Cosmic-Ray Intensities during the Space Age and the Holocene

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Global Change and the Solar-Terrestrial Environment
Aspen, CO
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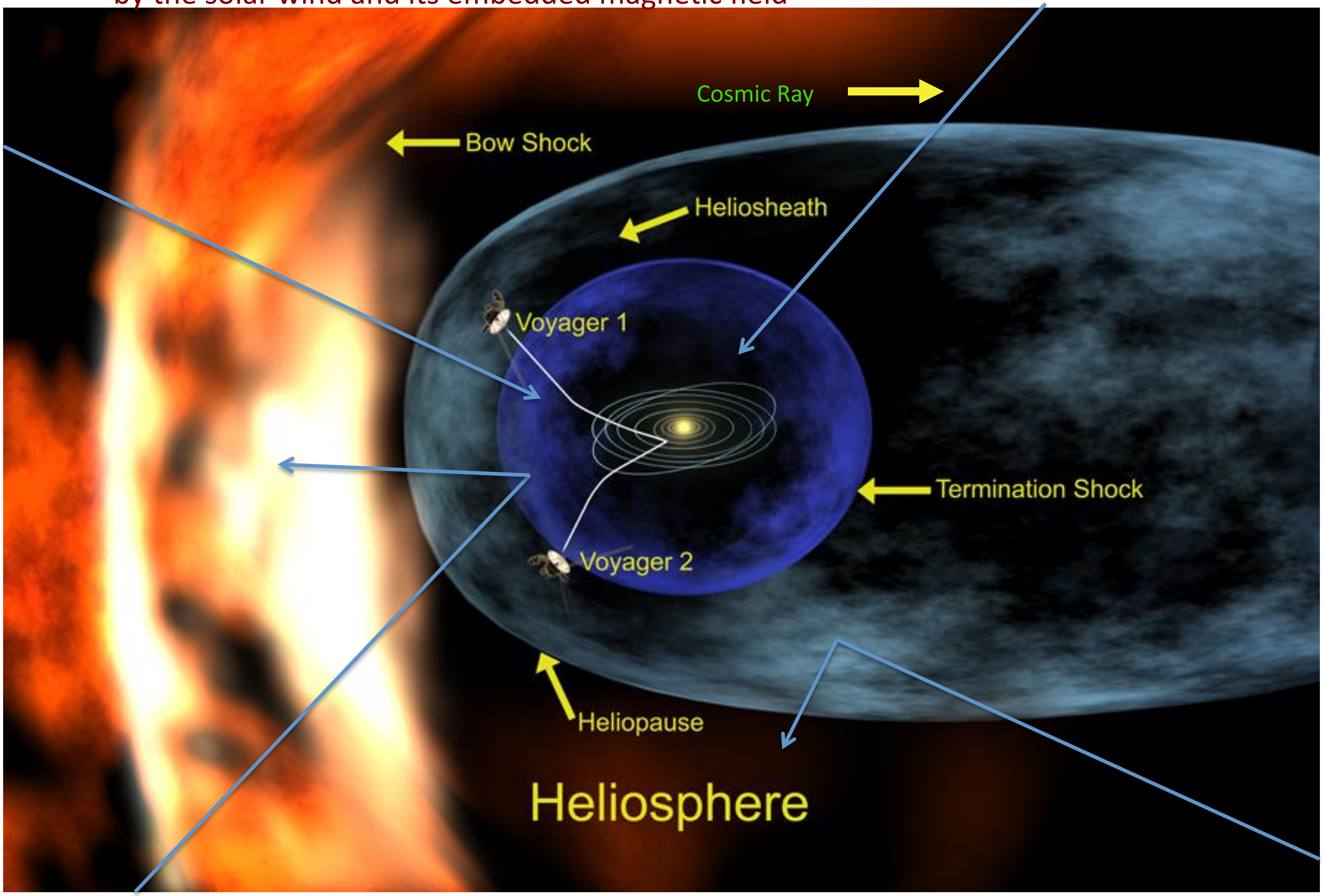
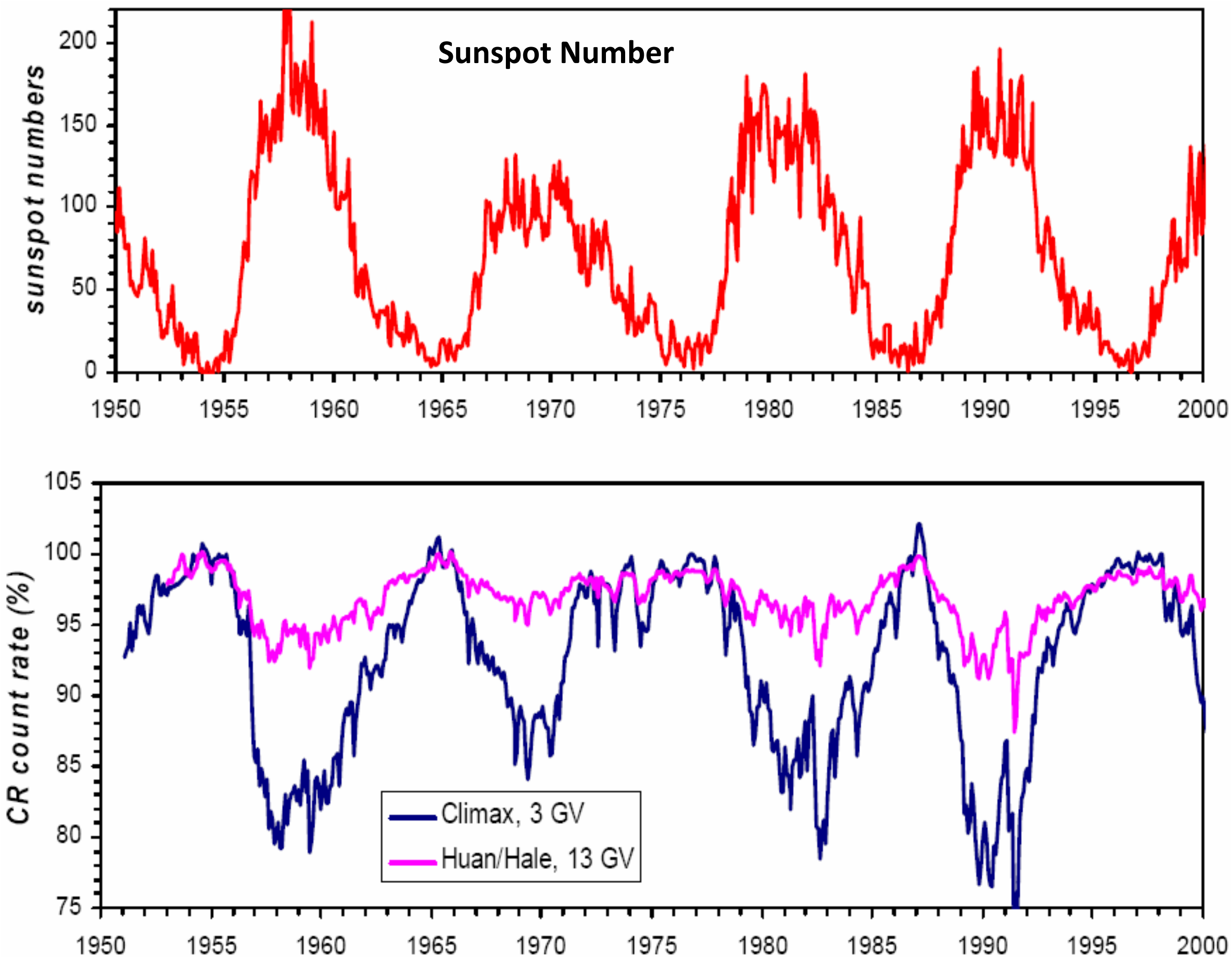
The intensity of cosmic rays that reach in the inner solar system is modulated by the solar wind and its embedded magnetic field



Cosmic-ray intensity variations are anti-correlated with solar activity

Cosmic-ray modulation is a complex process - it is usually parameterized by changes in the interplanetary diffusion coefficient (K) due to variations in the turbulence in the interplanetary magnetic field (ΔB/B) .

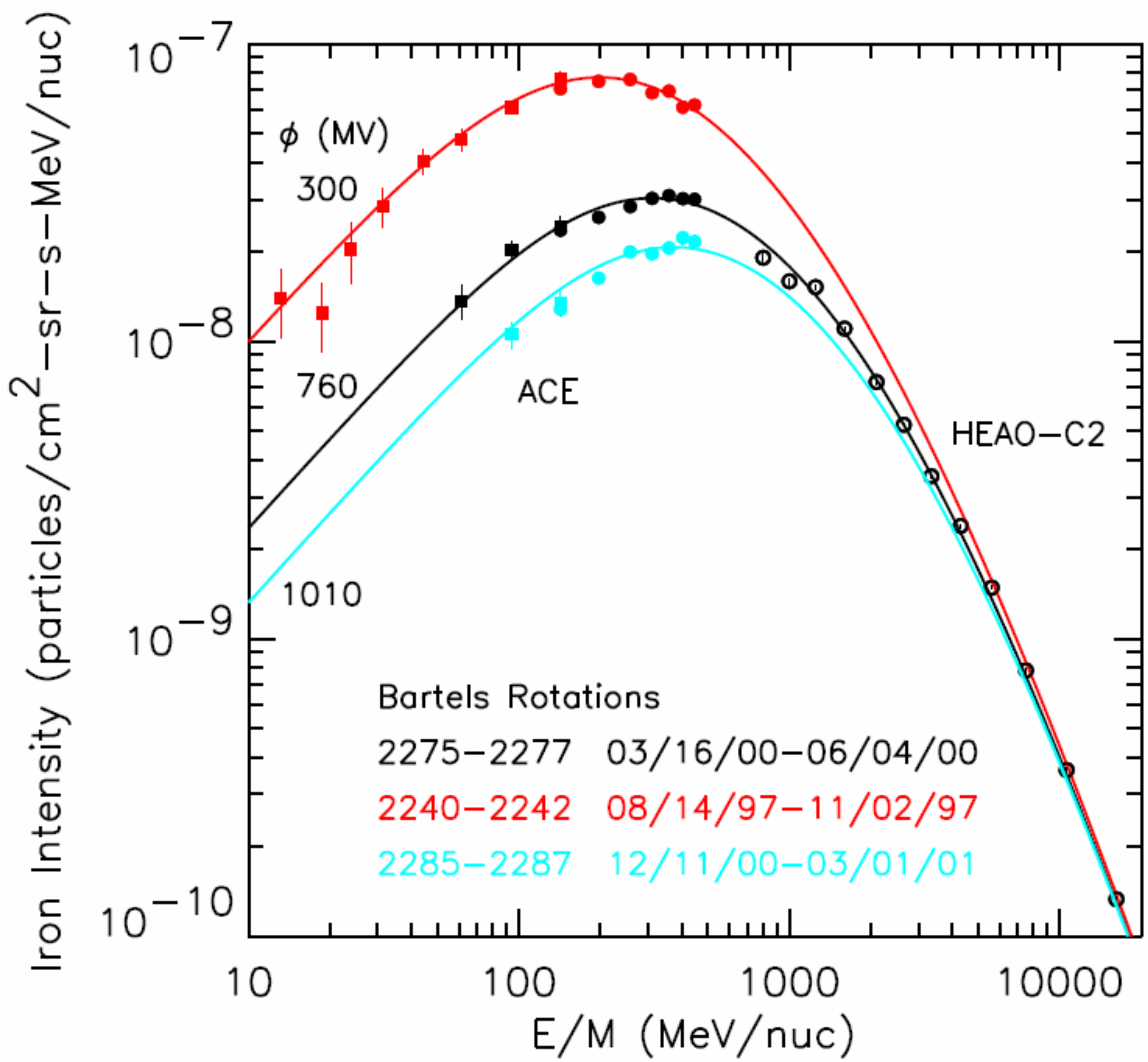


Neutron monitor count rates at 3 and 13 GV cutoff rigidities

Note the 22-year periodicity

Usoskin

Cosmic-ray spectral variations over the solar cycle



Spectral shape changes are reasonably-well accounted for by the "modulation parameter" (ϕ):

$$\phi \propto \int_{1\ \mathrm{AU}}^{\mathrm{boundary}} \frac{V_{SW}}{\kappa}\, dr$$

Here Vsw is the solar wind speed, and K is the diffusion coefficient, which depends on the magnetic field strength and turbulence level.

from Wiedenbeck (2007)

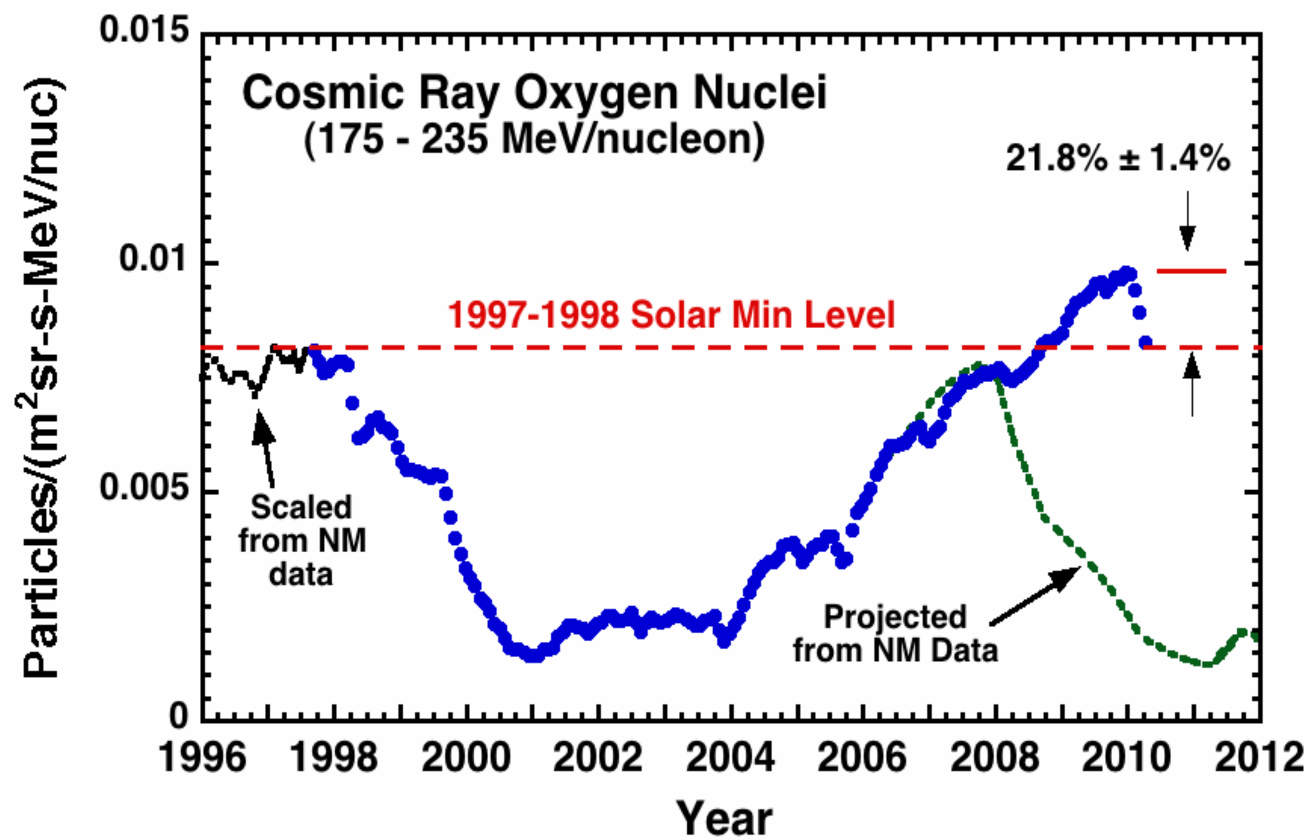
Outline

Introduction
Cosmic ray access to the heliosphere
Evidence for record-breaking intensities in 2009-2010
Energy spectra
Cosmic Rays in the Atmosphere
What enabled the 2009 intensity increase?
Cosmic rays over the past 80, 600, and 9300 years
Deriving the solar magnetic field and TSI
Voyager in the ISM
Summary

Sources of Data

Cosmic rays: ACE, HEAO, IMP-8, Voyager,
Lebedev Balloon Flights, BESS, PAMELA, Newark and Climax neutron monitors, ^{10}Be and ^{14}C data from Beer et al.
Solar Wind: ACE, Ulysses
CMEs: SOHO, STEREO

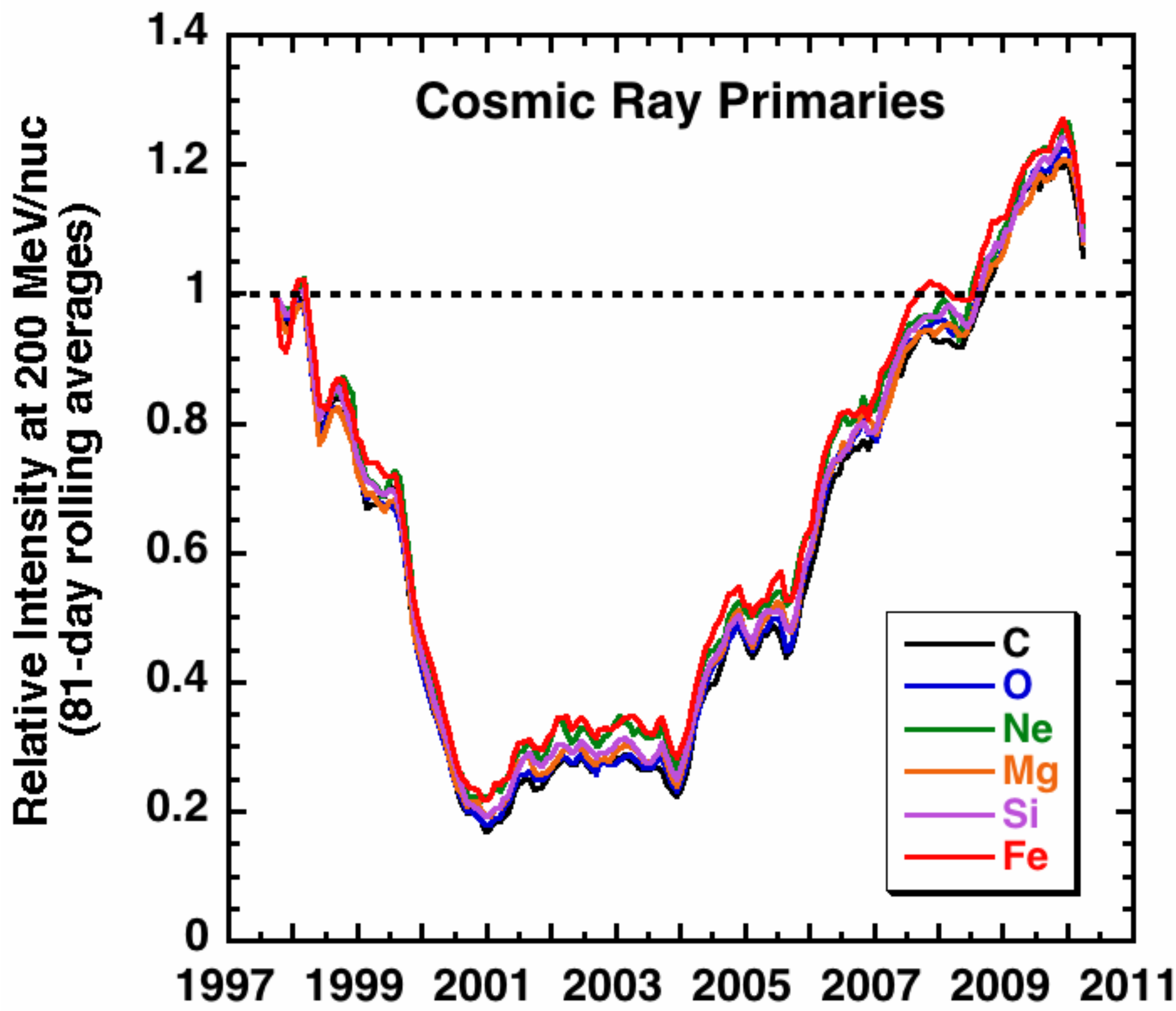
Cosmic Ray Oxygen Intensities during Solar Cycle 23



