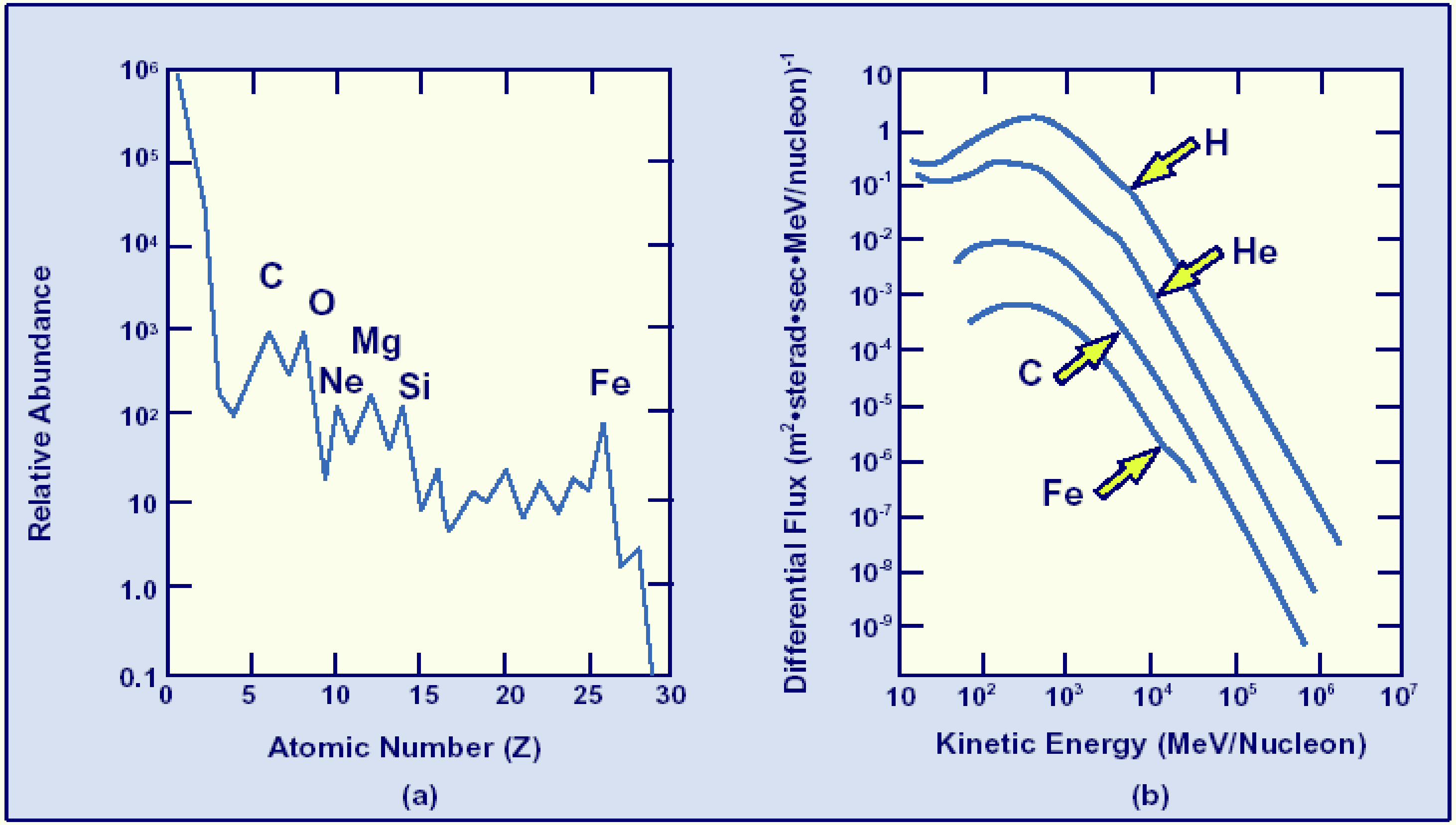


Since Voyager 1 crossed the termination shock in December 2004 it has continued to observe an increase in the GCR intensity.

