Record-Breaking Cosmic-Ray Intensities in 2009 and 2010

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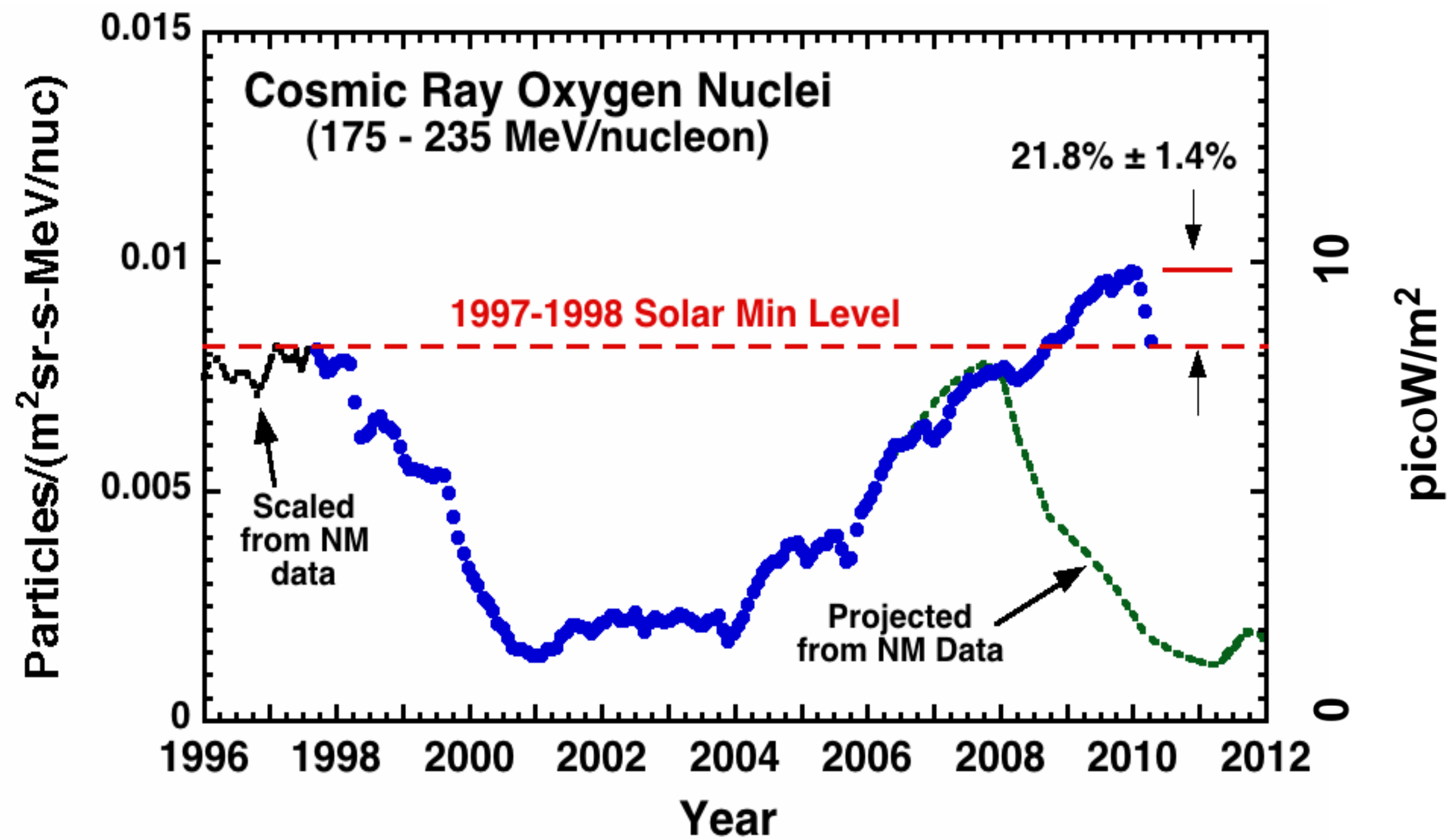
Cosmic Ray Oxygen Intensities during Solar Cycle 23



- 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

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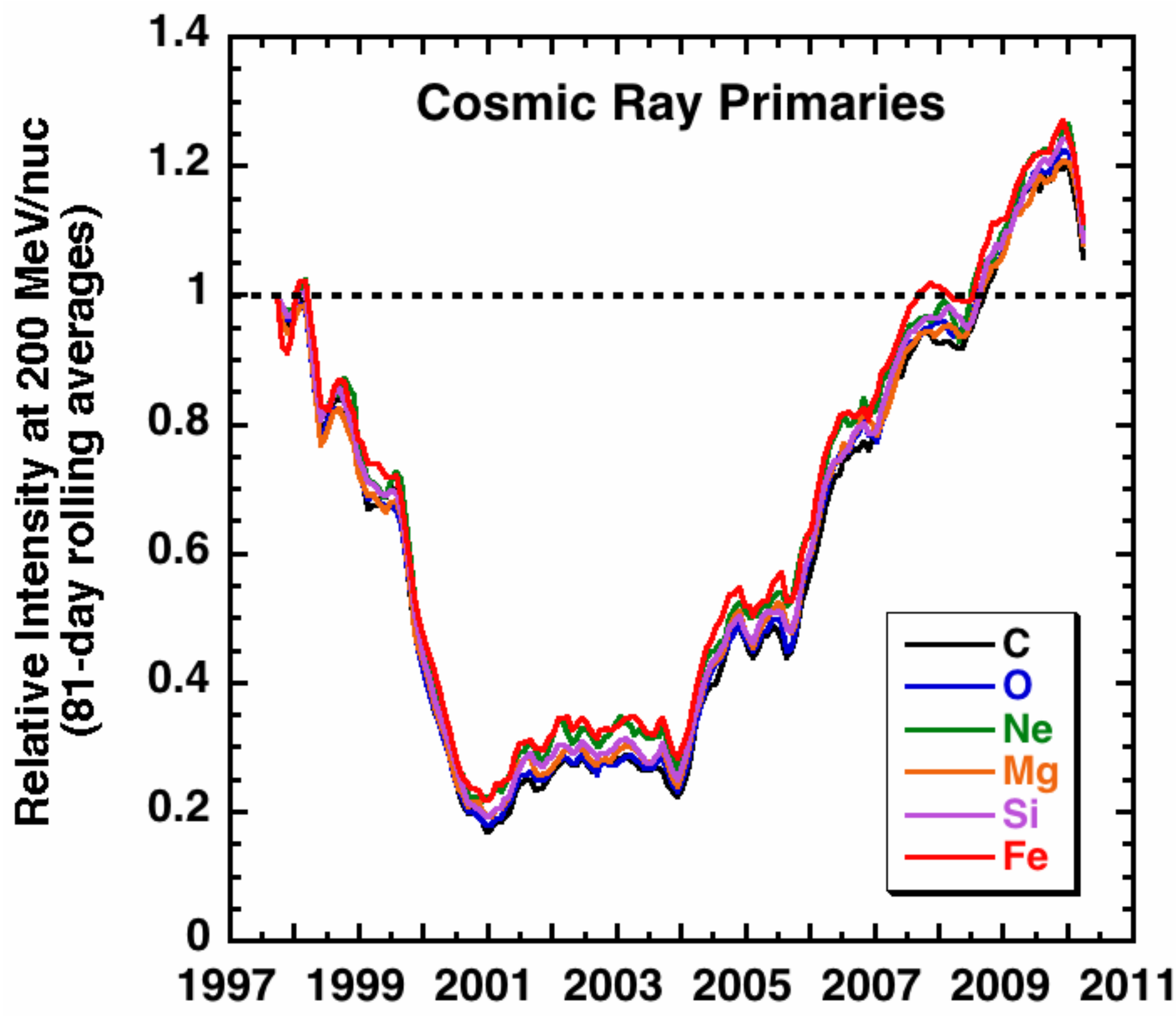
Outline