- **Based on solar cycles 19-22 the GCR intensity was expected to decline in 2008.**
- **At the time GCR intensities were approaching those in 1997-98 and in 1976.**
- **Instead, solar minimum persisted, and GCRs began to increase in early 2008, reaching record levels in 2009**
- **In early 2010 the intensities suddenly returned to 1997 levels**

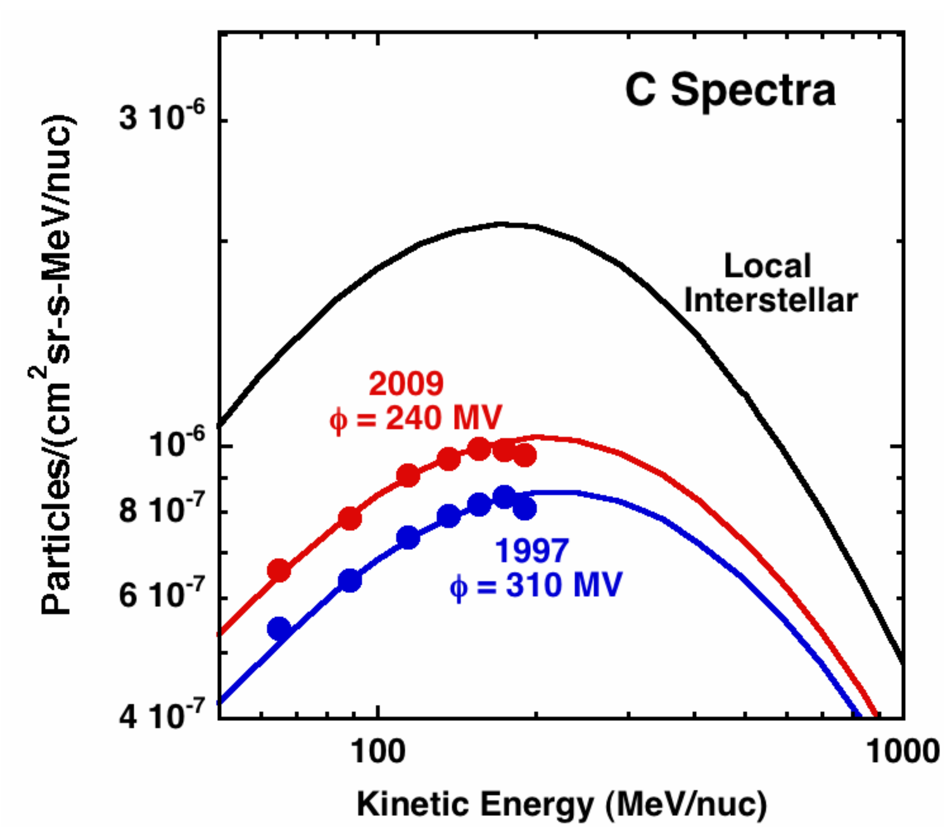
Mewaldt et al. 2010

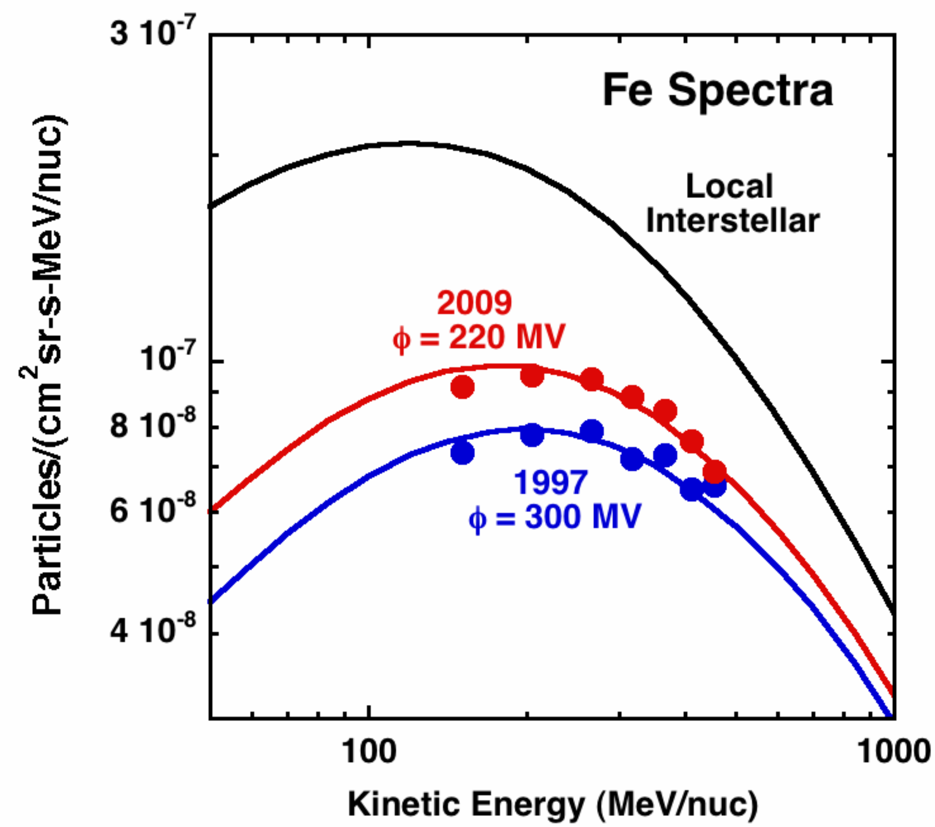
All Abundant Species Have Similar Excesses in 2009-2010



Mewaldt et al. 2010

Cosmic Ray Energy Spectra

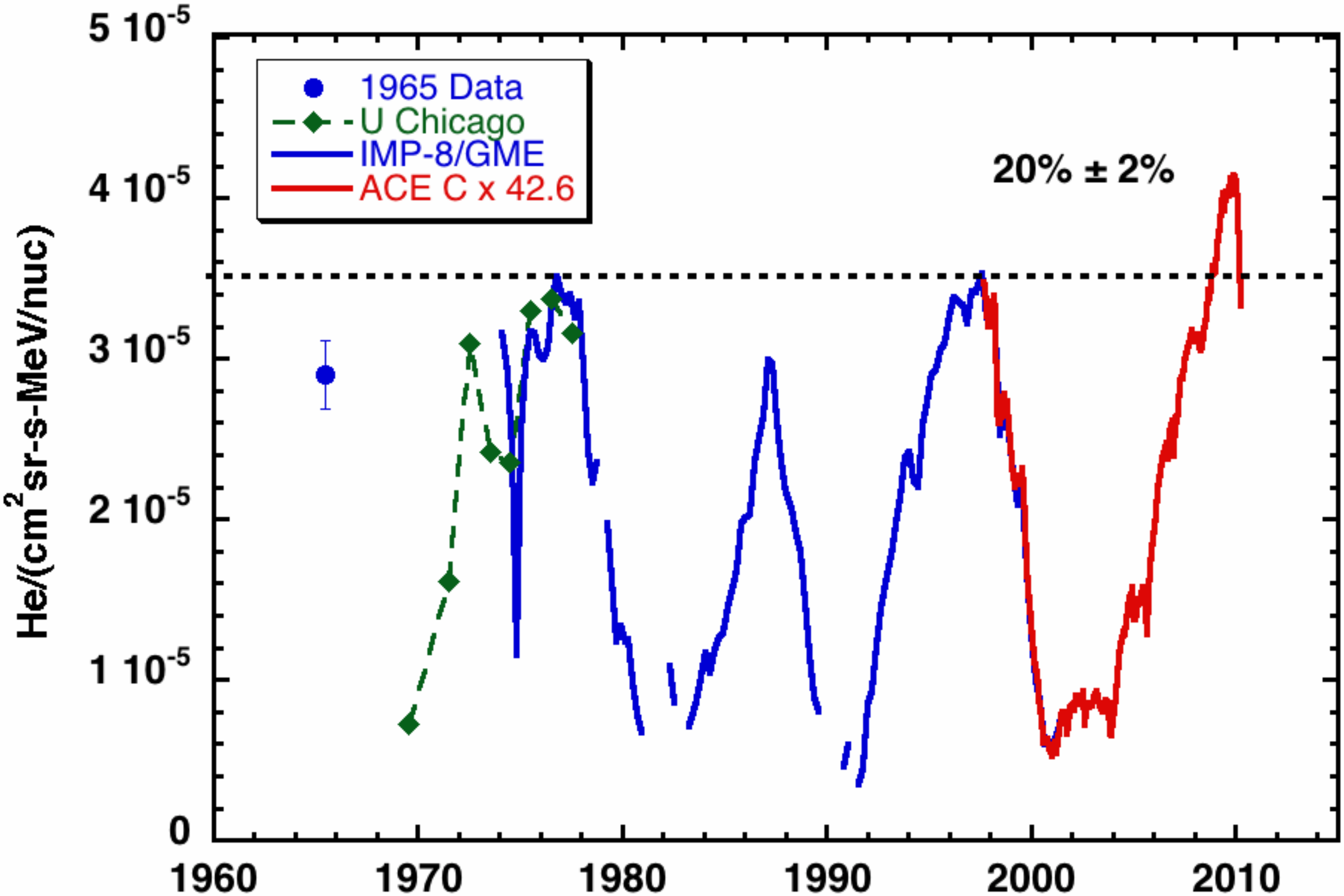




The "modulation parameter": $$\phi \propto \int_{1\ \mathrm{AU}}^{\mathrm{boundary}} \frac{V_{SW}}{\kappa}\, dr$$

ACE/CRIS Data

Comparing 100-200 MeV/n He over 5 Solar Minima

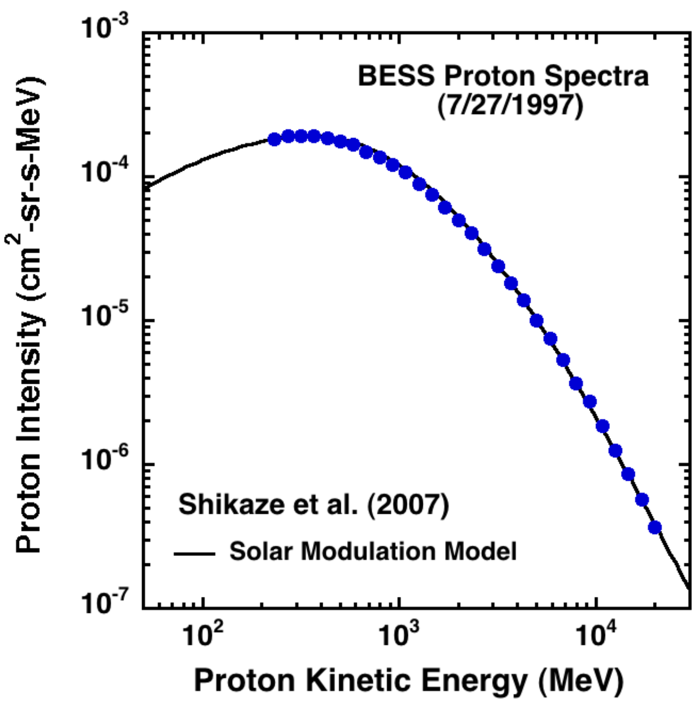


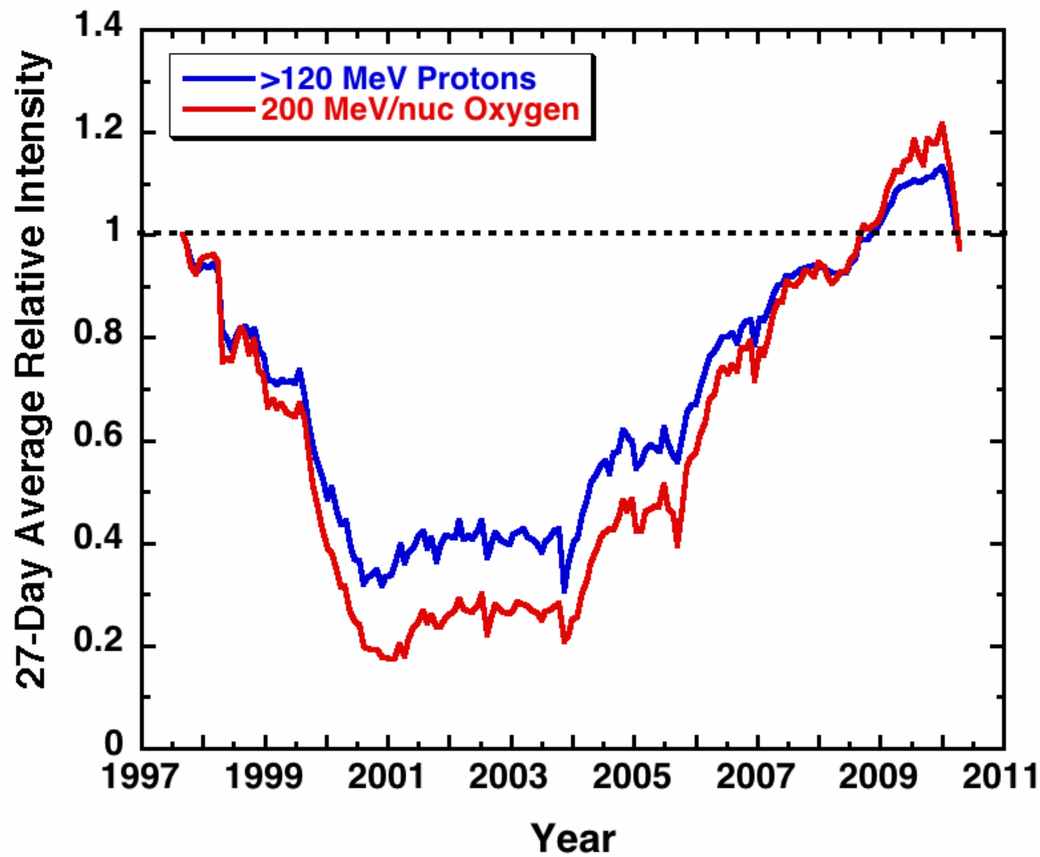
Mewaldt et al. 2010

What About Protons?

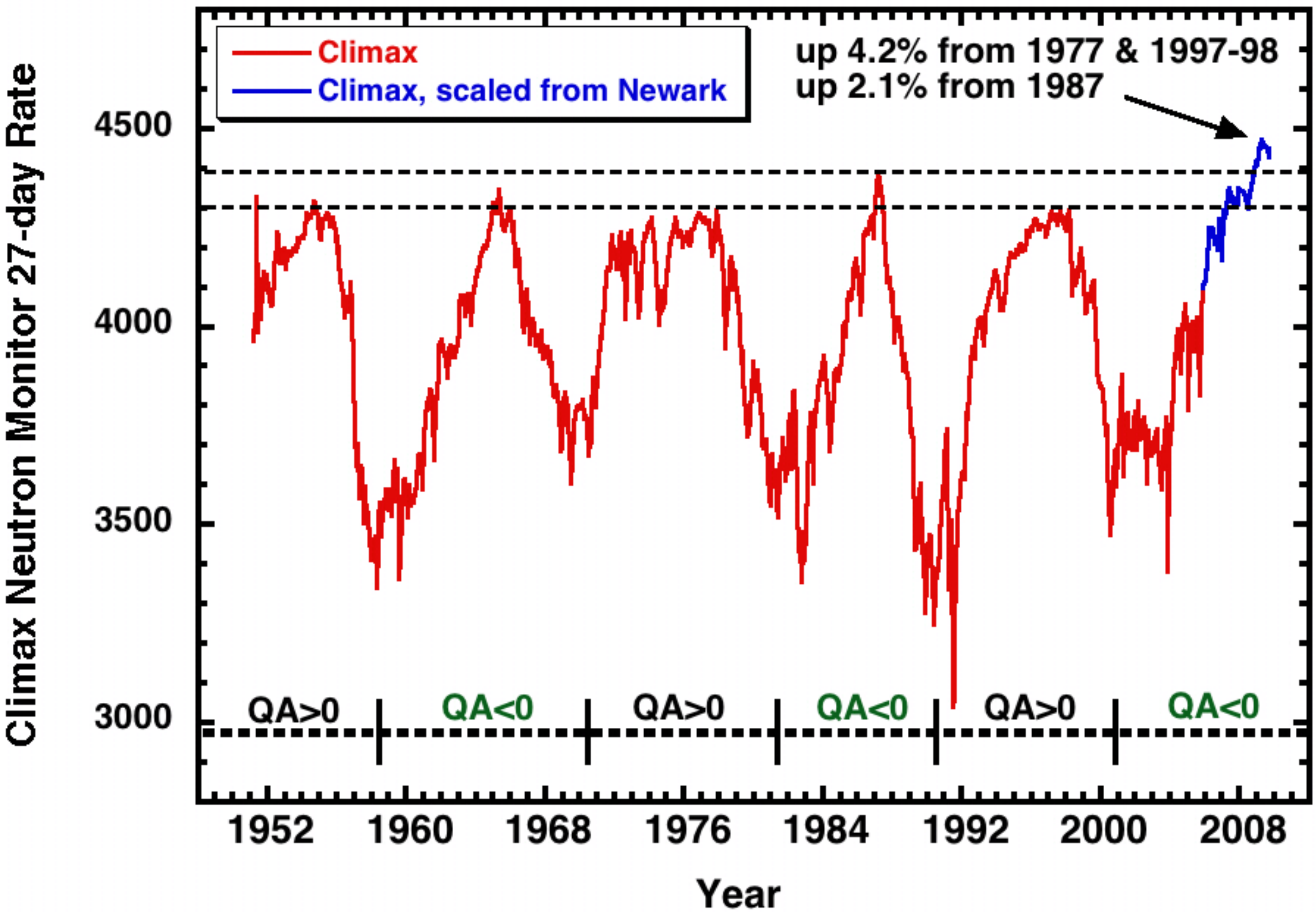
ACE has a count rate that responds to >120 MeV protons

We find a >120 MeV excess of 13.7 ± 2.0% in late 2009
The radiation dose increased by a similar amount