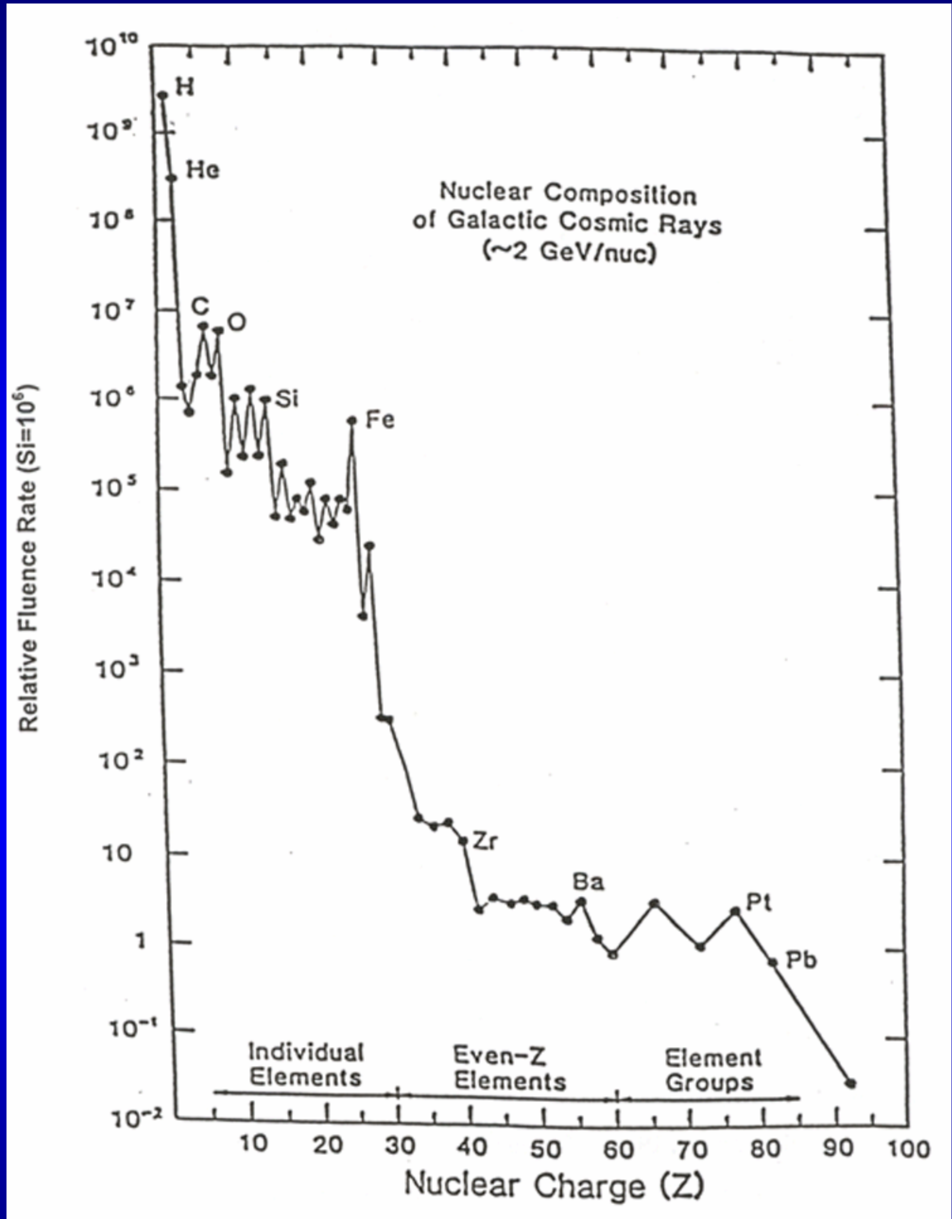
This increase is seen at Voyager 2 as well.

Apparently significant modulation is occurring in the heliosheath.