Introduction
Cosmic ray access to the heliosphere
Evidence for record-breaking intensities
Energy spectra
What enabled the intensity increase?
Local Interstellar Spectra
Summary

Sources of Data

Cosmic rays: ACE, IMP-8, Voyager,
BESS, PAMELA, Newark and Climax neutron monitors
Solar Wind: ACE, Ulysses
CMEs: SOHO, STEREO

All Abundant Species Have Similar Excesses in 2009-2010



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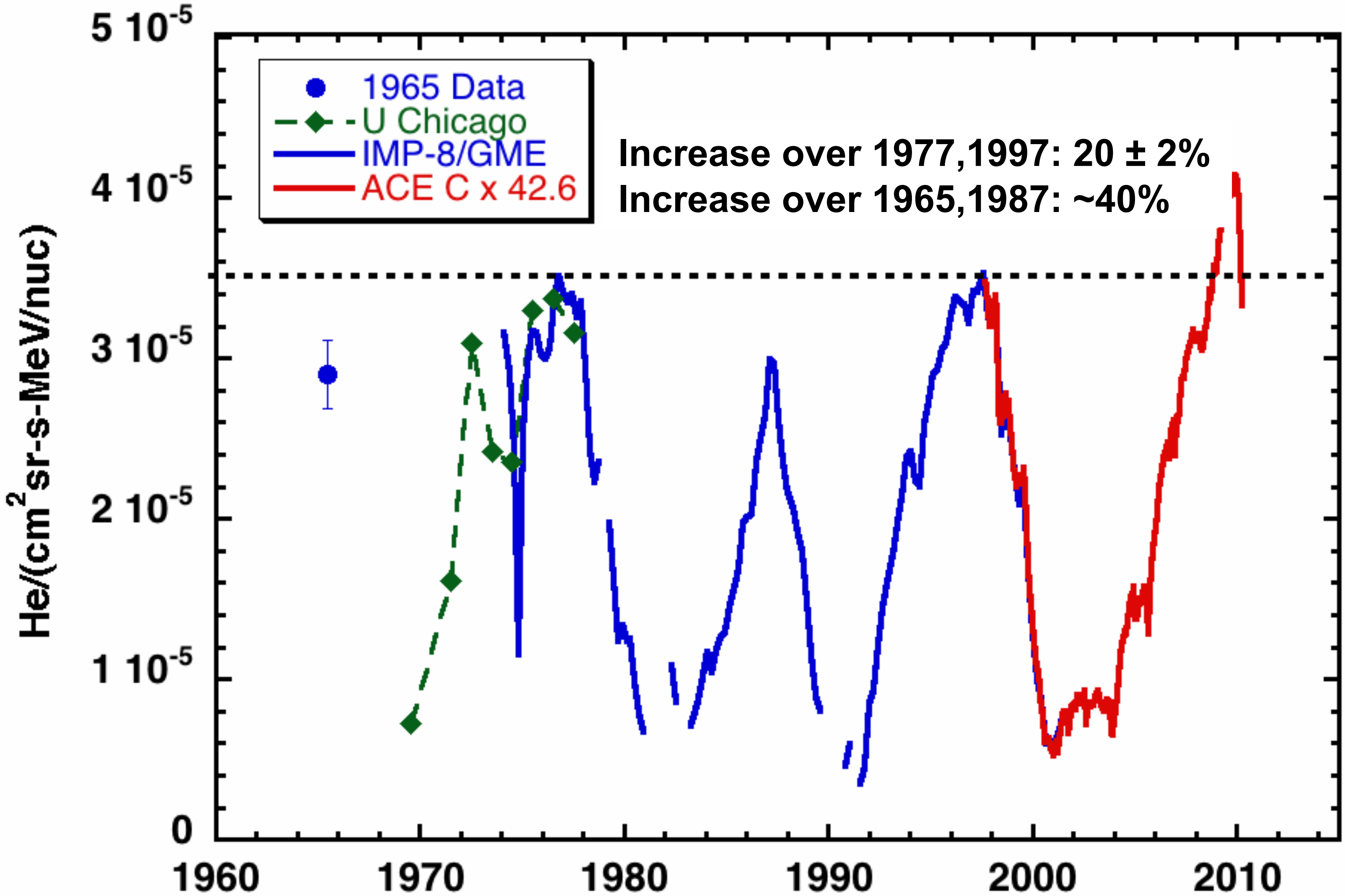
Comparing 100-200 MeV/n He over 5 Solar Minima