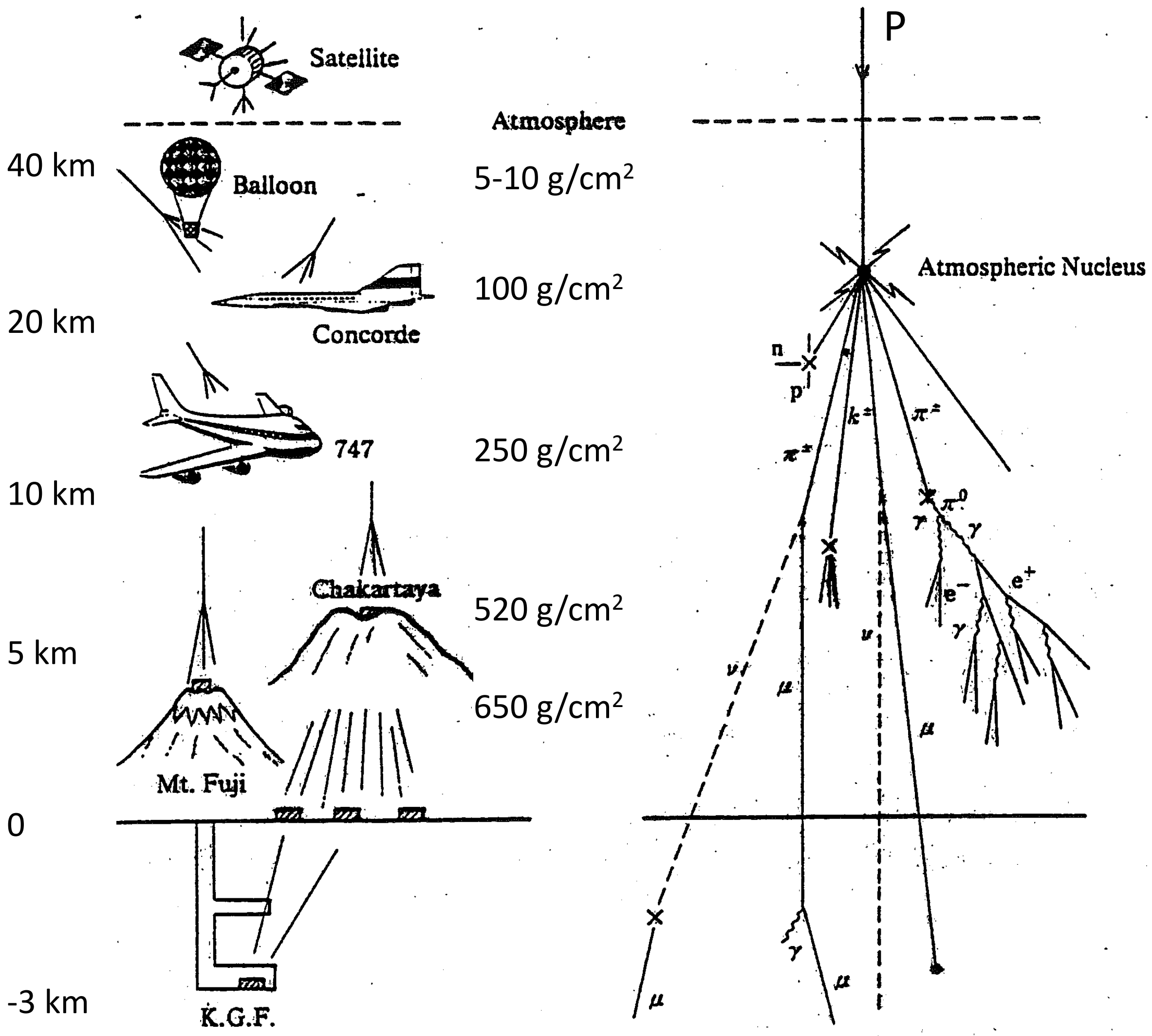


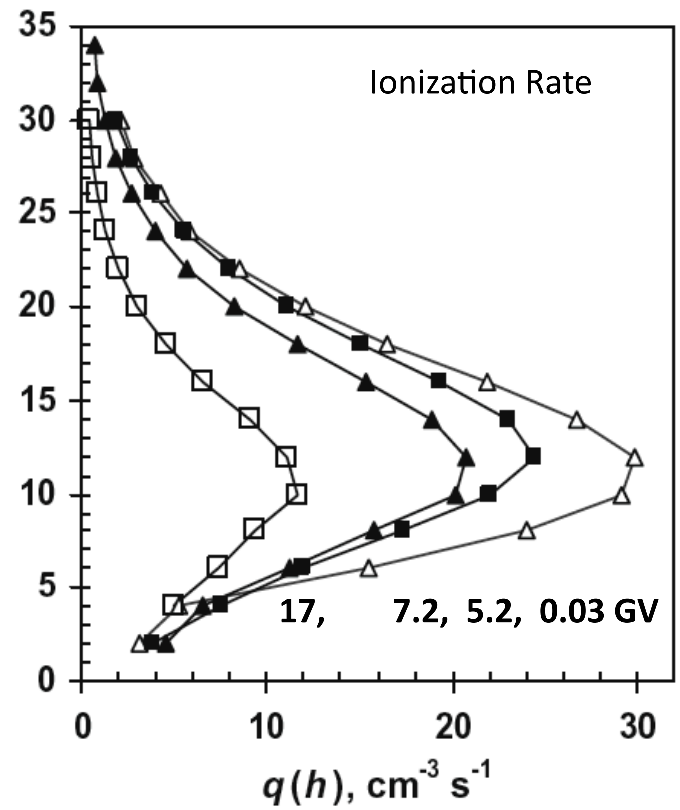


Scaling from the Newark neutron monitor, Climax would be at record levels in 2009!



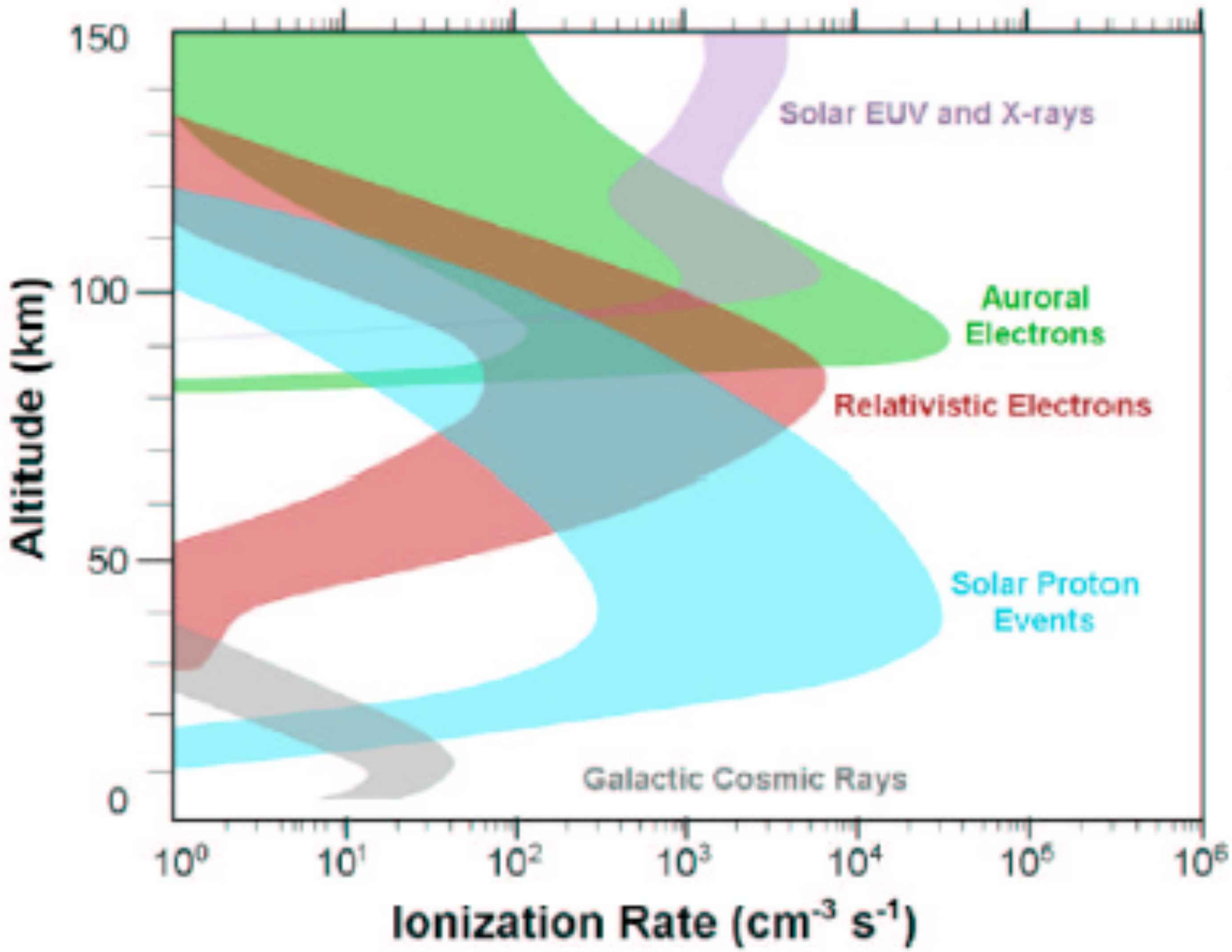
Cosmic Rays in Space and the Atmosphere





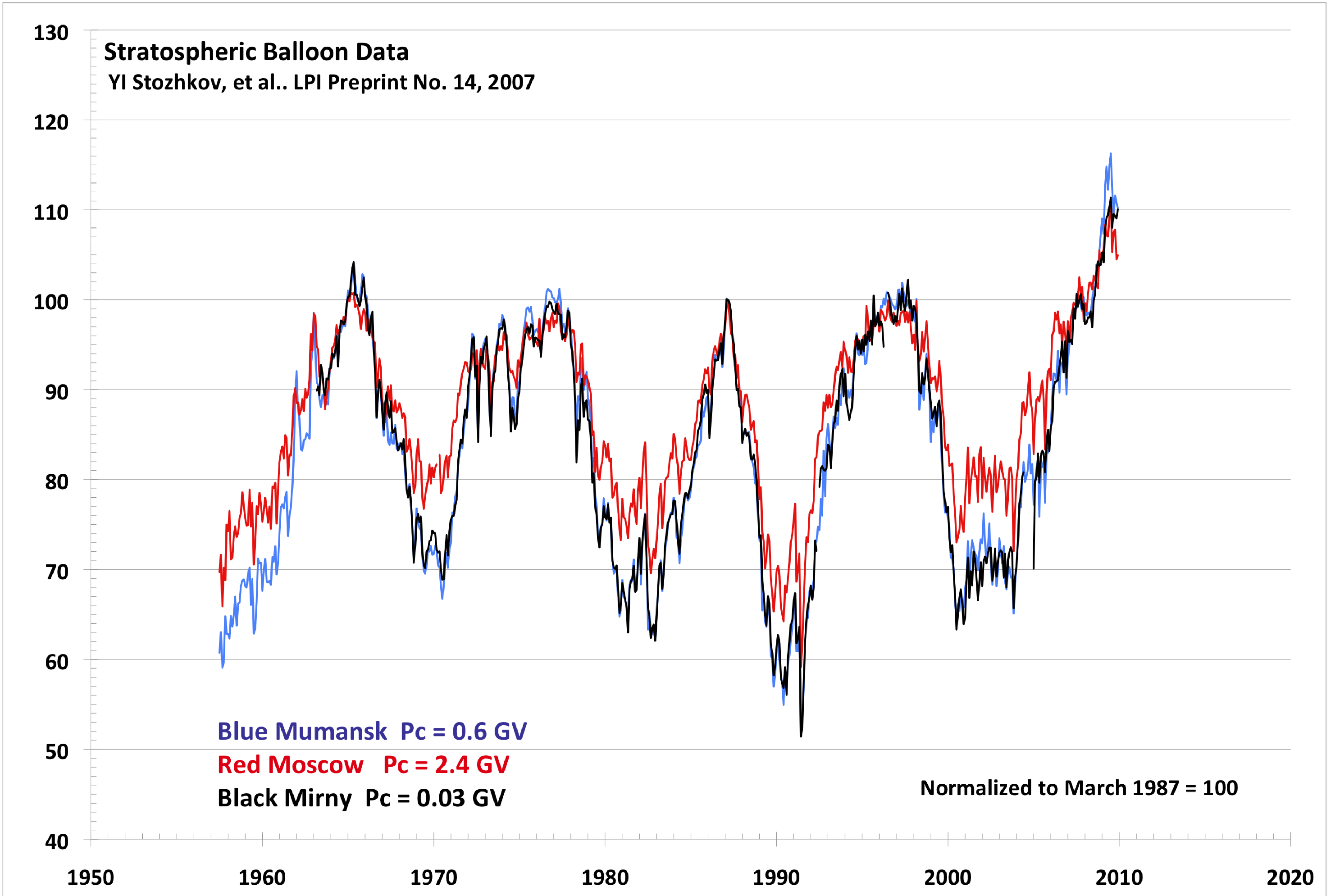
Stozhkov et al. 2007

Atmospheric Particle Coupling



After Lean (1994)

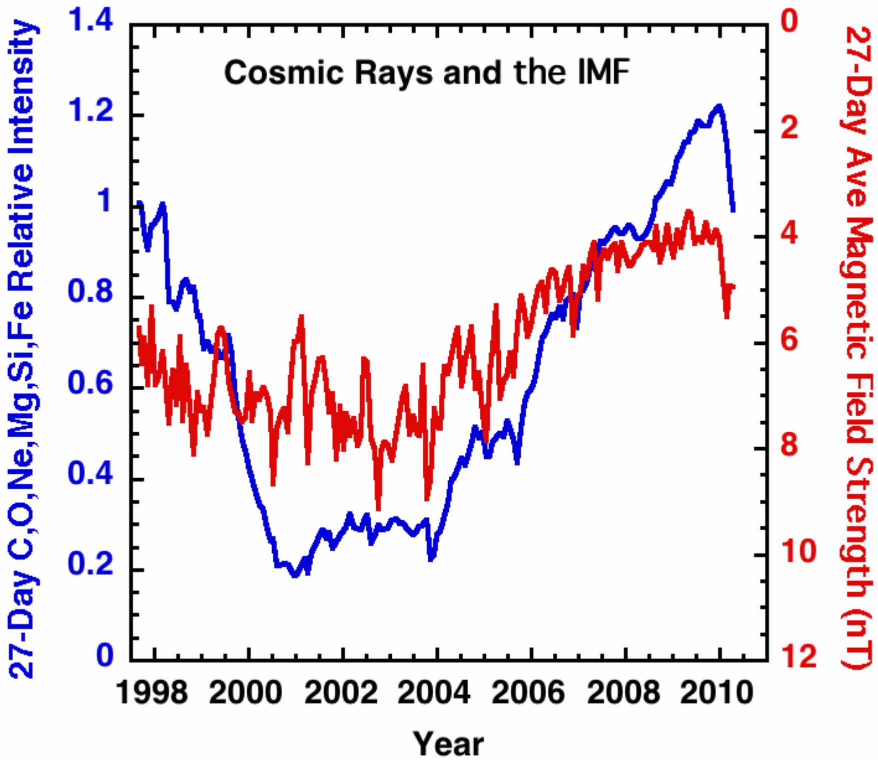
50 Years of Cosmic-ray Intensities in the Stratosphere

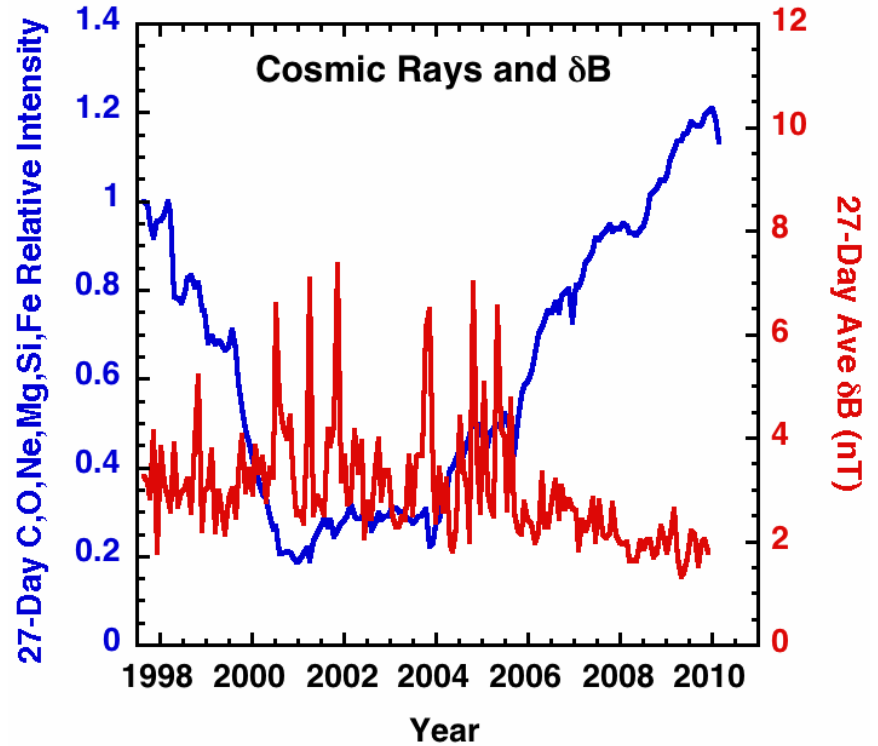


Solar/Interplanetary parameters affecting cosmic ray intensity:

1) The interplanetary magnetic field is at its lowest level of the space age (Smith & Balough 2008). Solar wind turbulence has also decreased

- The magnetic field strength determines the gyroradius of cosmic rays and the turbulence level affects their scattering rate
- Burlaga & Ness (1998) and Cane et al. (2003) have shown that cosmic-ray intensity is anti-correlated with the IMF strength