Figure D.1. Abundances (a) and Energy Spectra (b) of GCR

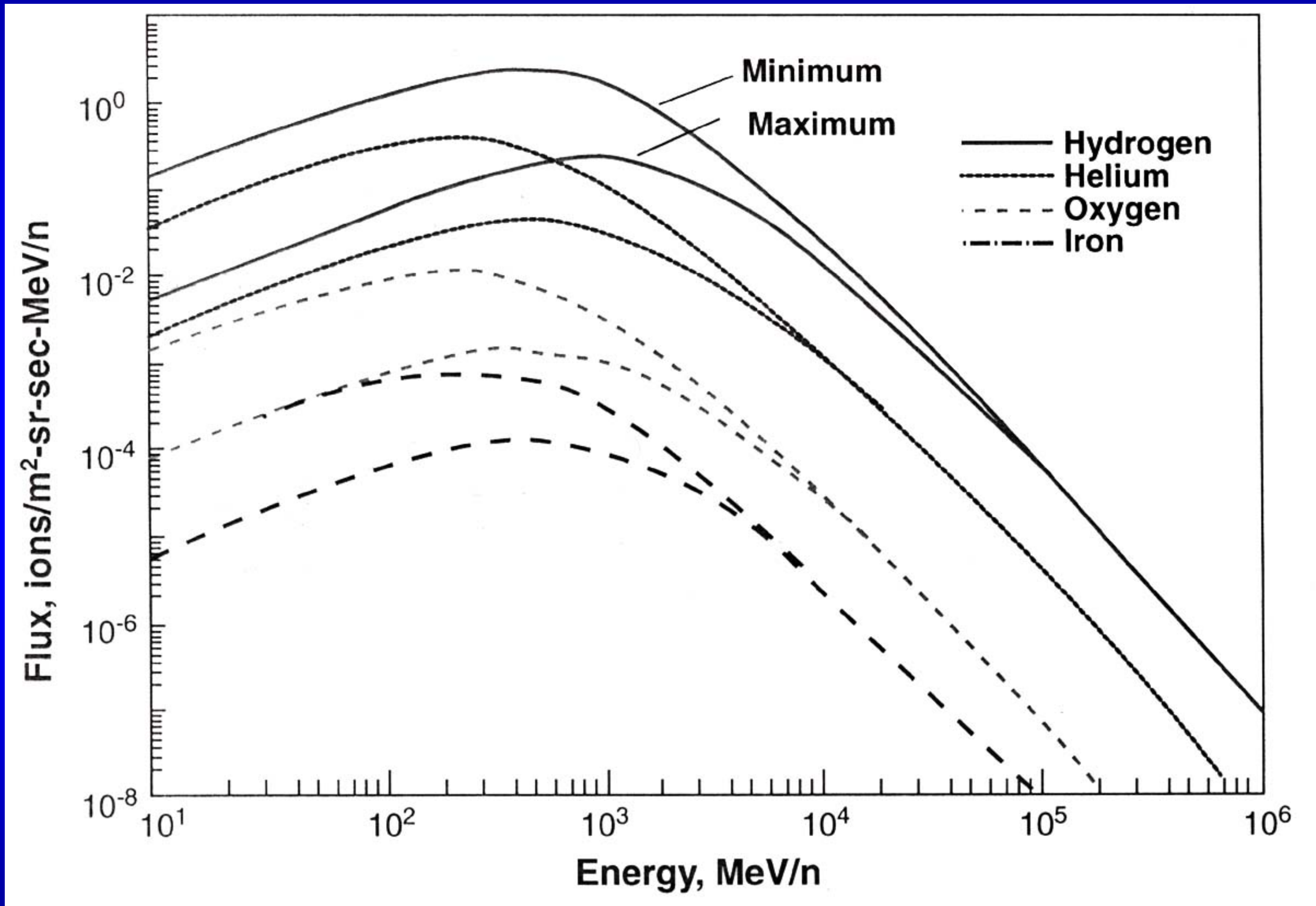


From NASA 1996
Understanding the
Strategic Program Plan
Space Radiation Environment



Nuclear Composition
of Galactic Cosmic Rays
(~2 GeV/nuc)
Relative Fluence Rate (Si=10^6)
Nuclear Charge (Z)
H
He
C
O
Si
Fe
Zr
Ba
Pt
Pb
Individual Elements
Even-Z Elements
Element Groups

Solar Modulation Effects



Local Interstellar Spectrum

- There is Ice Core data that suggests that the LIS may vary substantially in addition to the effects of Solar Modulation.
- Factors of 2 cannot be ruled out at present.
- Such changes cannot be predicted.
- We currently seem to be at a relatively low ebb with respect to the “recent” past.

The Space Radiation Environment Summary

- **Solar Particle Events**
  - Acute Dose Threat
  - Relatively “Soft” spectrum
  - Greater Problem on Lunar Surface & in Deep Space than LEO
  - Unpredictable, but most likely amenable to shielding…
- **Trapped Radiation**
  - Earth Orbit Issue Only
  - Intense but low energy-Amenable to shielding…
- **GCR**
  - Chronic Dose Threat
  - Relatively Hard Spectrum
  - Substantial Relativistic Heavy Ion Composition
  - Not Easily Amenable to Shielding…
  - Variability due to Modulation & Possible Variation in LIS…

Summary of Solar Cycle Issues

- **SPE's**
  - Much more likely at Solar Maximum
  - Rare at Solar Minimum
- **Trapped Radiation**
  - Affected by Solar activity—Greater @ Solar Max
- **GCR**
  - Modulated by Solar Wind and Field Turbulence
  - Maximum GCR Fluence at Solar Minimum in the inner Solar System & vice versa…
- **Solar Cycle Polarity**
  - Alternate Cycles are different due to different magnetic field orientations and charge asymmetry (protons are positive…), especially regarding the interaction with the Earth's magnetic field…