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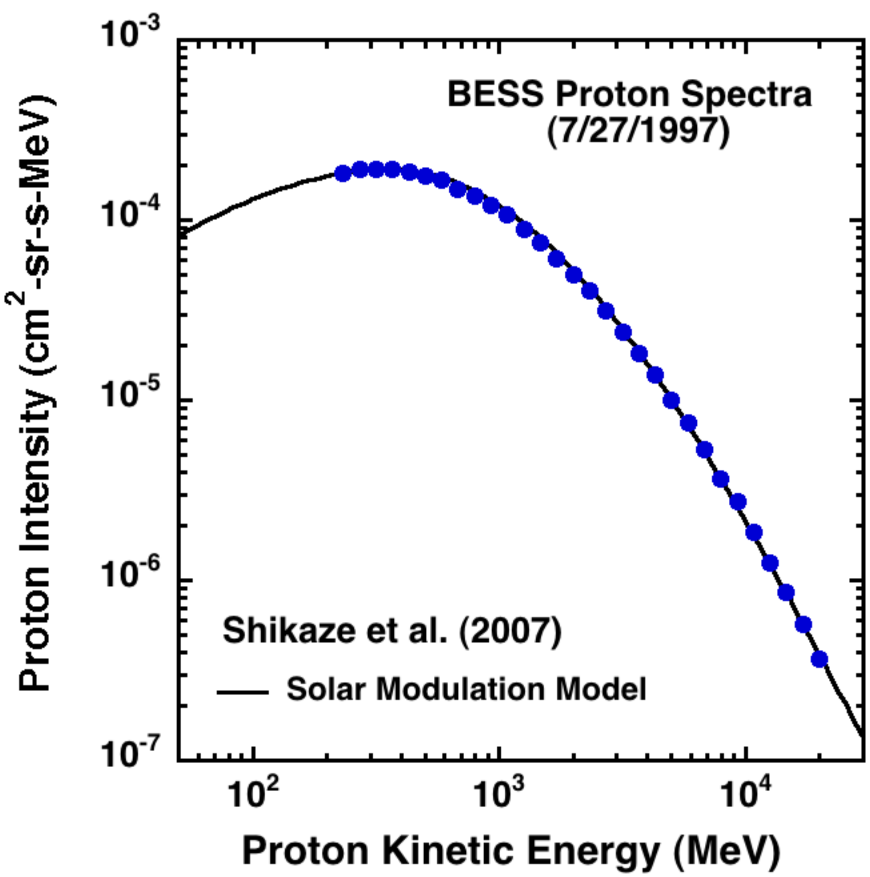
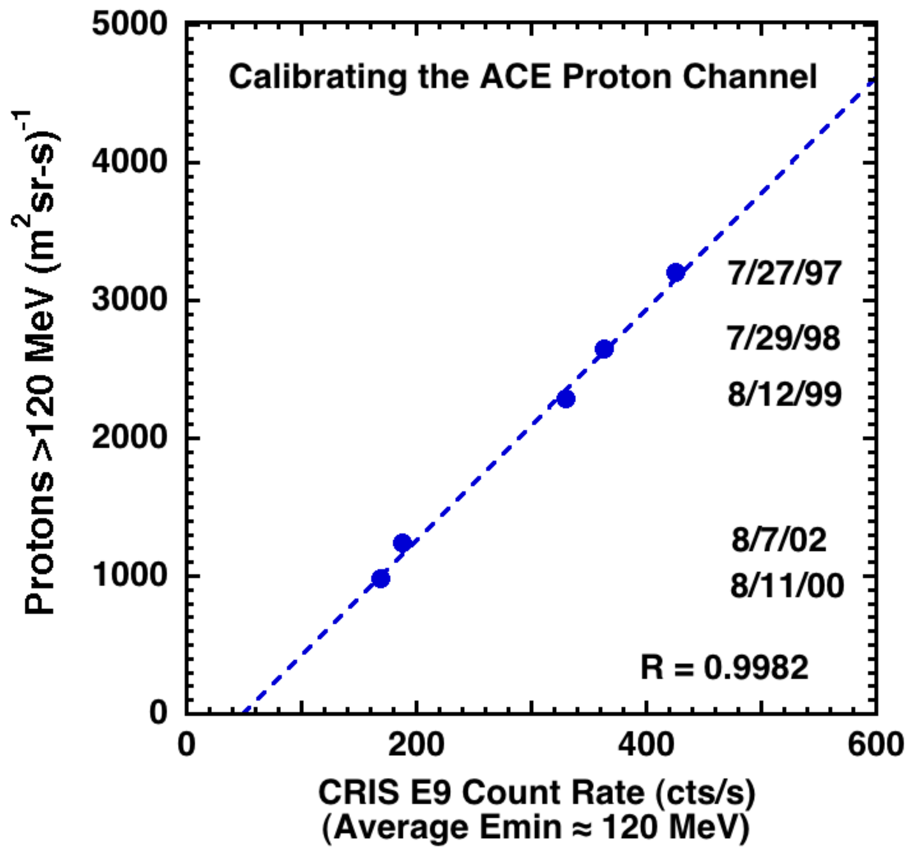
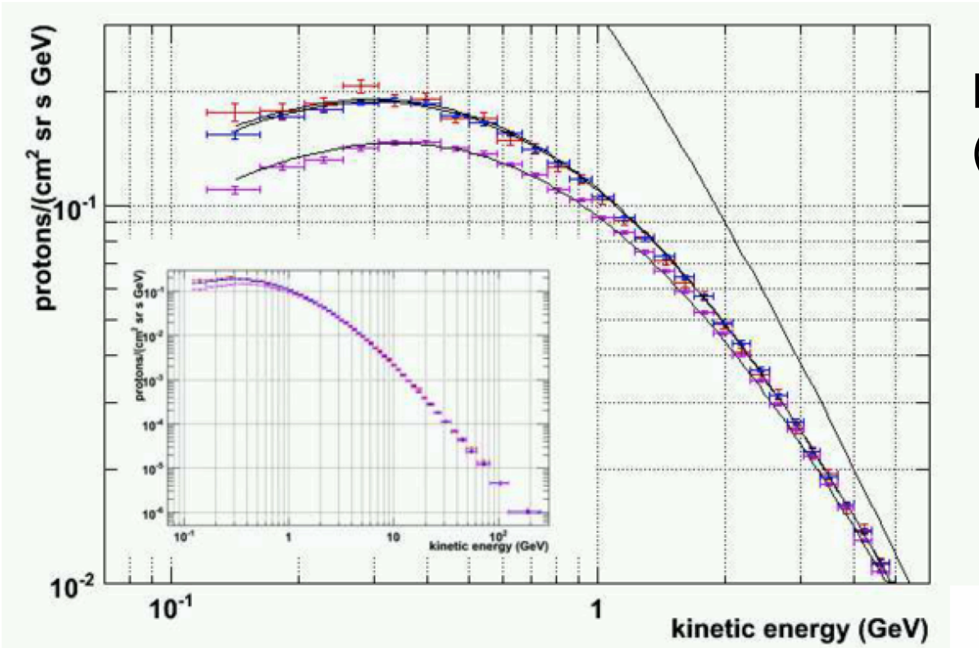
What About Protons?