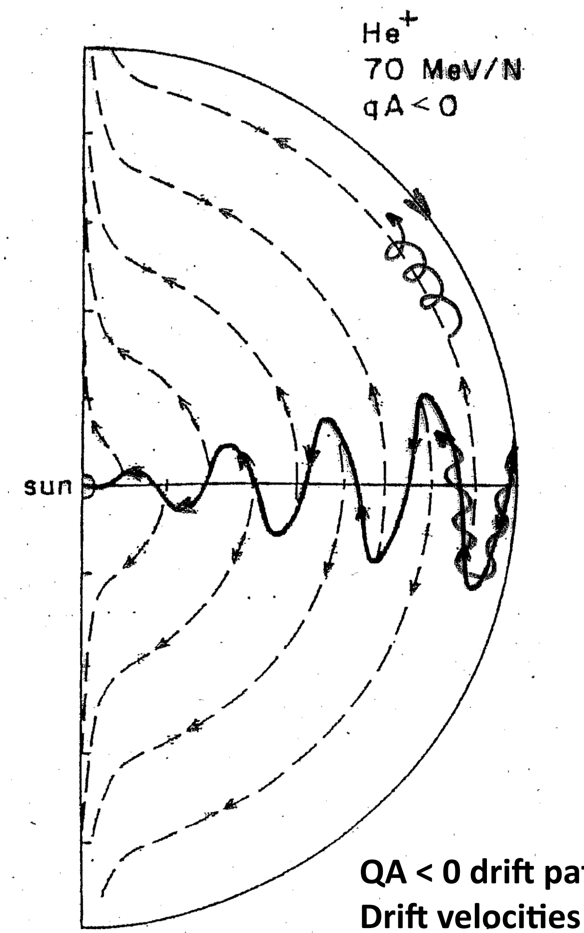




ACE/MAG & CRIS data

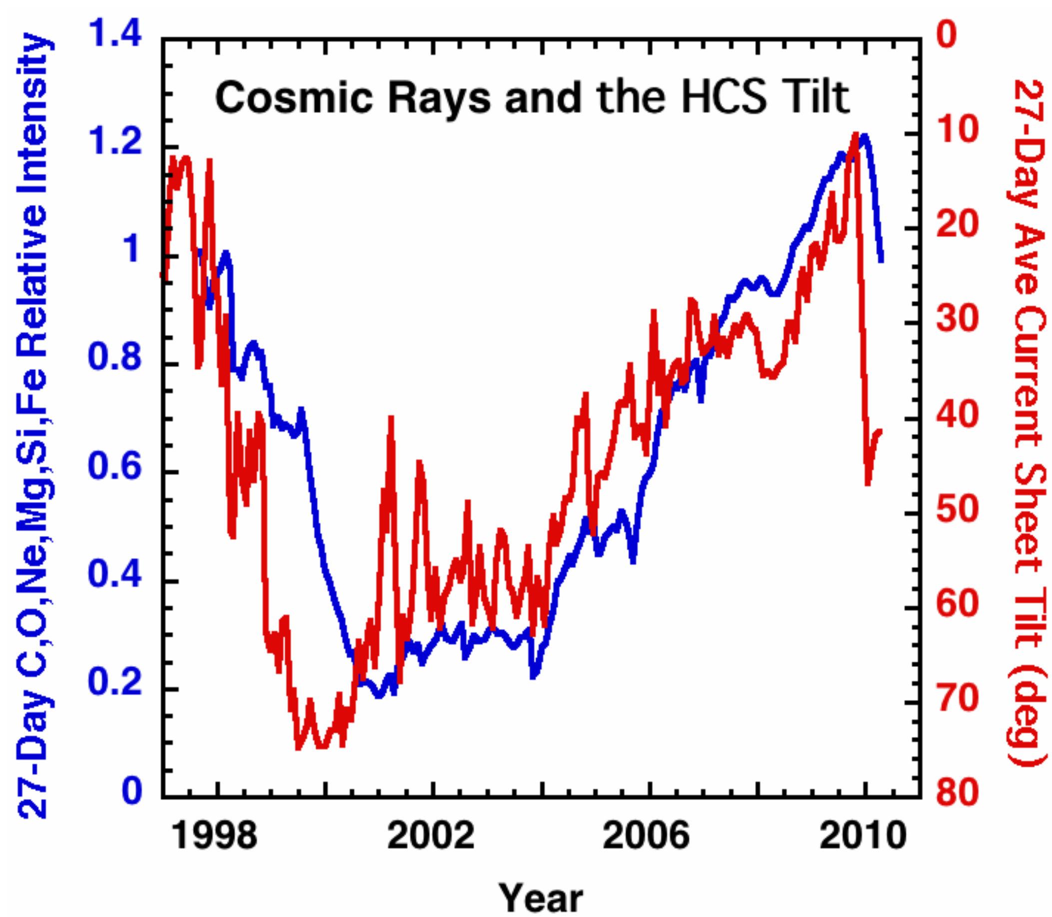
2) The Tilt-Angle of the Heliospheric Current Sheet

- The GCR increase in 2008 was triggered in part by a decrease in the tilt of the heliospheric current sheet (HCS)
- There is a good inverse correlation of intensity and tilt-angle



QA < 0 drift patterns.
Drift velocities ≥ Vsw

Jokipii and Thomas, 1981



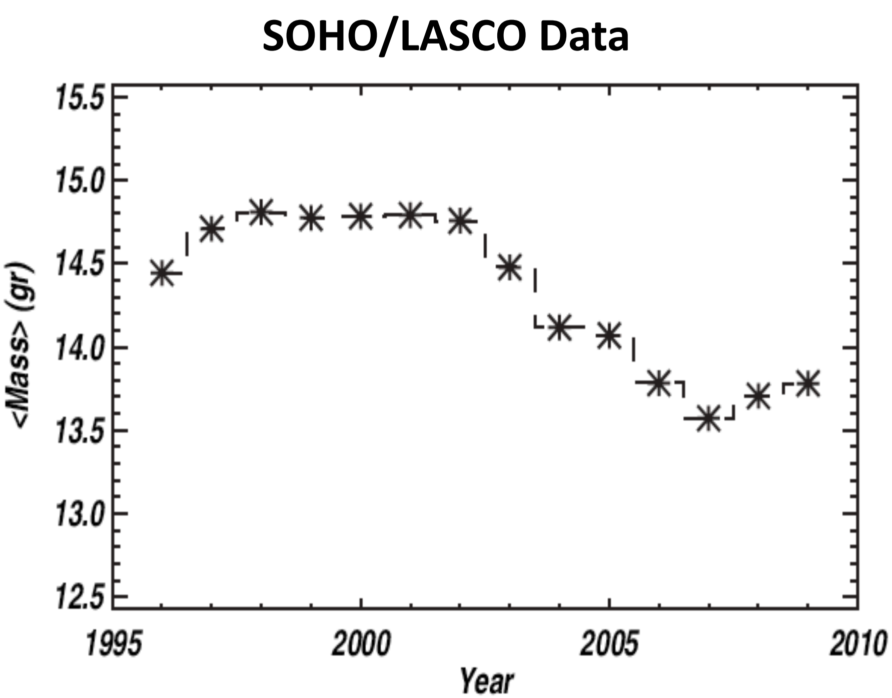
HCS tilt data from Wilcox Solar Observatory

Mewaldt et al. 2010

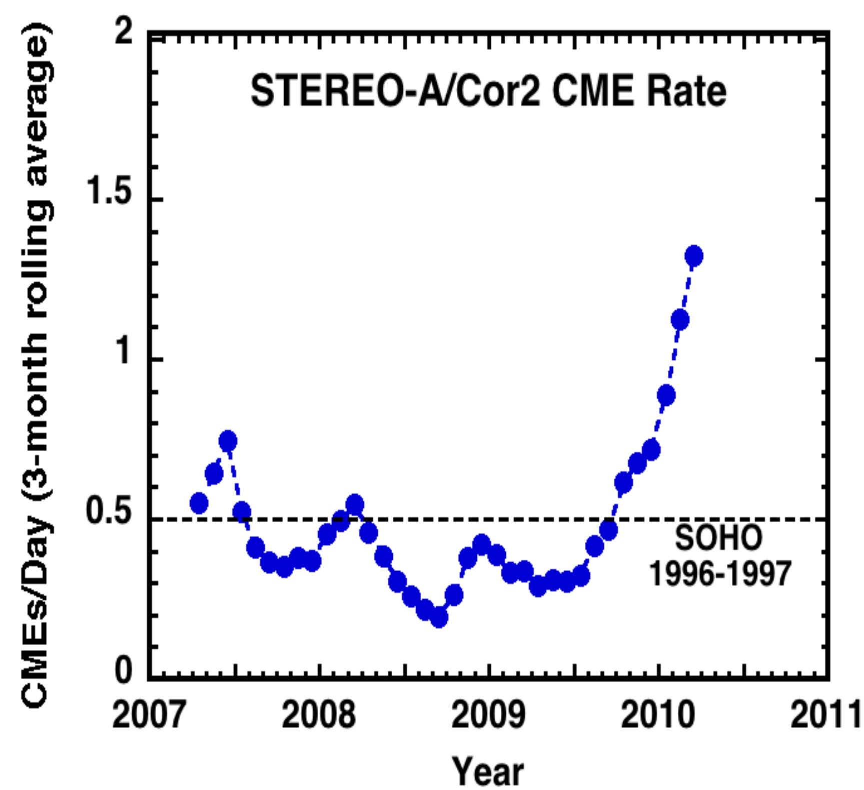
Solar/Interplanetary Parameters affecting cosmic ray intensity:

3) CMEs and other Solar Transients

- **Both the CME rate and mass reached minimum levels in 2007-2008**
- **The CME rate has been increasing since mid-2009**



Vourlidas et al. (2010)



(Robbrecht et al.; St. Cyr, 2009)

Cosmic Rays before the Space Era

Robert A. Millikan launching two balloons in 1938 to measure cosmic rays high in the atmosphere.

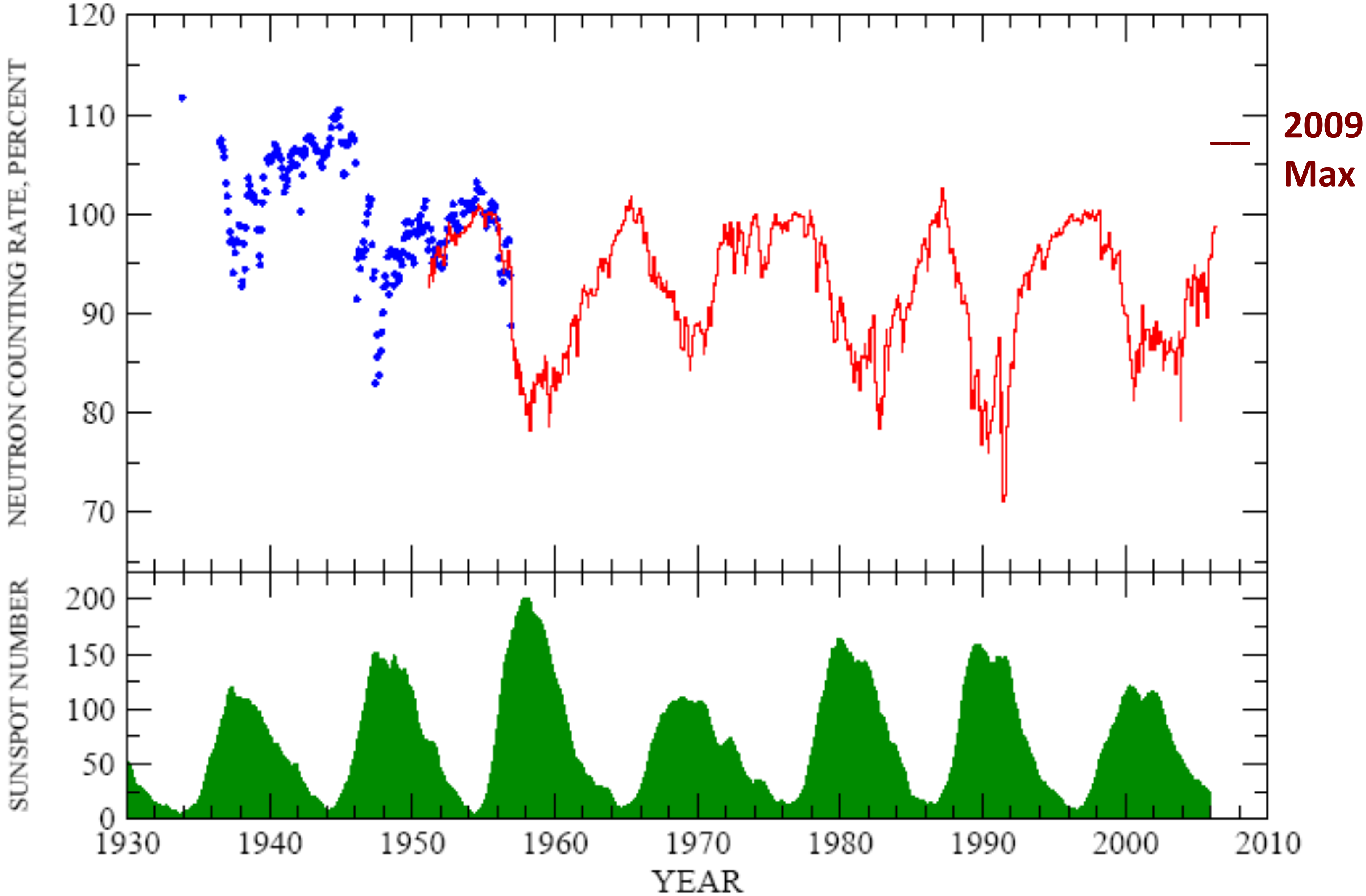
Courtesy of the Caltech Archives

Reconstructed Climax Neutron Monitor, 1933-2010

blue - Based on ionization chambers (Neher 1971, Forbush)

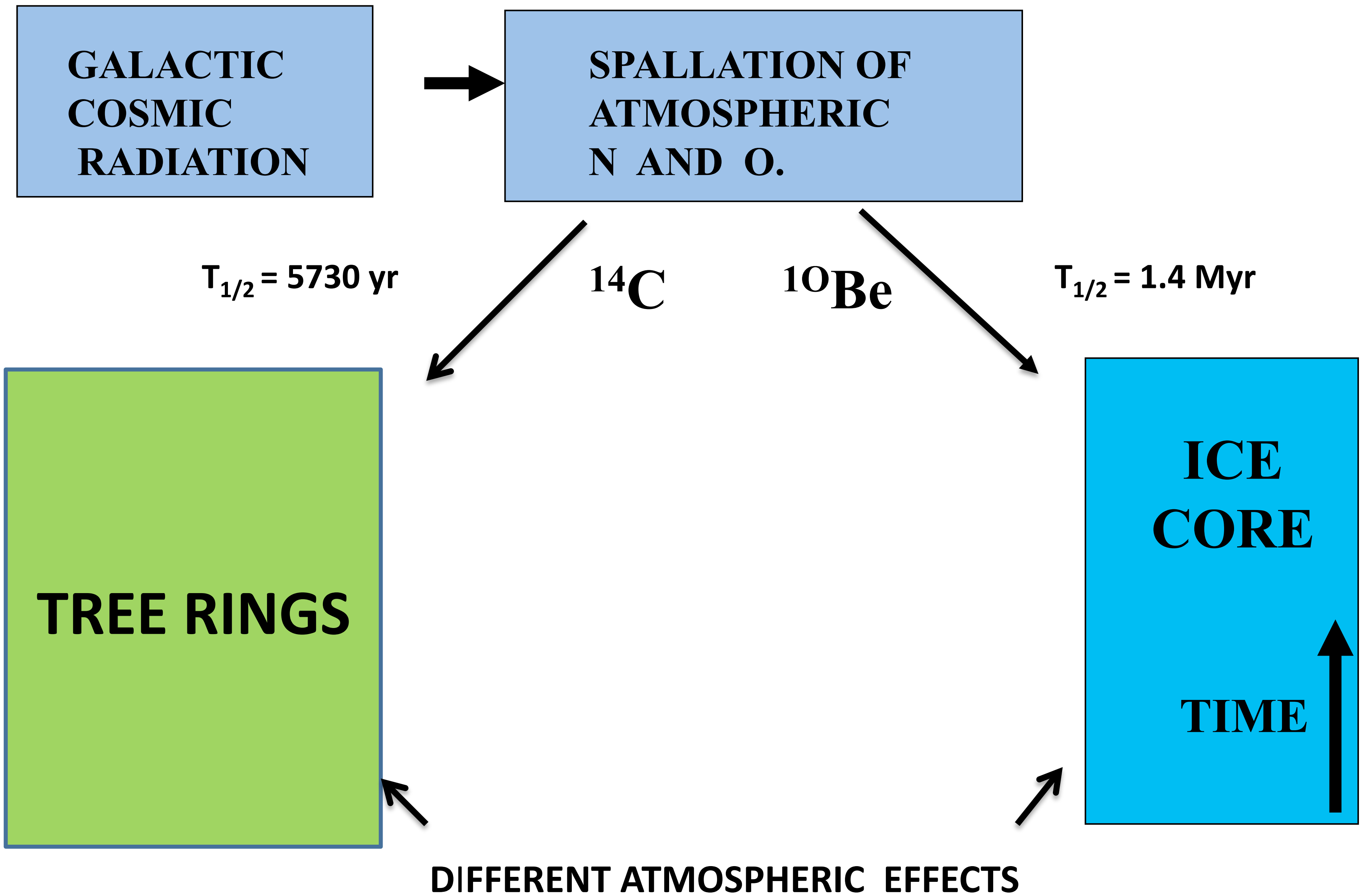
Red - Climax neutron monitor

Black – scaled from Newark Neutron Monitor by RM

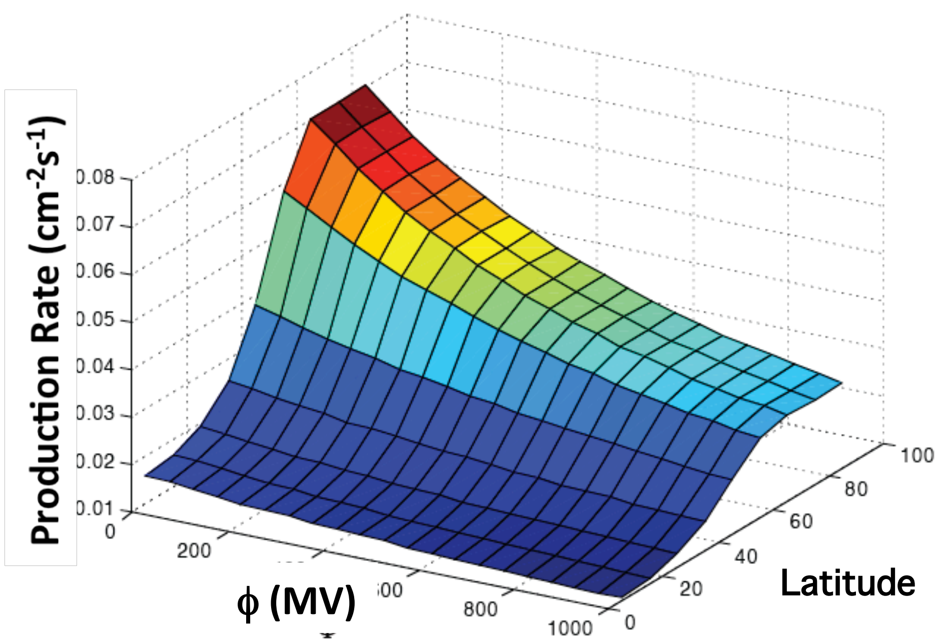


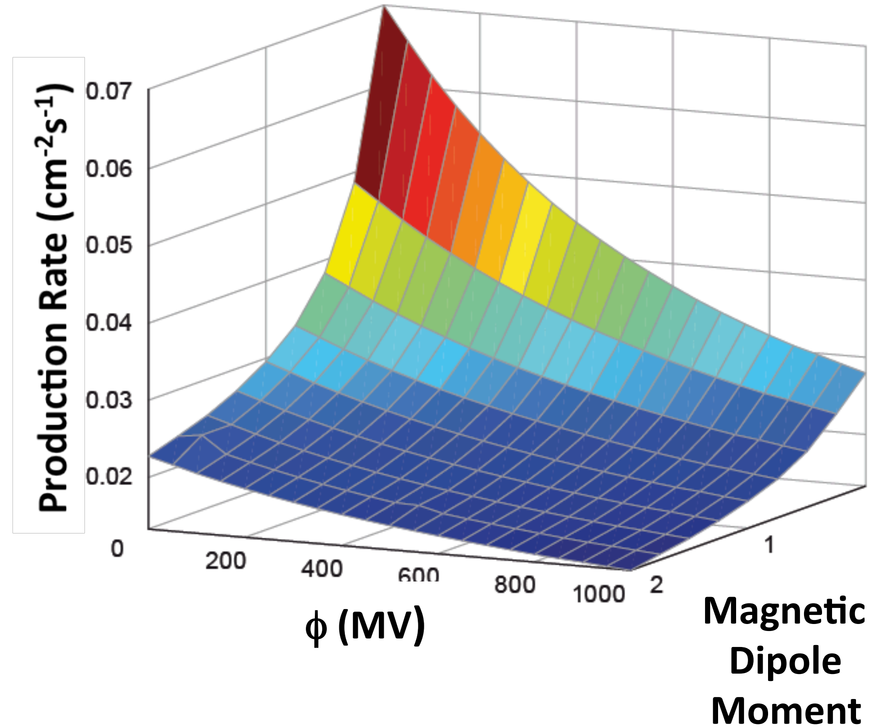
McCracken and Beer, 2007

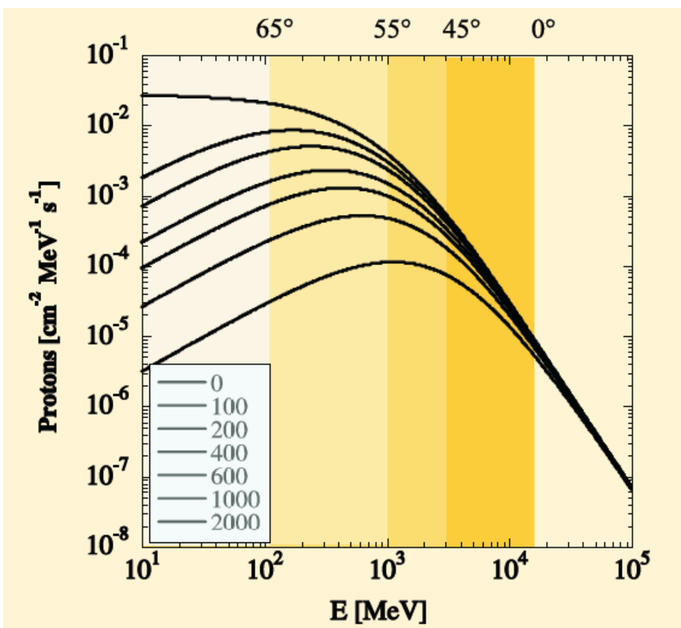
THE PALEO- COSMIC RADIATION RECORD



Effects on ^{10}Be Production Rates





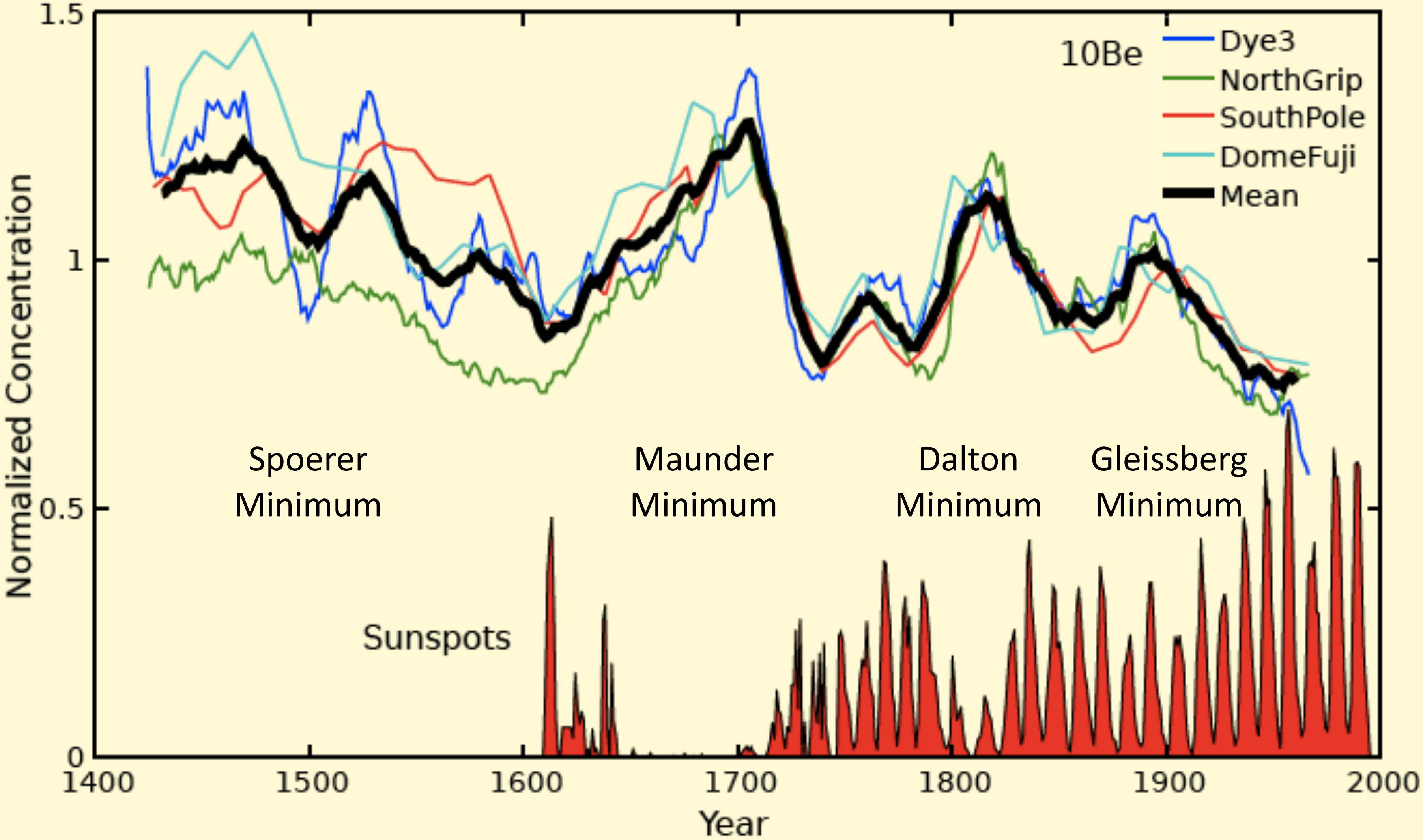


By correcting the measured production rate with the latitude and magnetic dipole moment at the time it is possible to derive a value for the "modulation parameter" in the past

Figures from Masarik and Beer (2009)

The space era has occurred during a period of low cosmic ray activity

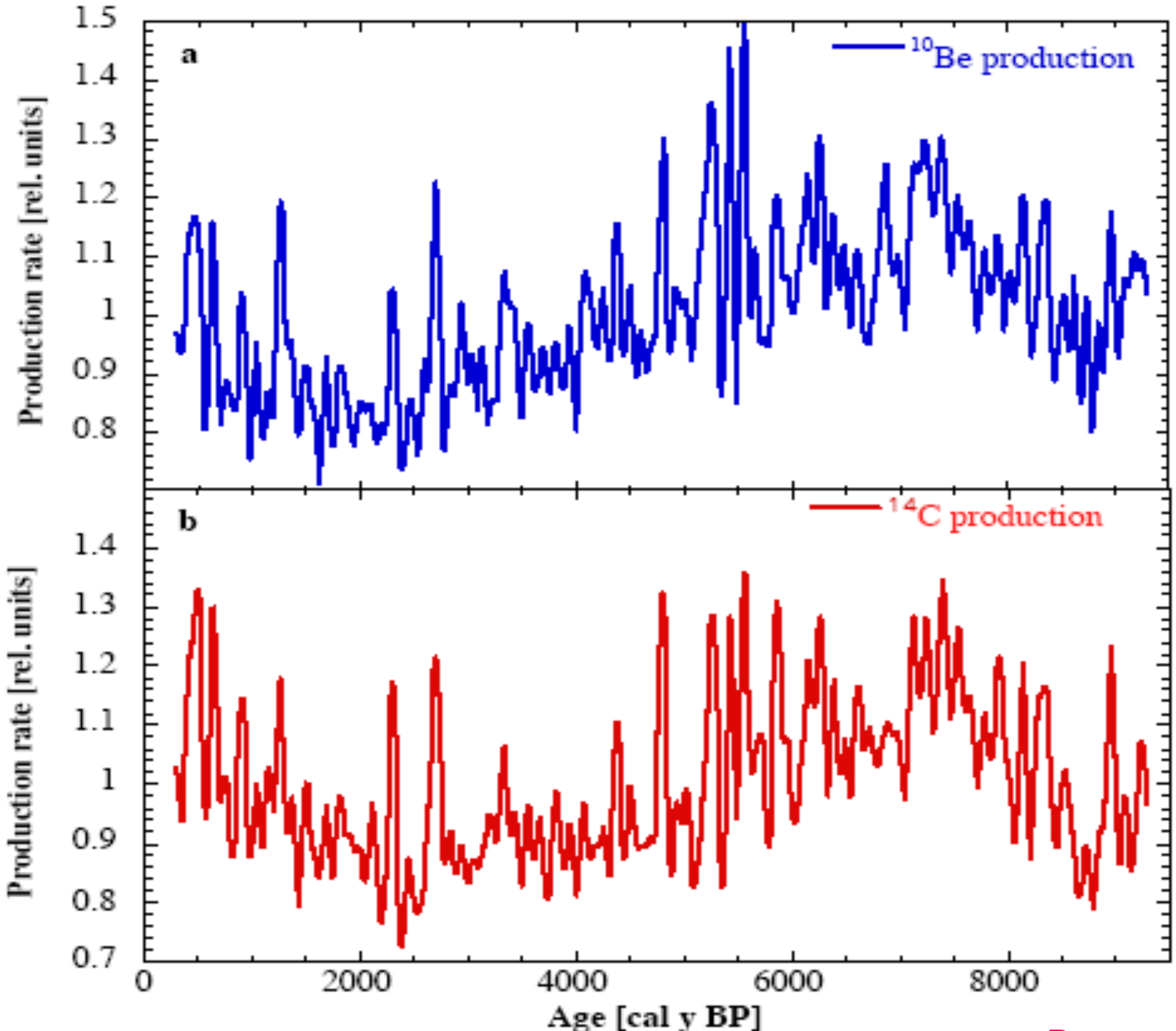
Similar long-term trend in different ^{10}Be records



Long-term 22year averages

Steinhilber et al. 2010

Consistent ^{10}Be and ^{14}C records over the last 9300 years



40-year running means

Beer et al, ICRC 2007

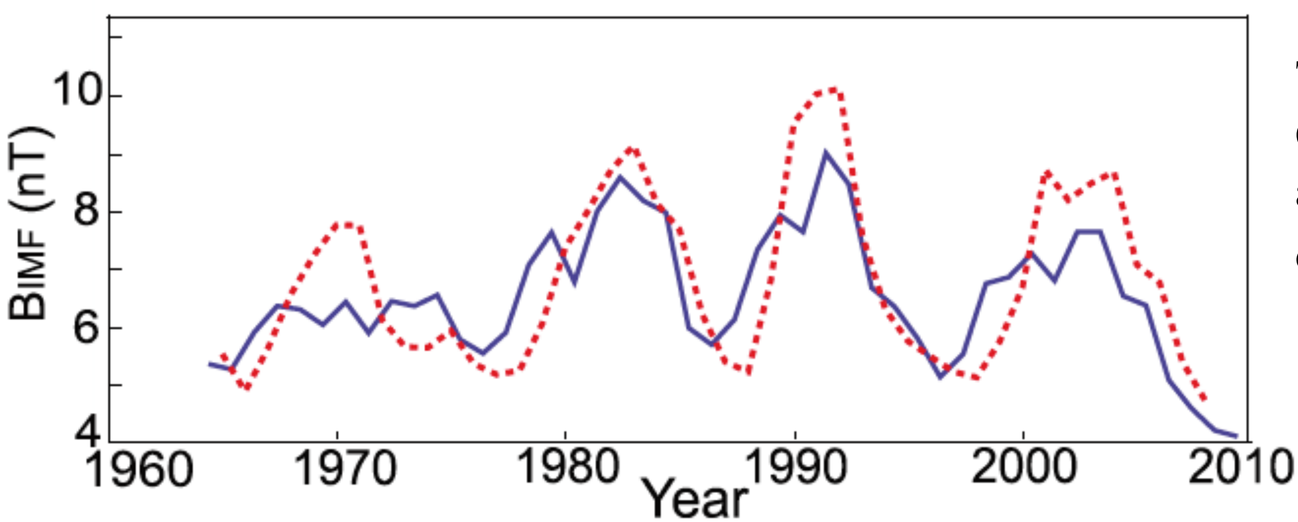
Deriving the Interplanetary Magnetic Field Strength (IMF) from the Modulation Factor (ϕ) - see Steinhilber et al. 2009, 2010

$$\phi(t,r) = \int_r^{r_b} \left(\frac{v_{\mathrm{SW}}(t,r')}{3\,\kappa(t,r')}\right) \mathrm{d}r',$$

If $\kappa \propto B^{-\alpha}$ Caballero-Lopez et al. (2004)

Then

$$B_{\mathrm{IMF}}(t) = B_{\mathrm{IMF},0} \times \left(\frac{\phi(t)}{\phi_0}\,\frac{v_{\mathrm{SW},0}}{v_{\mathrm{SW}}}\right)^{1/\alpha}$$

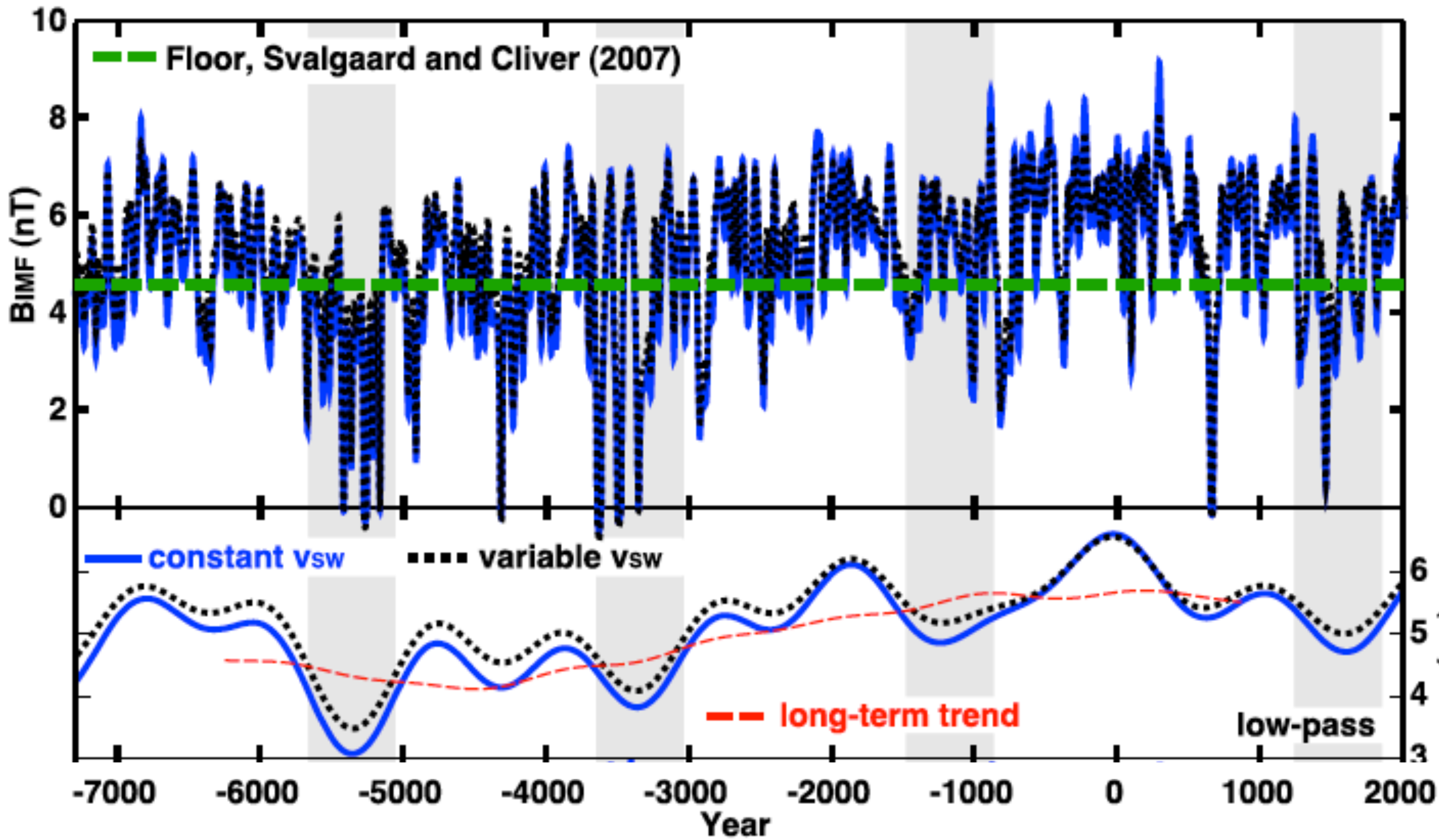


Test using 1964-2010 OMNI2 IMF data (—) and neutron monitor determination of ϕ (---)

Steinhilber et al. 2009

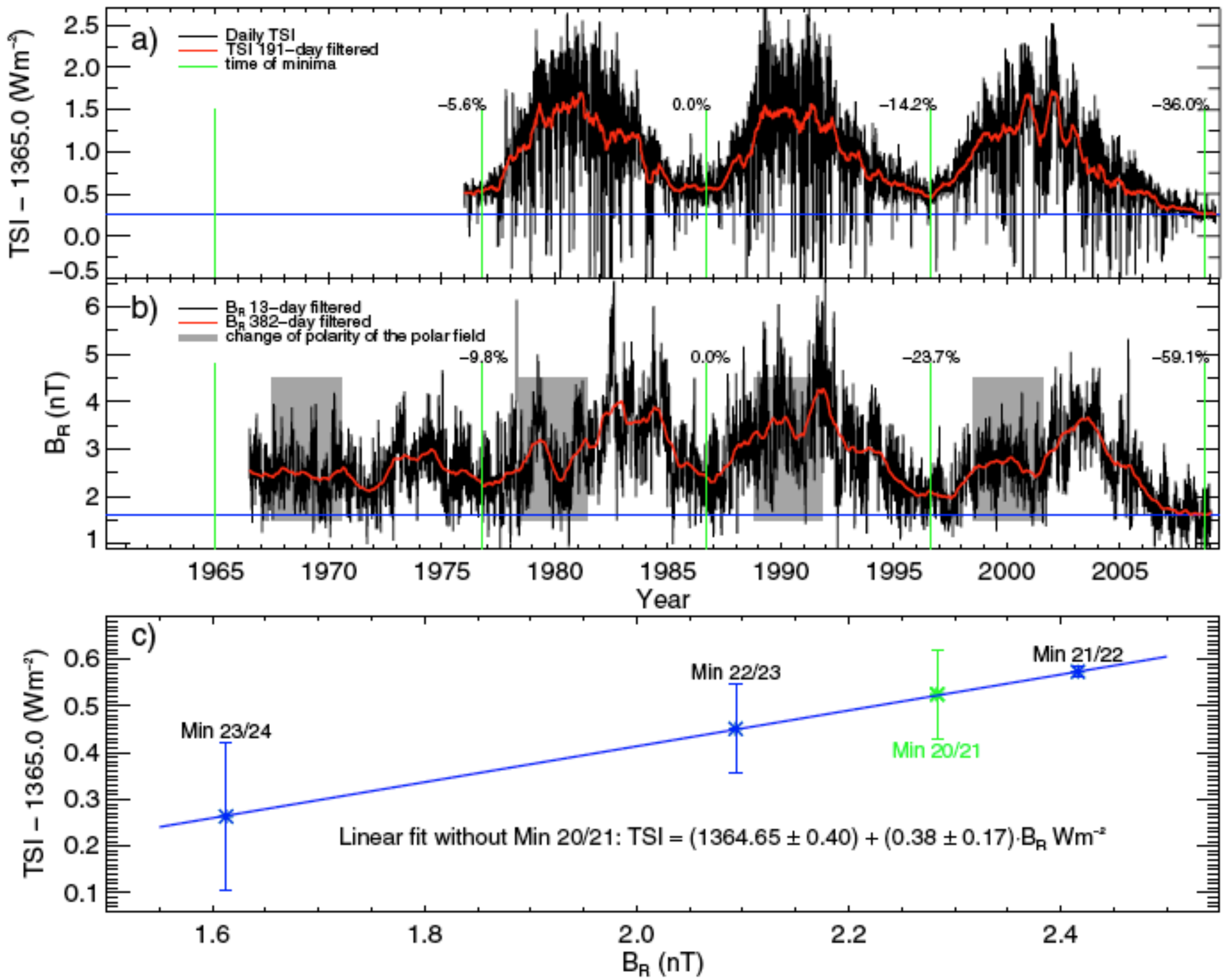
B_{IMF} over the last 9300 years

Assuming an average value for V_{SW} Steinhilber et al (2010) derived B_{IMF} for the past 9300 years:



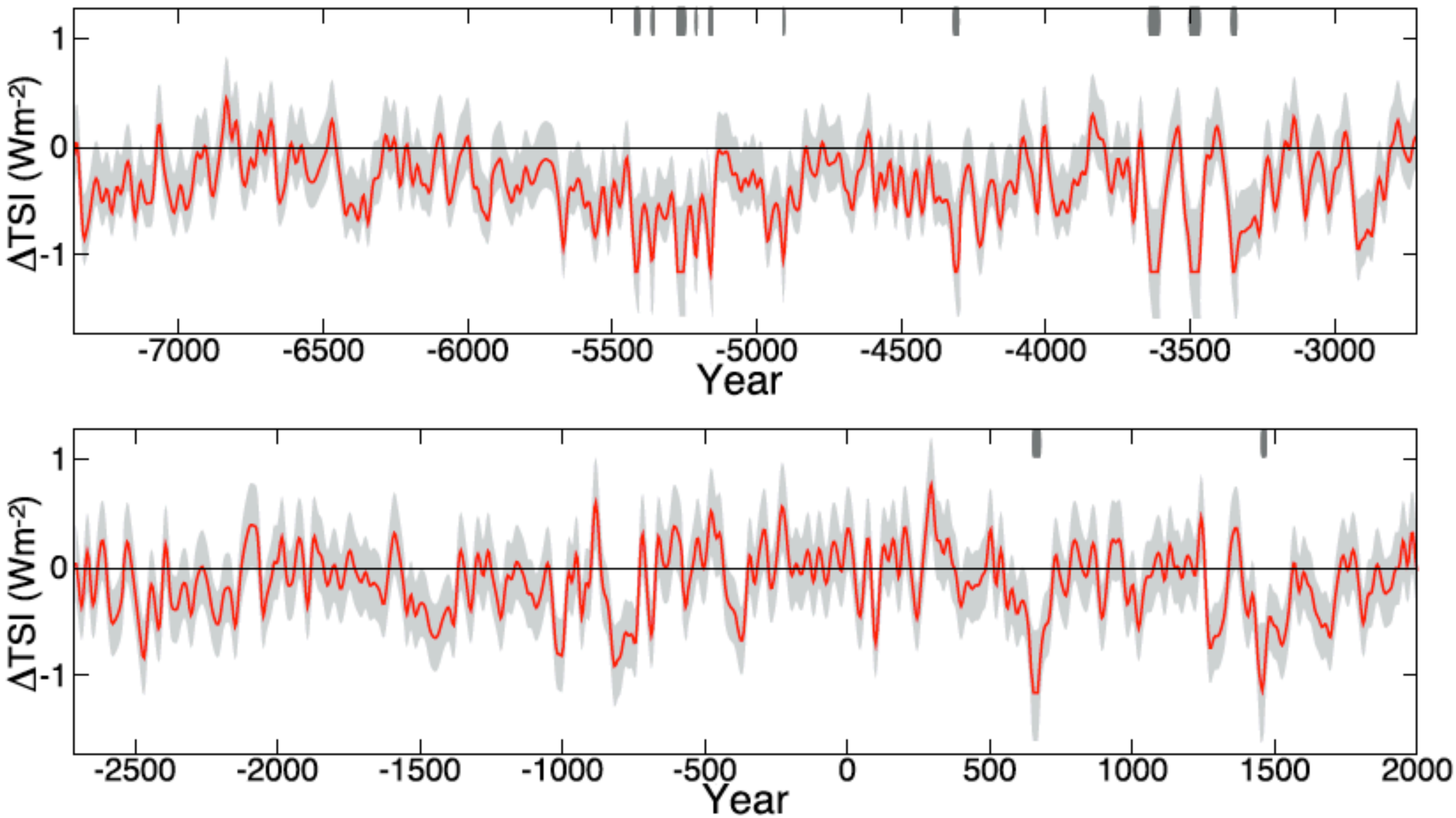
Steinhilber et al. 2010

Relating TSI from the Open Component (B_R) of the IMF



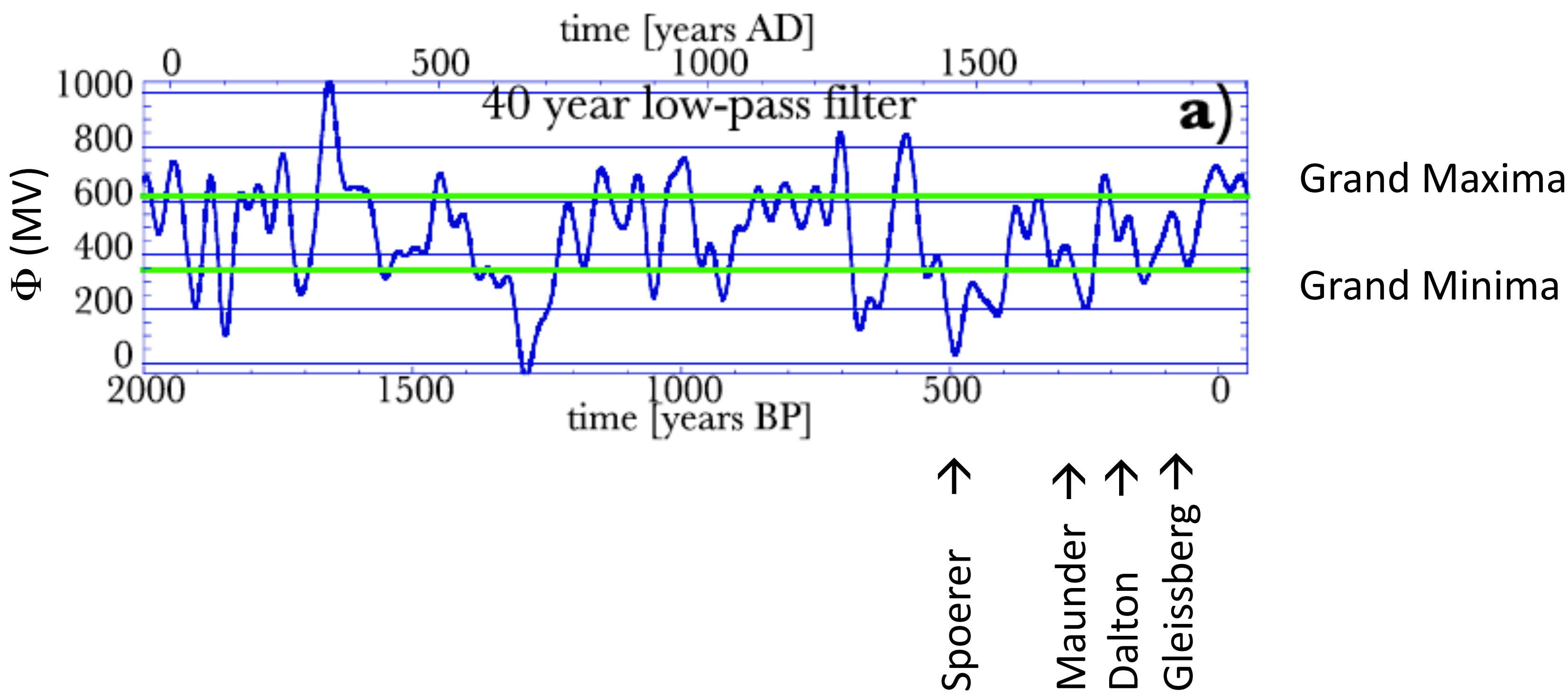
Frohlich (2009)

TSI during the Holocene – Steinhilber et al. 2010



Relative to 1365.57 W/m^2 as measured in 1986

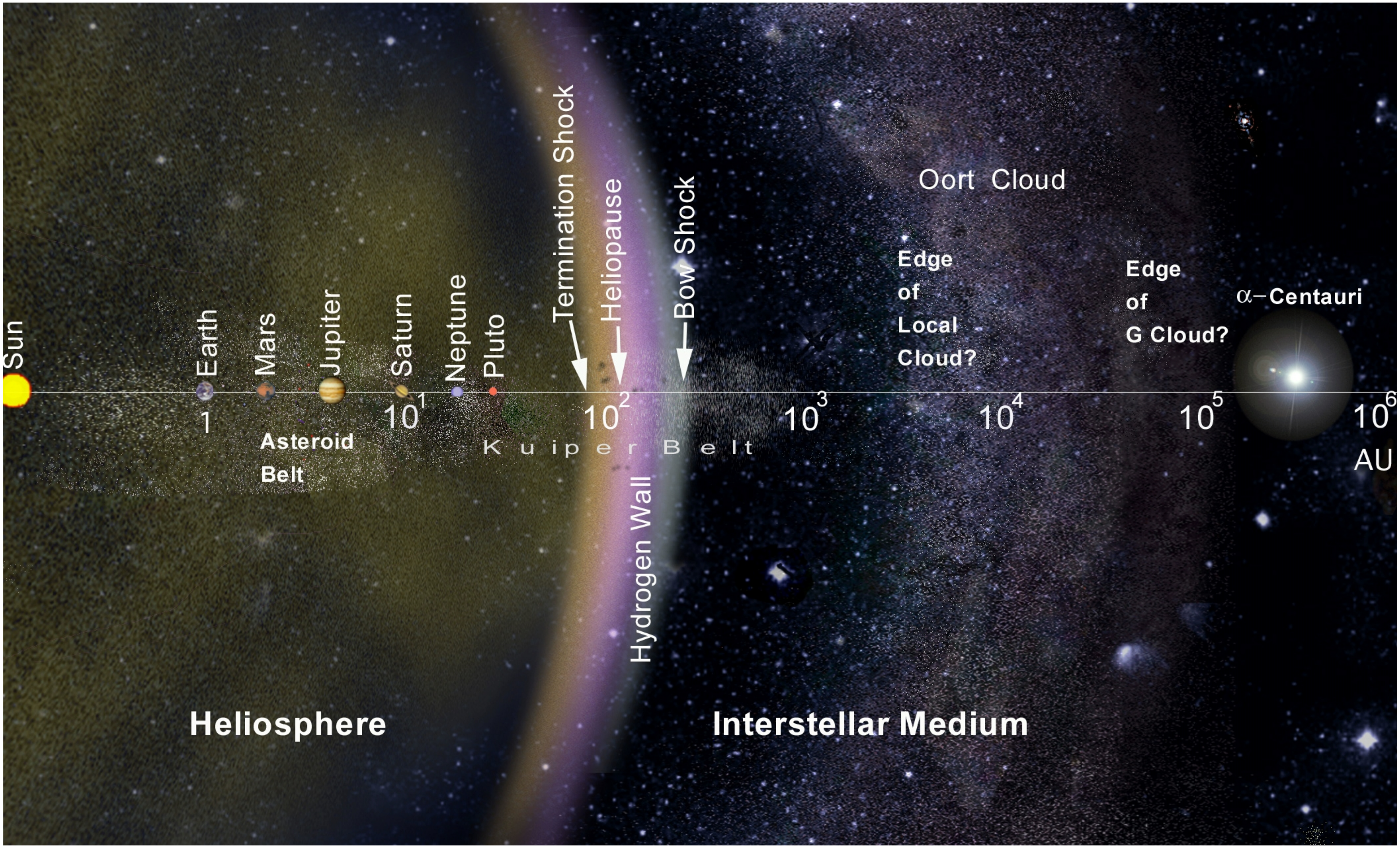
Grand Maxima and Minima



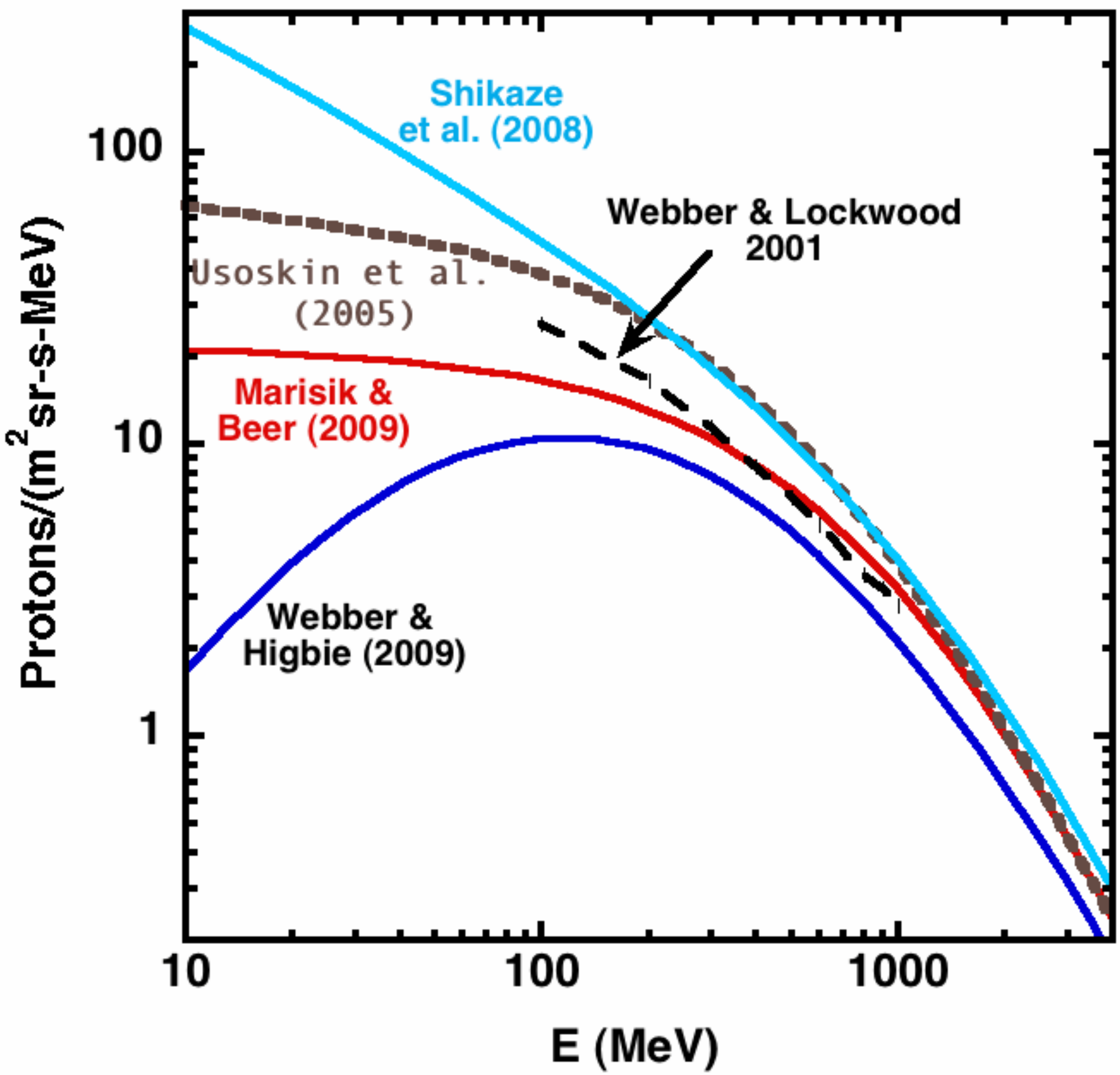
We have been in a Grand Maximum since ~1945. Based on the length of previous Grand Maxima, Abreu et al. (2008) conclude that it is likely to end within ~15 years

Abreu et al. 2008

In the next few year Voyager-1 will enter our nearby galactic neighborhood where it may measure local-interstellar cosmic-ray energy spectra



Comparison of LIS Spectra for Hydrogen



Summary

- The current solar minimum created "perfect storm" conditions for "super-fluxes" of cosmic rays at 1 AU.
  - weakened $\langle B \rangle$ and $\langle \delta B \rangle$
  - reduced CME rate, mass, and kinetic energy
  - the extended solar minimum => time to equilibrate
  - reduced solar wind dynamic pressure
  - (eventually) flattened heliospheric current sheet

- The extended solar minimum provides the opportunity to isolate these contributions

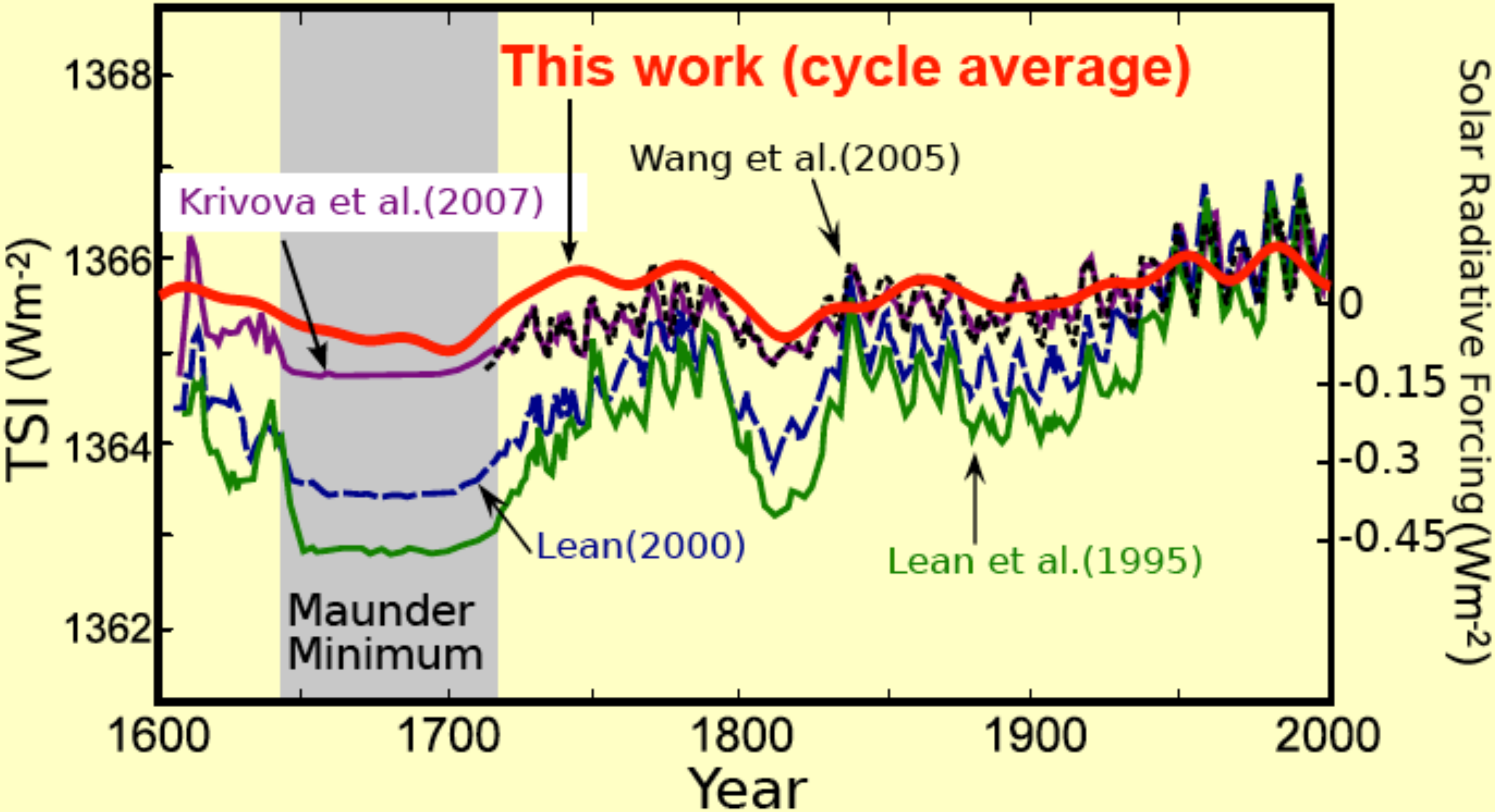
- The ^{10}Be record shows that higher GCR intensities have been the rule in the past. We may now be returning to a more normal interplanetary radiation environment

- The cosmic ray intensity is inversely correlated with the IMF, which in turn is correlated with TSI. As a result, these cosmogenic nuclei can trace solar activity in the past.