Finding a proxy for high-energy protons

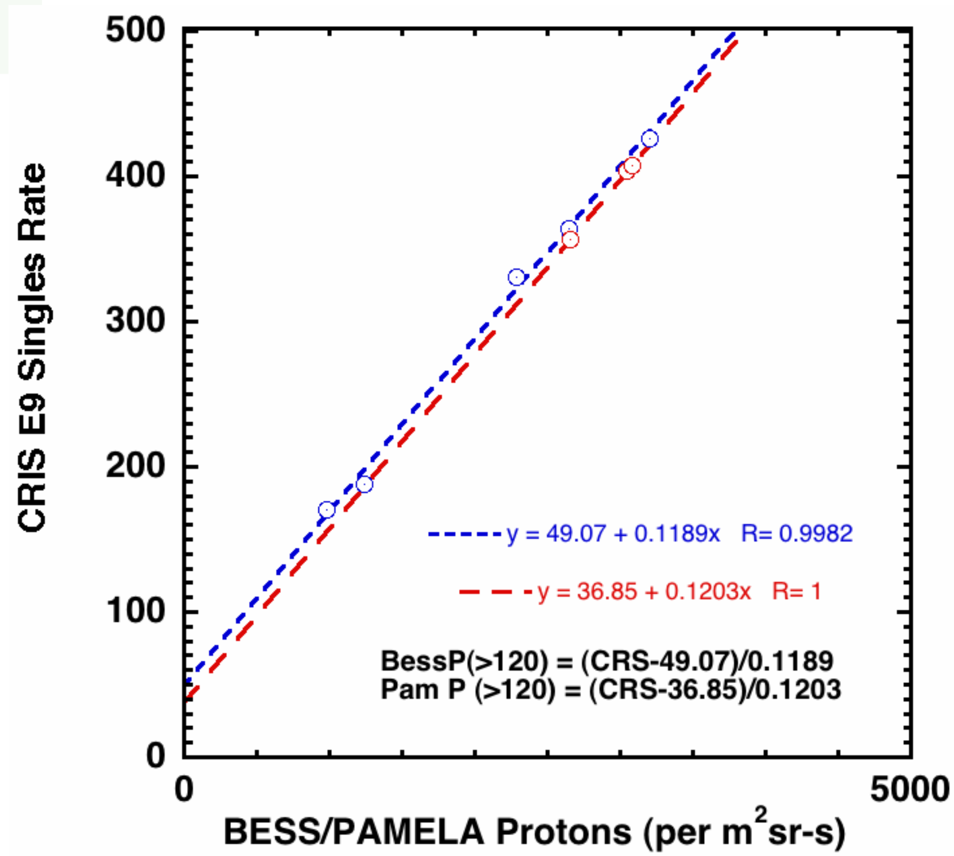




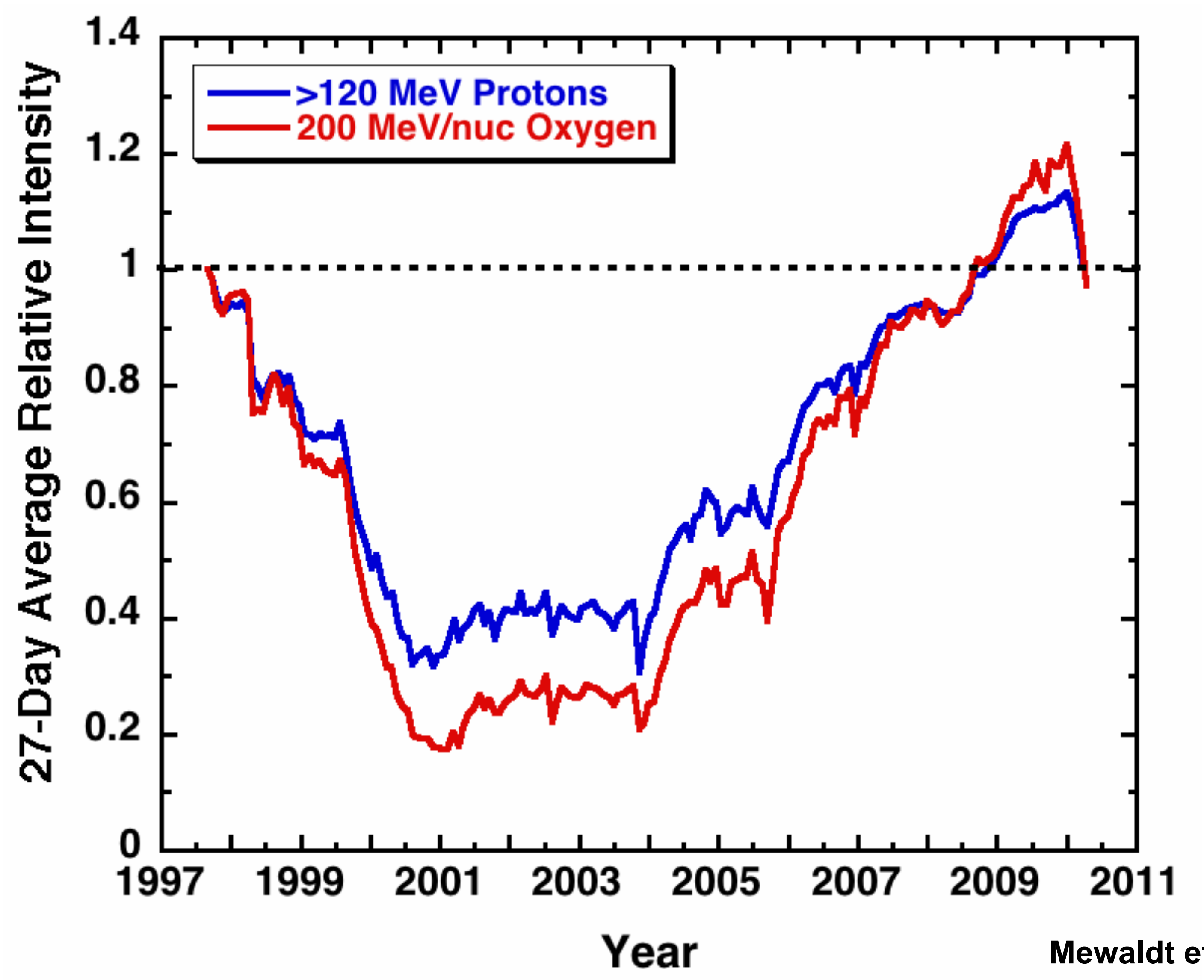


PAMELA Spectra 7/2006, 8/2007, 2/2008
(Casolino et al. 2009)

Compare BESS and PAMELA Calibrations agree to within 2%



Measure >120 MeV excess of 13.7 ± 2.0%
Radiation dose increases by 14 ± 2%



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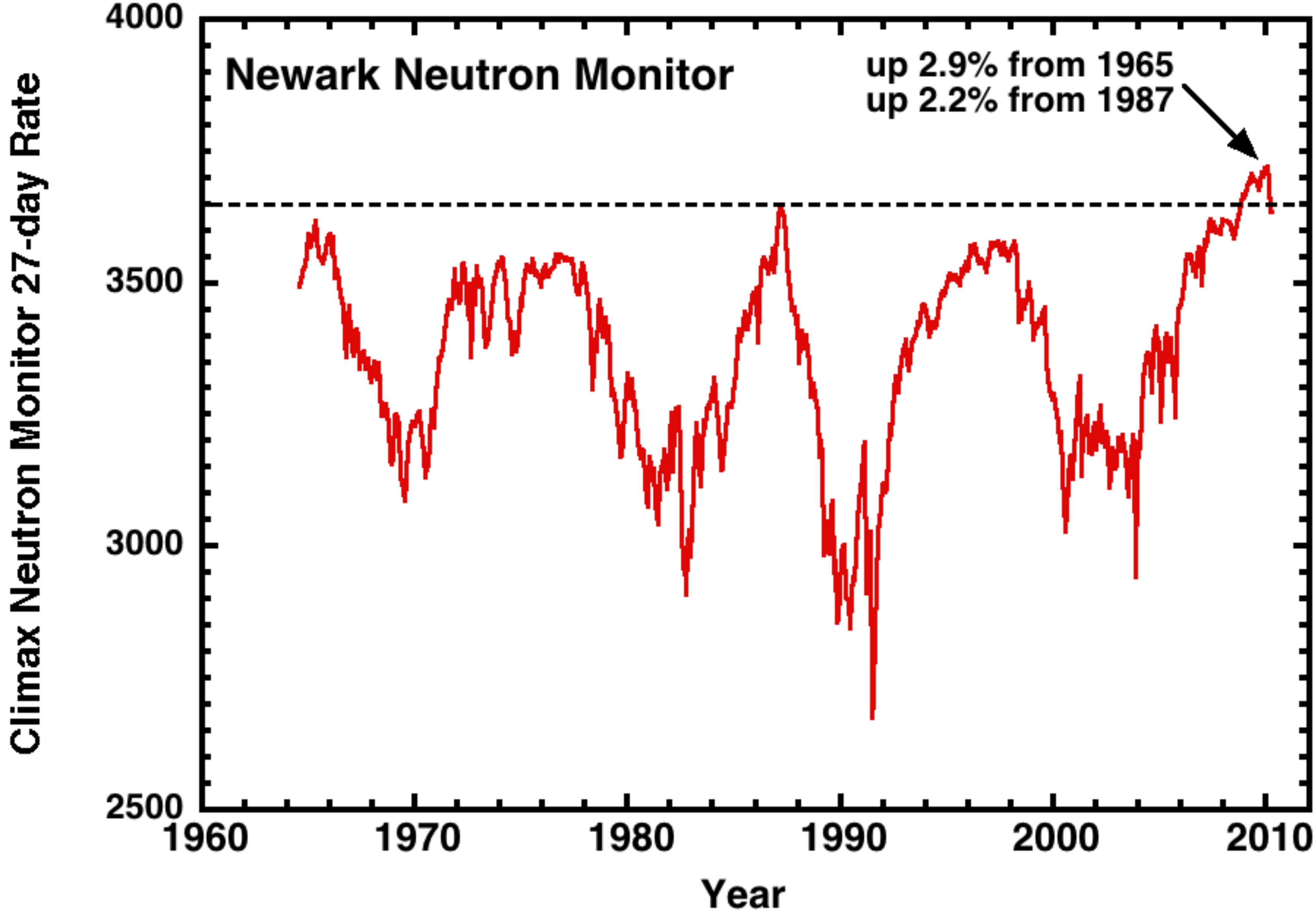
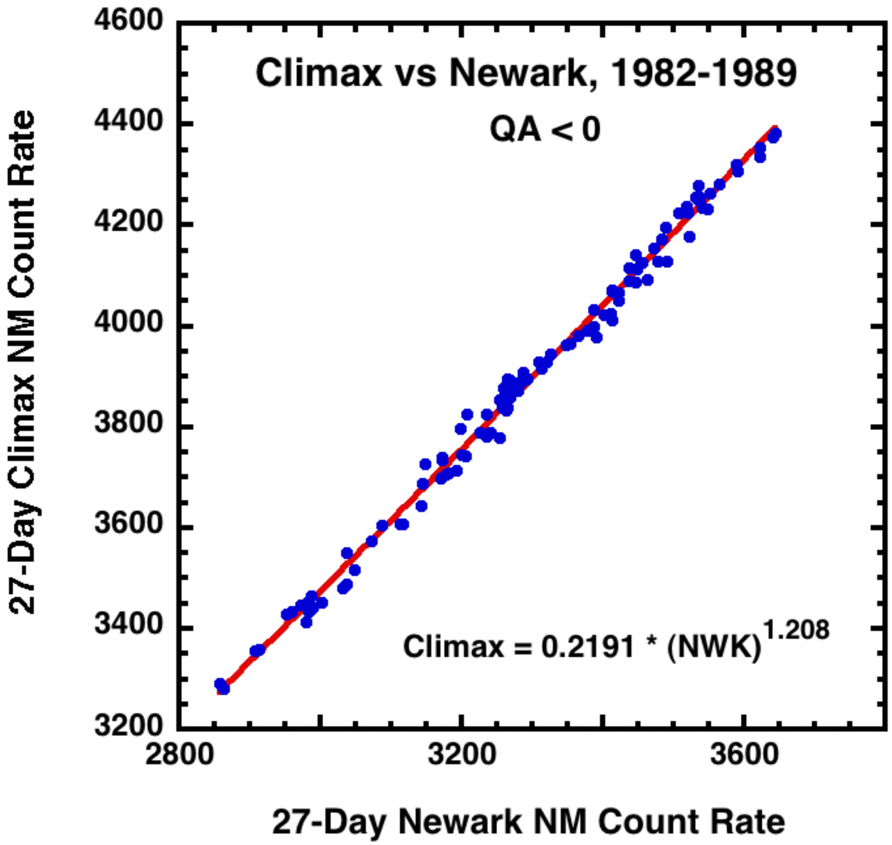
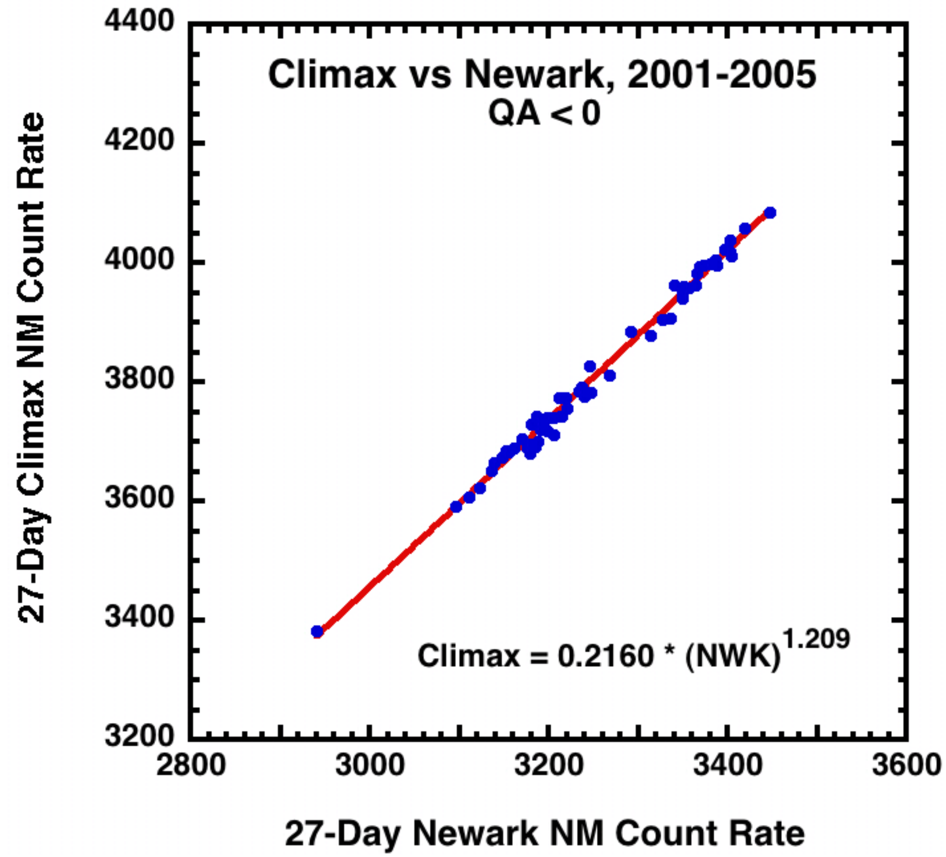