- According to Abreu et al., the current Grand Maximum is likely to end in the next 15 years or so

- In the next few years Voyager may measure the local interstellar spectra. They could reveal the maximum GCR intensity in the past (and the future), and will affect the interpretation of ^{10}Be in ice cores

TSI - Comparison with other Reconstructions



Steinhilber et al. 2010b

Do Cosmic Rays affect Cloud Cover?

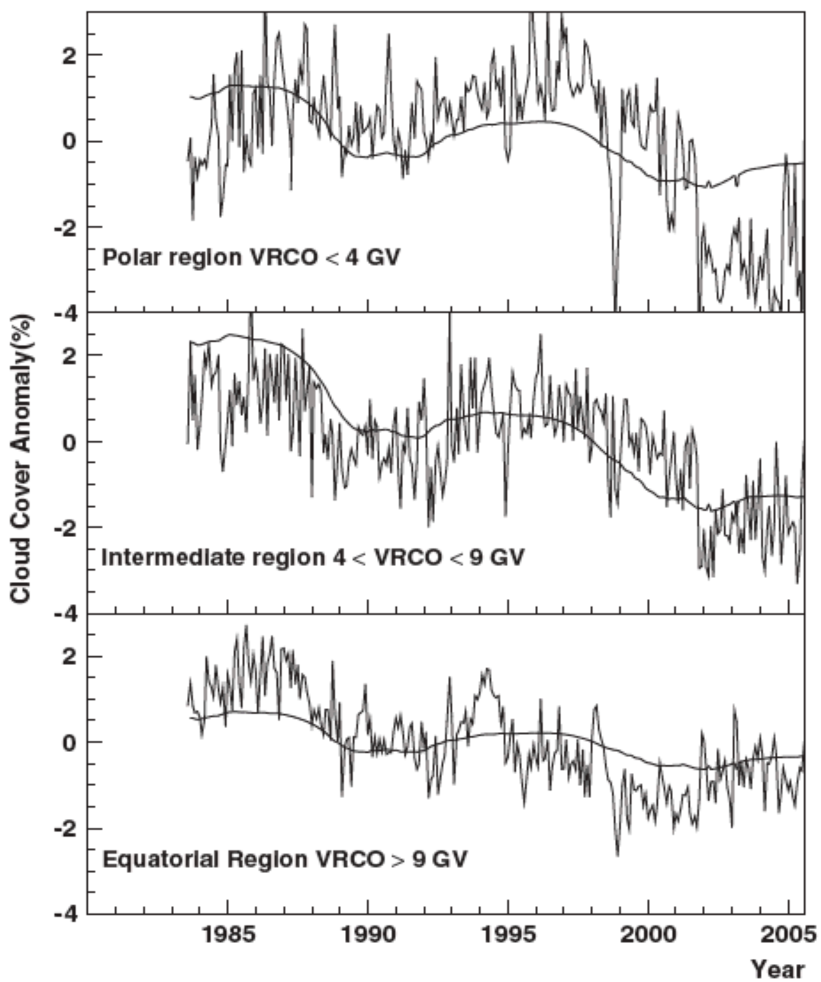
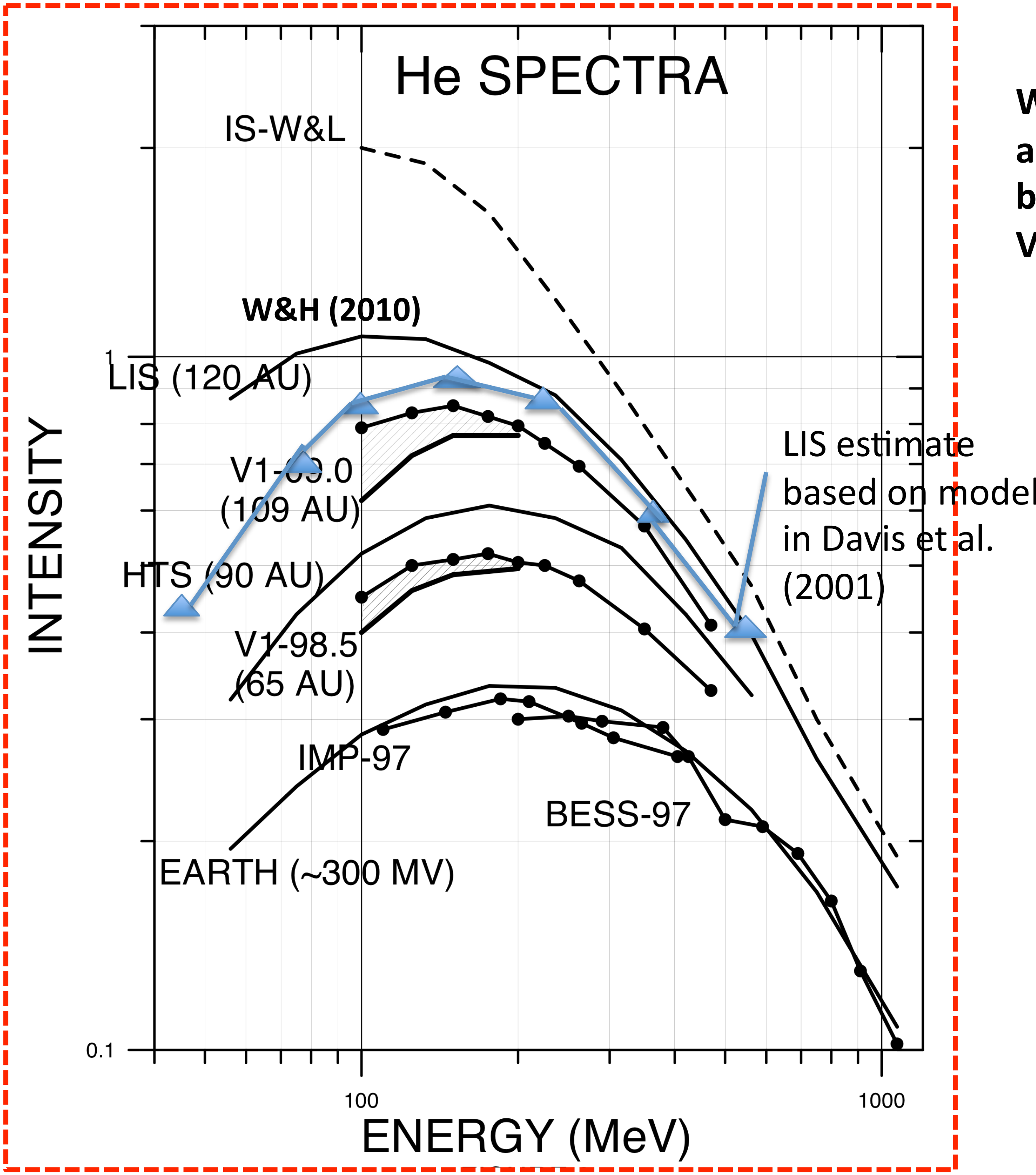


Figure 1. The LCC anomaly as a function of time for various ranges of vertical cut off rigidity (VRCO). The smooth curve shows a fit of the monthly mean of the daily sun spot number (SSN) with an assumed linearly falling systematic change. The SSN is anti-correlated with the CR count rate with a lead time of some months.

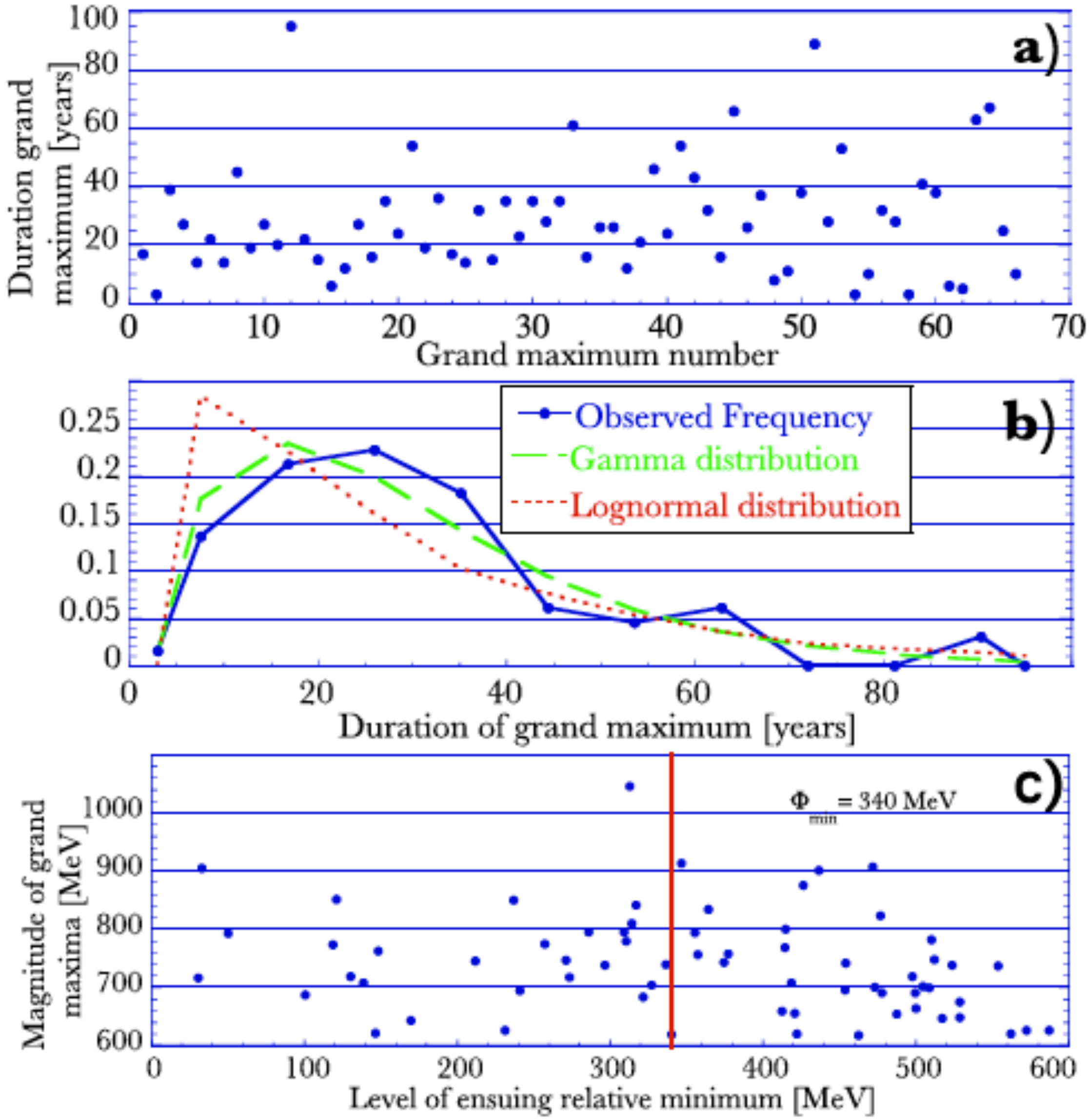
In a series of papers, Svensmark and co-workers have concluded that cosmic rays play a major role in producing clouds.

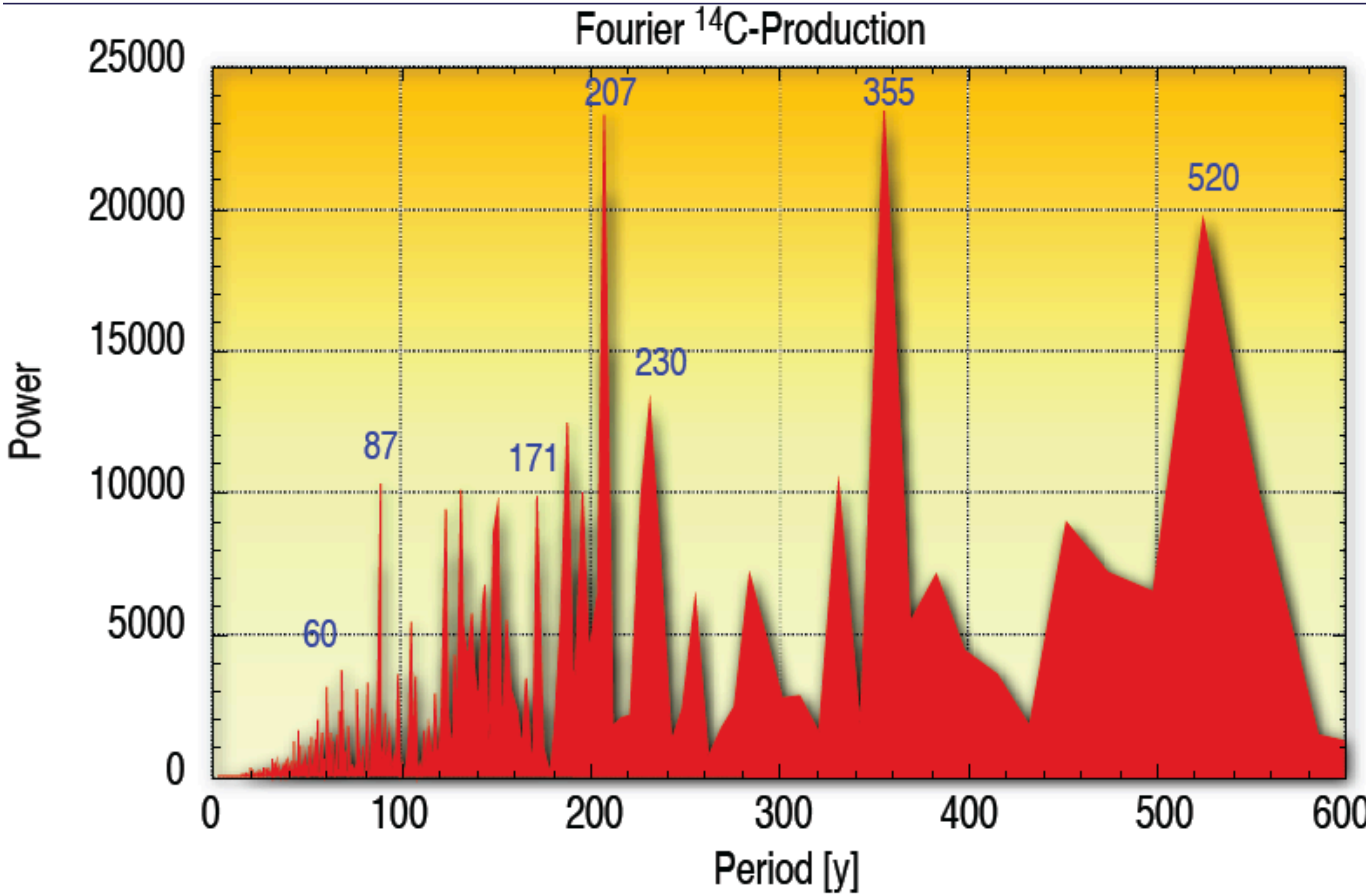
Sloan and Wolfendale (2008) conclude that <23% (95% confidence level) of the 11-year cycle change in the globally-averaged cloud cover in solar cycle 22 was due to change in the rate of ionization from the solar modulation of cosmic rays



Webber & Higbie (2010a) also re-evaluated the He LIS based on a new model and Voyager data