Newark Neutron Monitor
up 2.9% from 1965
up 2.2% from 1987
Climax Neutron Monitor 27-day Rate
4000
3500
3000
2500
1960
1970
1980
1990
2000
2010
Year

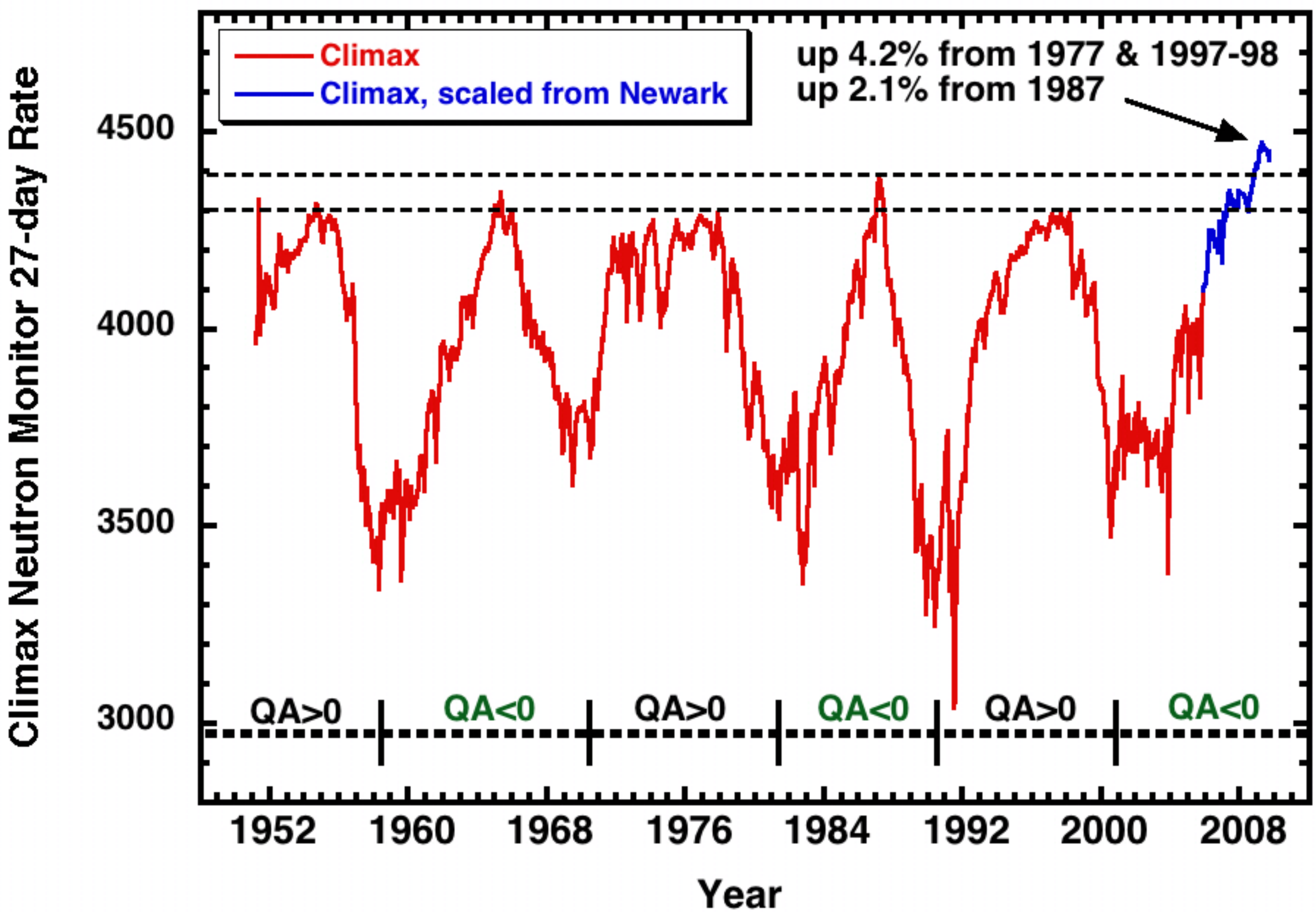
What would the Climax Neutron Monitor be reading in 2009?



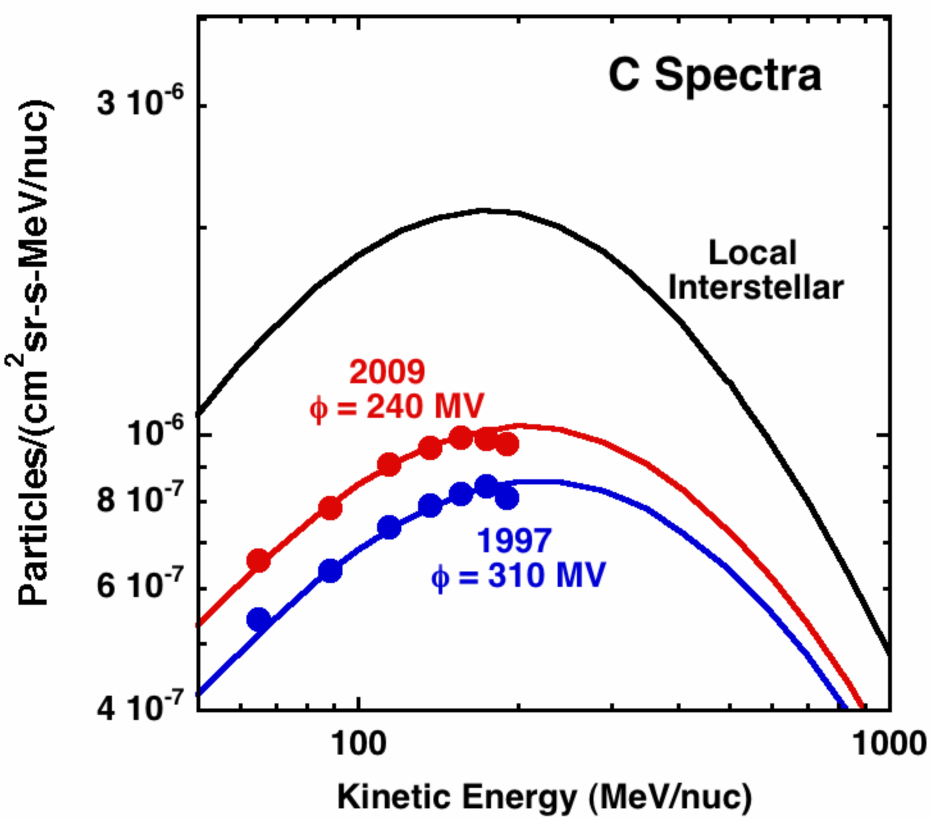


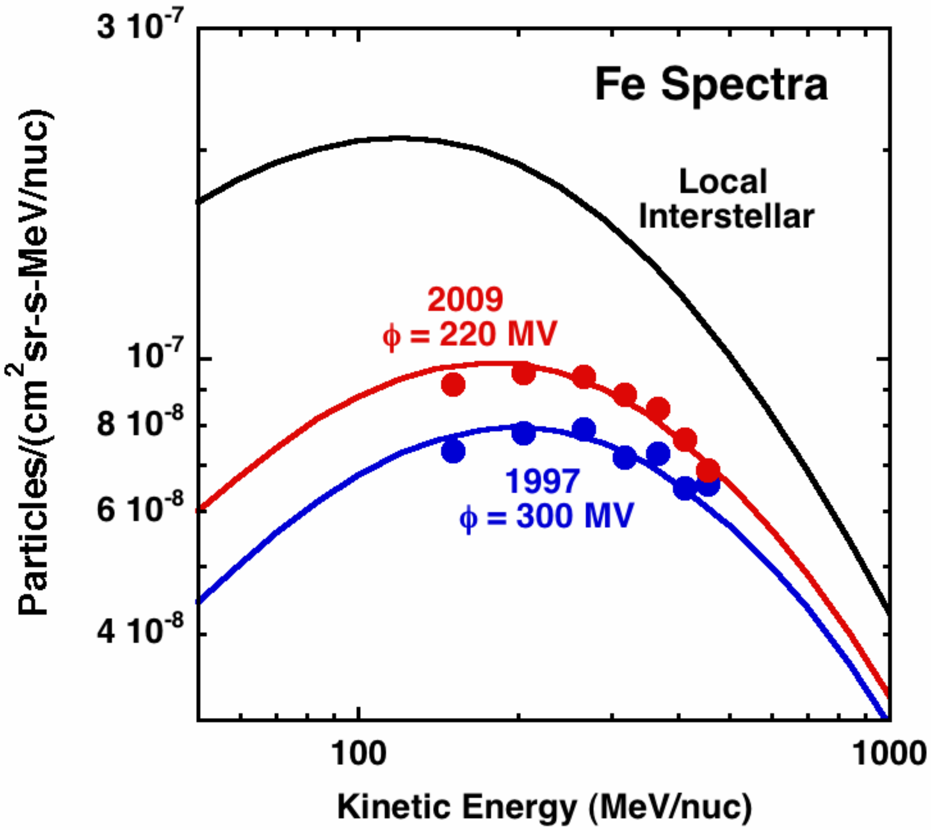
To project the Climax NM rate past 2005 when it was de-commissioned in late 2005 we use data from earlier QA < 0 periods from the Newark NM (with a similar cutoff rigidity). The 1982-1989 and 2001-2005 comparisons give similar fits and we use the average of these fits for scaling data from 2006-2009. As a check, the predicted and actual peak rates in 1965 (also QA < 0), agree to within 0.1%.

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



Cosmic Ray Energy Spectra





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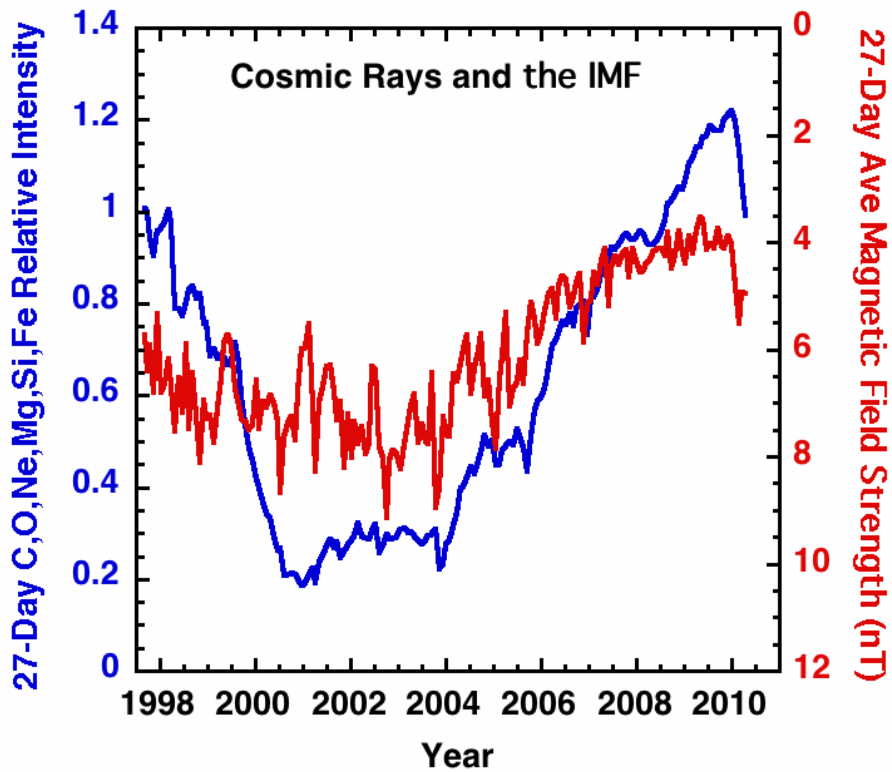
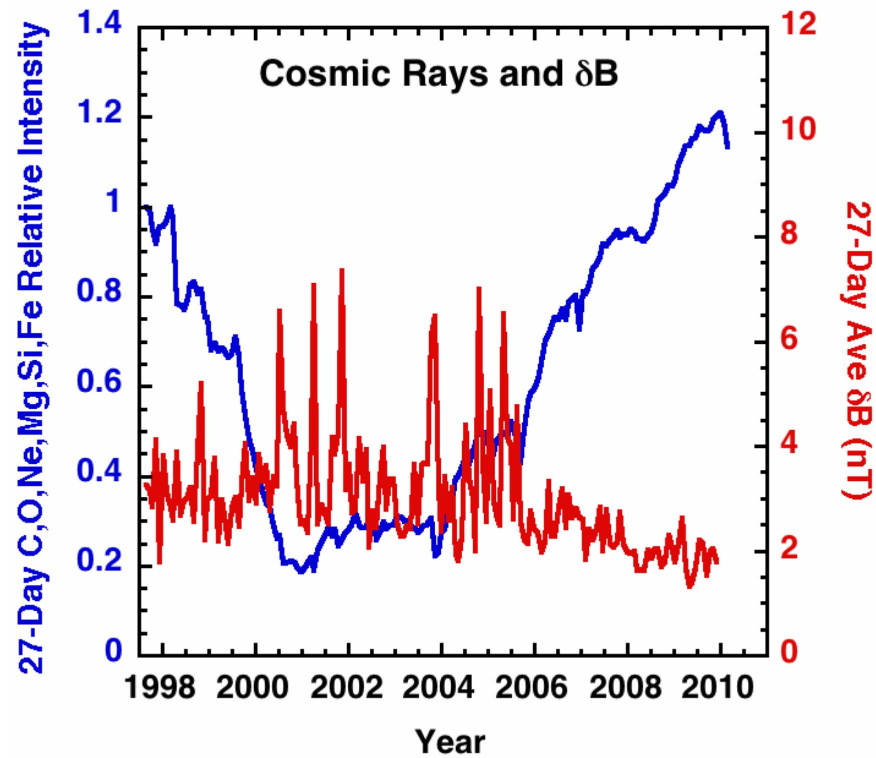
ACE/CRIS Data