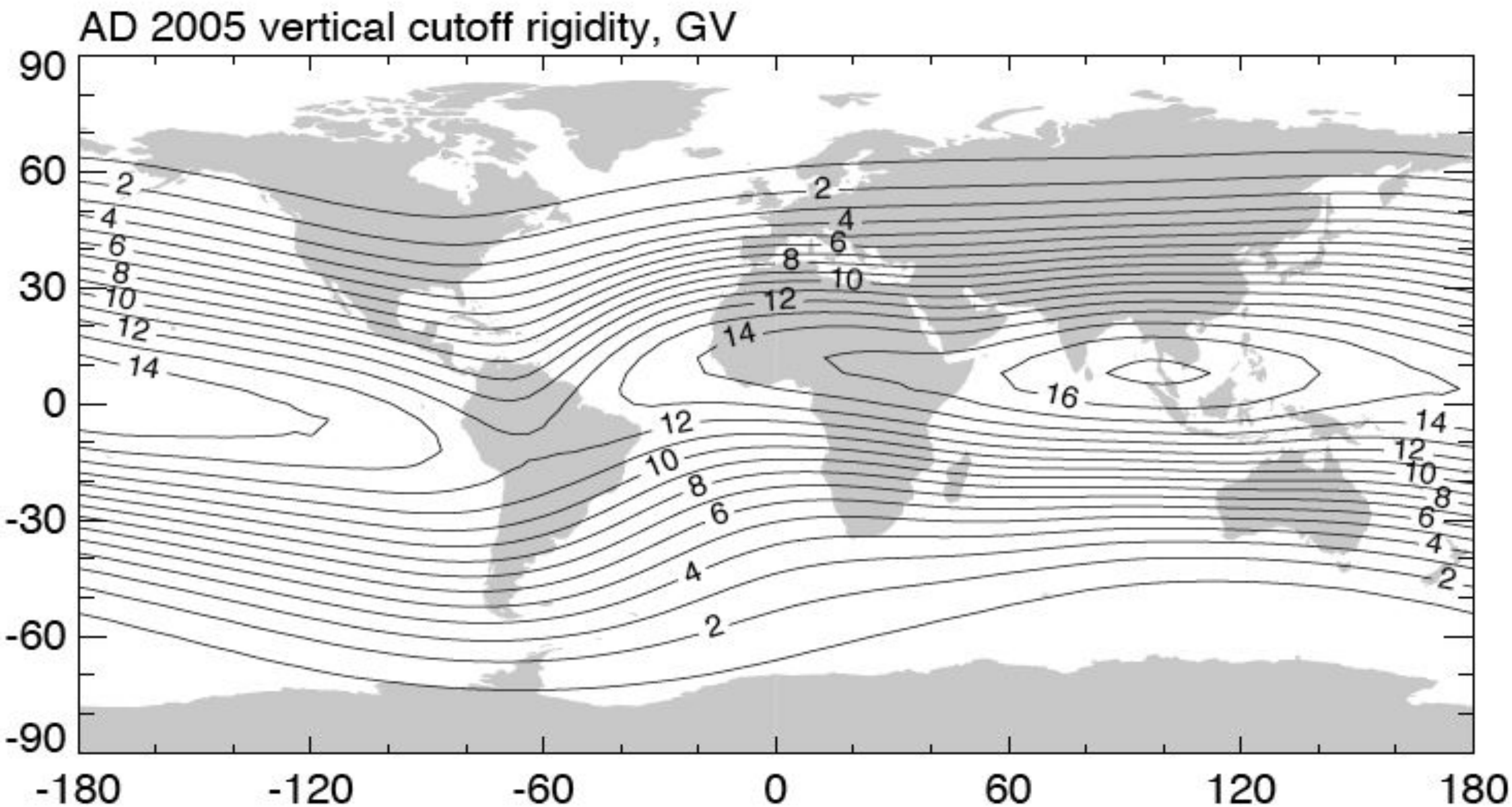
Statistics of Grand Maxima – Abreu et al. (2009)





Fourier ^{14}C-Production
Power
Period [y]
25000
20000
15000
10000
5000
0
0
100
200
300
400
500
600
60
87
171
207
230
355
520

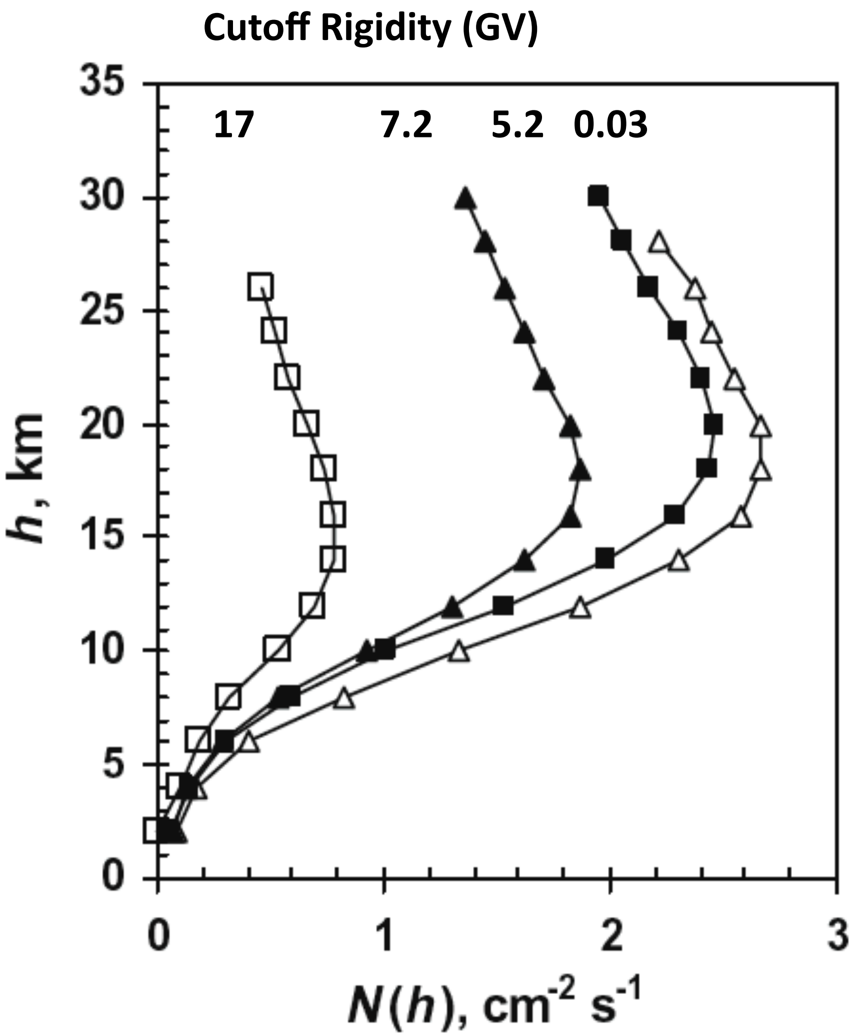
For vertically incident particles the minimum rigidity particle that can reach the upper atmosphere of Earth is given approximately by: $R_c = 14.5 \cos^4\lambda$ GV, where R_c is called the geomagnetic cutoff rigidity (in GV) and λ is the geomagnetic latitude. The plot below is based on a more exact calculation.



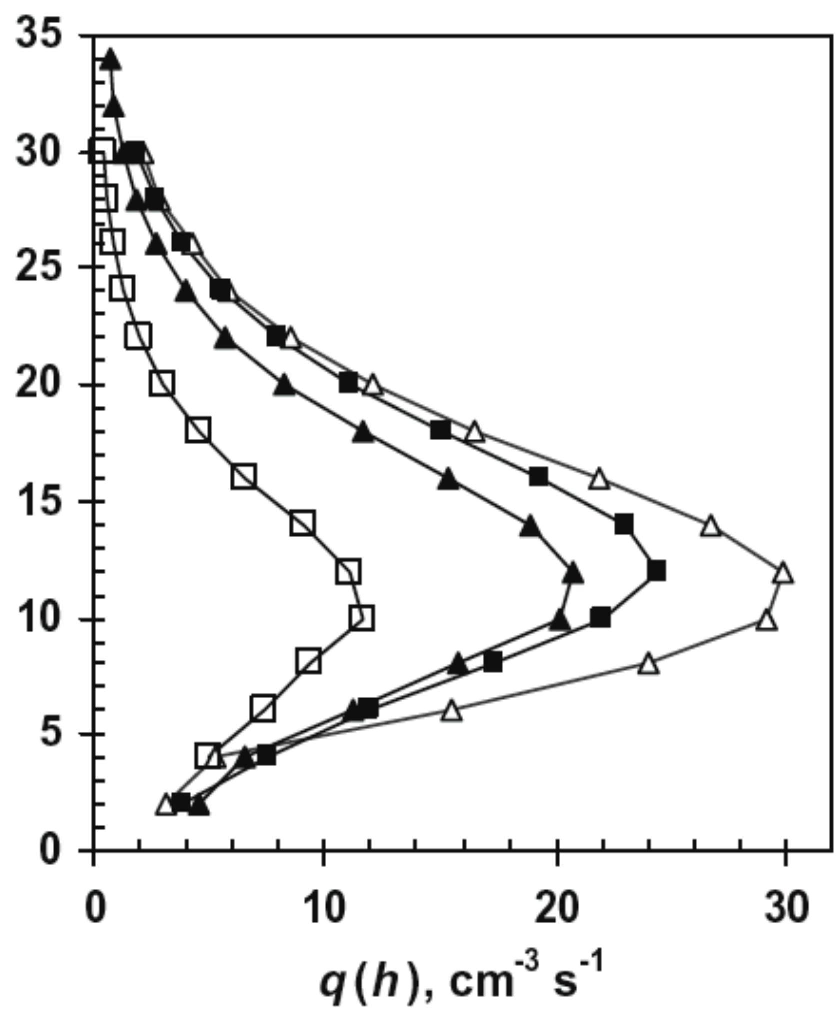
Selesnick et al. 2007

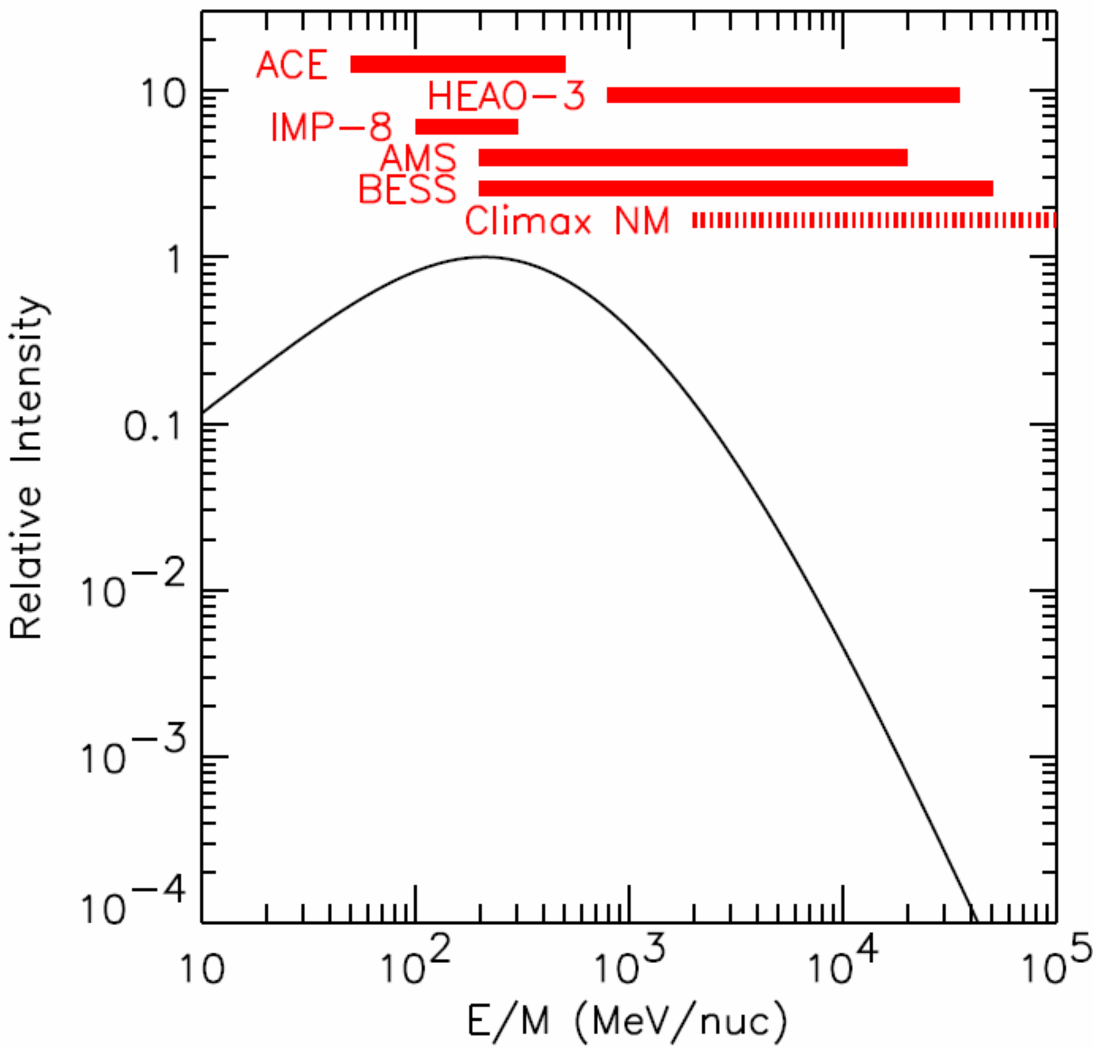
Cosmic Ray Intensity and Ionization Rate at Various Cutoff Rigidities
(Data from Lebedev Institute Balloon Flights)

Omni-directional Comic-Ray Intensity



Ionization Rate





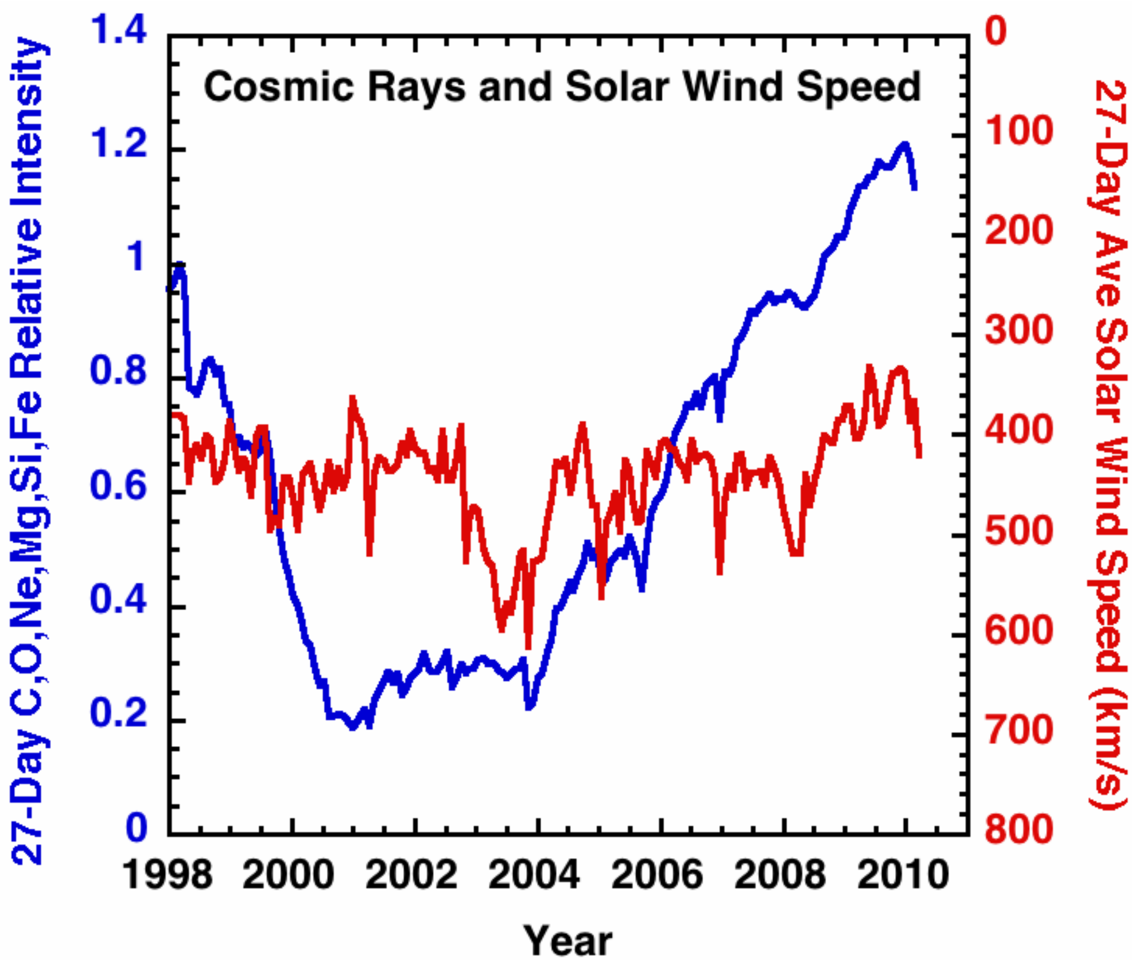
Where the measurements fall along the cosmic ray spectrum observed near Earth.

The peak of the intensity spectrum has been relatively well covered.

Solar/Interplanetary parameters affecting cosmic ray intensity:

2) Solar Wind Velocity (Vsw)

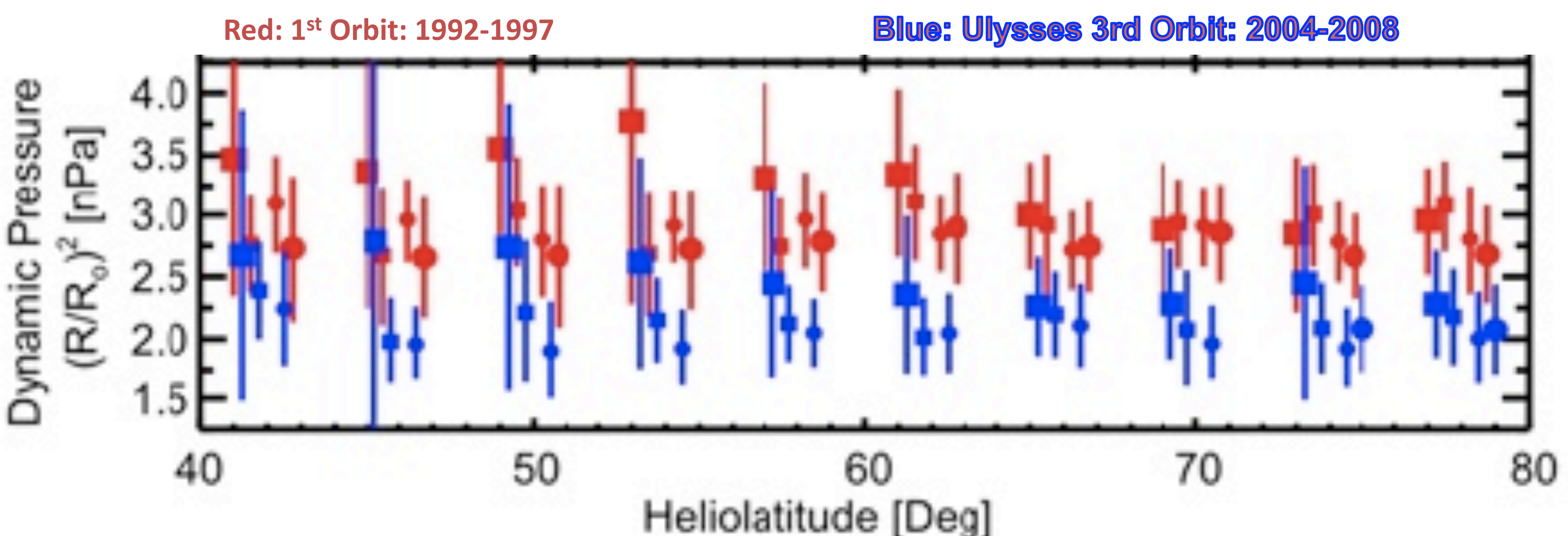
- **Vsw directly affects the loss rate of cosmic rays due to convection**
- **The drop in speed in 2008 is not unusual; there is an increase in early 2010 just as the GCR intensity drops**



Solar/Interplanetary parameters affecting cosmic ray intensity:

3) Decreased solar-wind dynamic pressure

- **This decrease means that the termination shock and heliopause are moving in => easier GCR access to 1 AU**
- **However, both Voyager and solar modulation models find small radial gradients in the outer heliosphere. This is probably not a major effect at 1 AU**



McComas et al., 2008