Solar/Interplanetary parameters affecting cosmic ray intensity:

1) **The interplanetary magnetic is at its lowest level of the space age (Smith & Balogh 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
- Common to assume diffusion coefficient of Kappa ~ 1/B





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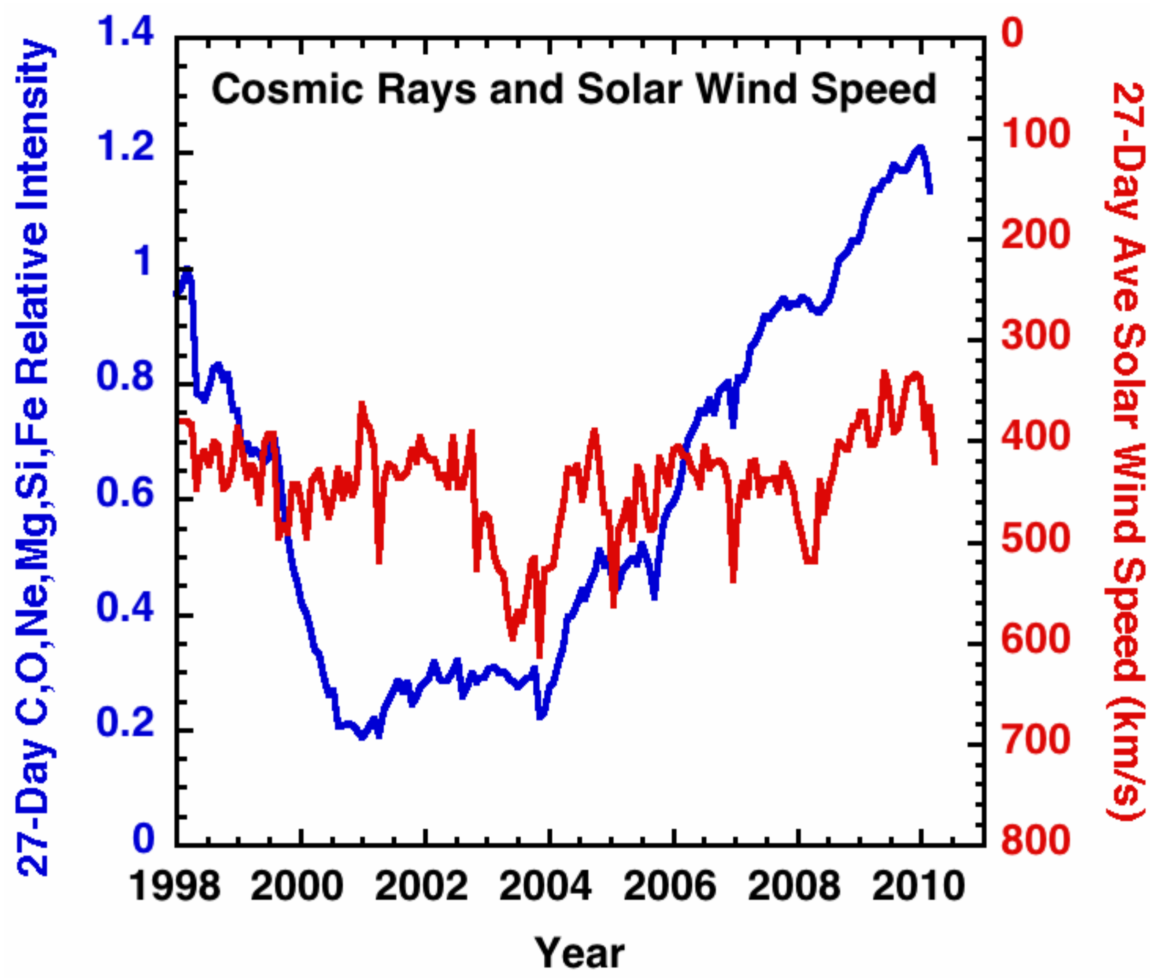
ACE/MAG & CRIS data

Solar/Interplanetary parameters affecting cosmic ray intensity:

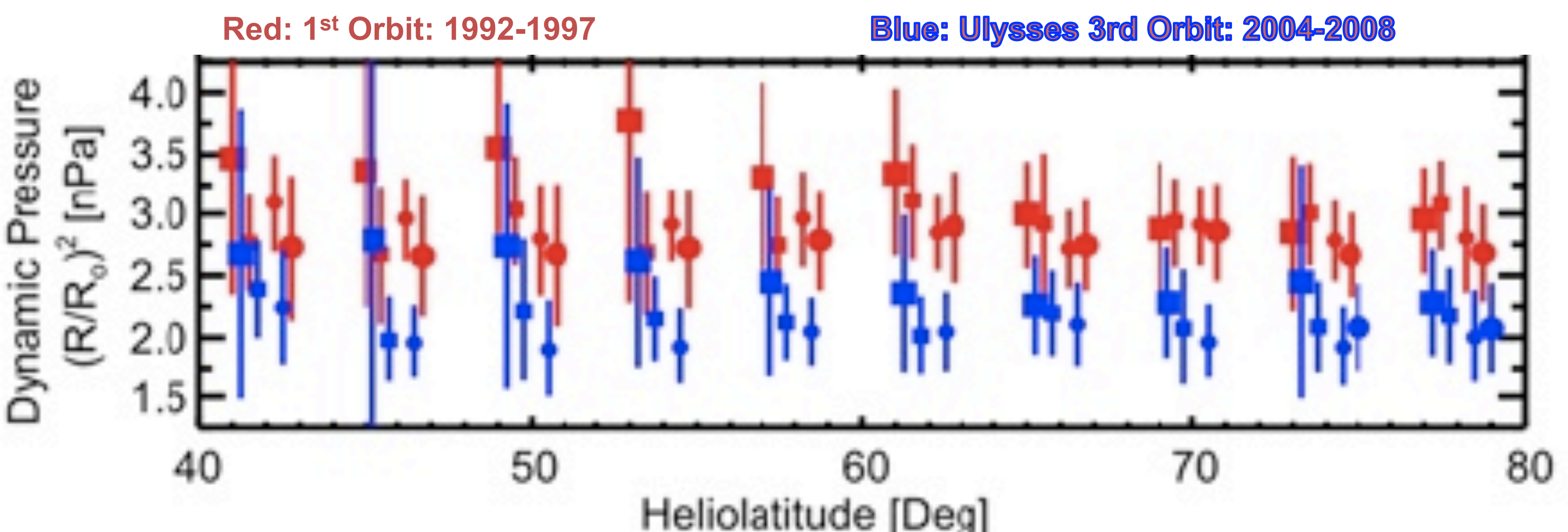
2) Solar Wind Velocity (Vsw)

- **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**



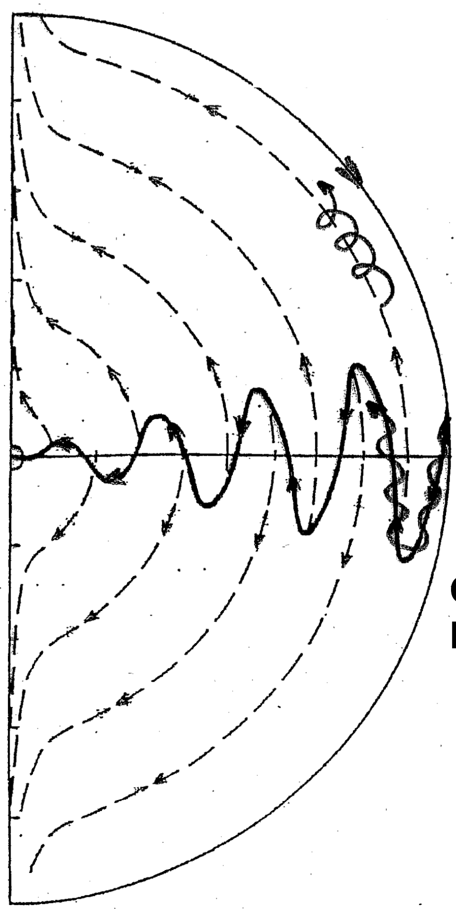
McComas et al., 2008

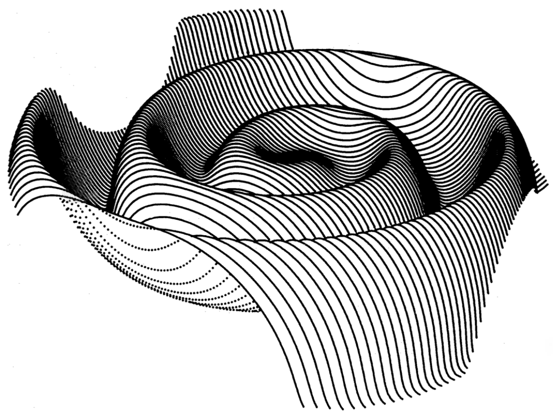
Solar/Interplanetary parameters affecting cosmic ray intensity:
4) Tilt of the heliospheric current sheet

Levy (1975, 1976), and Jokipii & Levy (1977); showed that drifts play a major role in cosmic ray transport.

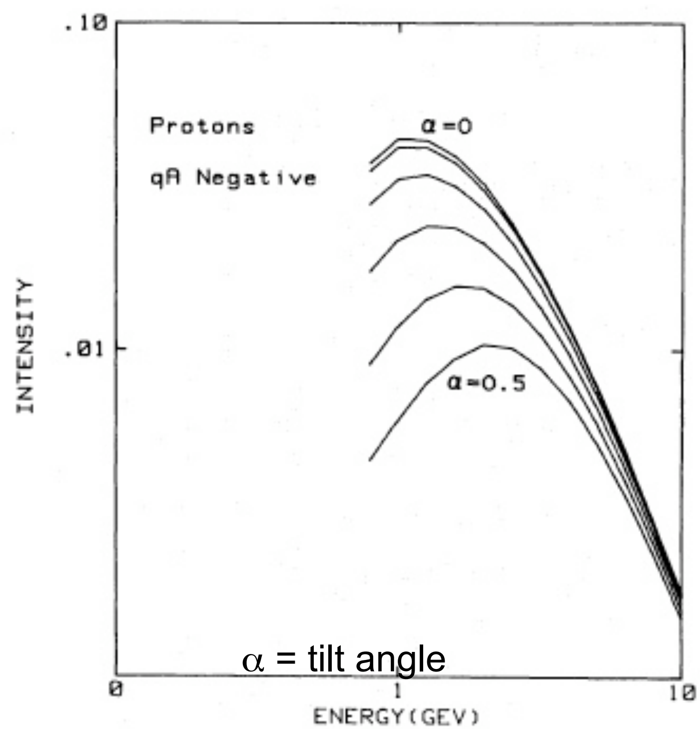
During A < 0 positively-charged ions drift in along the current sheet. As a result, their 1-AU intensity is sensitive to the HCS tilt

Sun





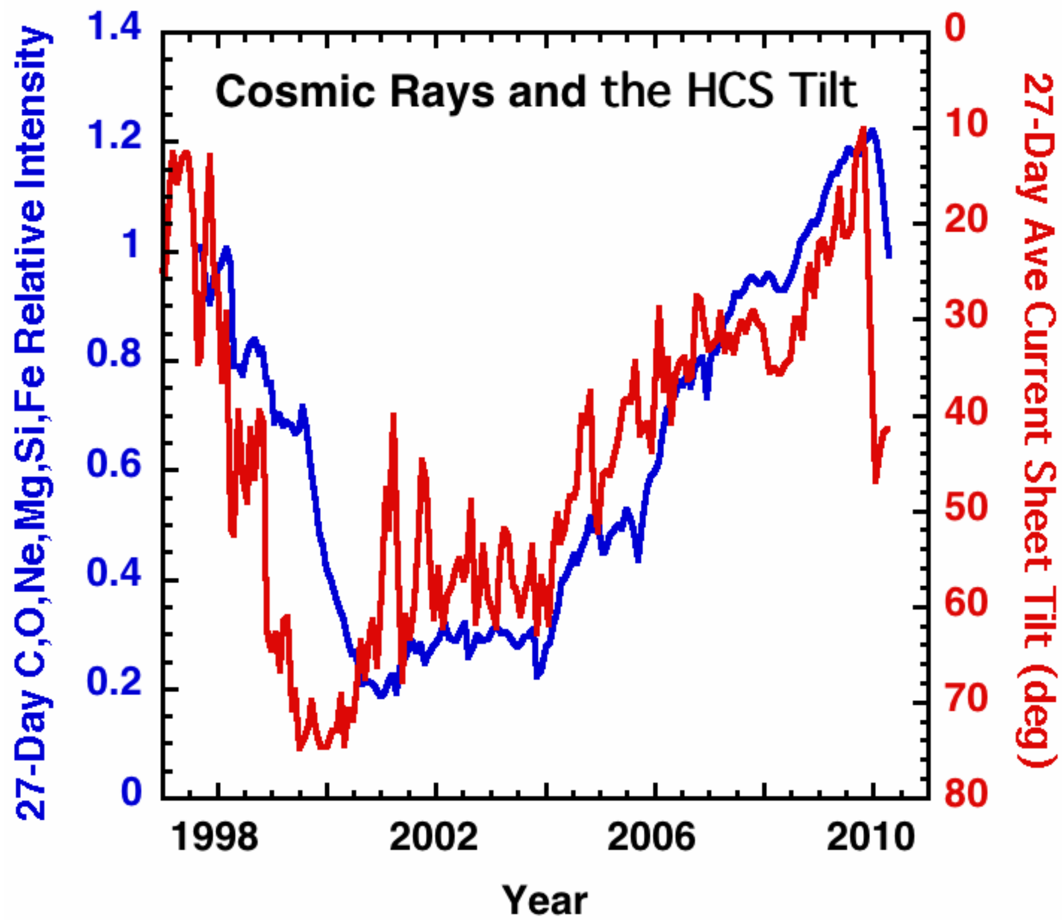
QA < 0 drift patterns.
Drift velocities ≥ Vsw



Jokipii and Thomas, 1981

Cosmic Ray Intensities and the Tilt-Angle of the Heliospheric Current Sheet

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



HCS tilt data from Wilcox Solar Observatory

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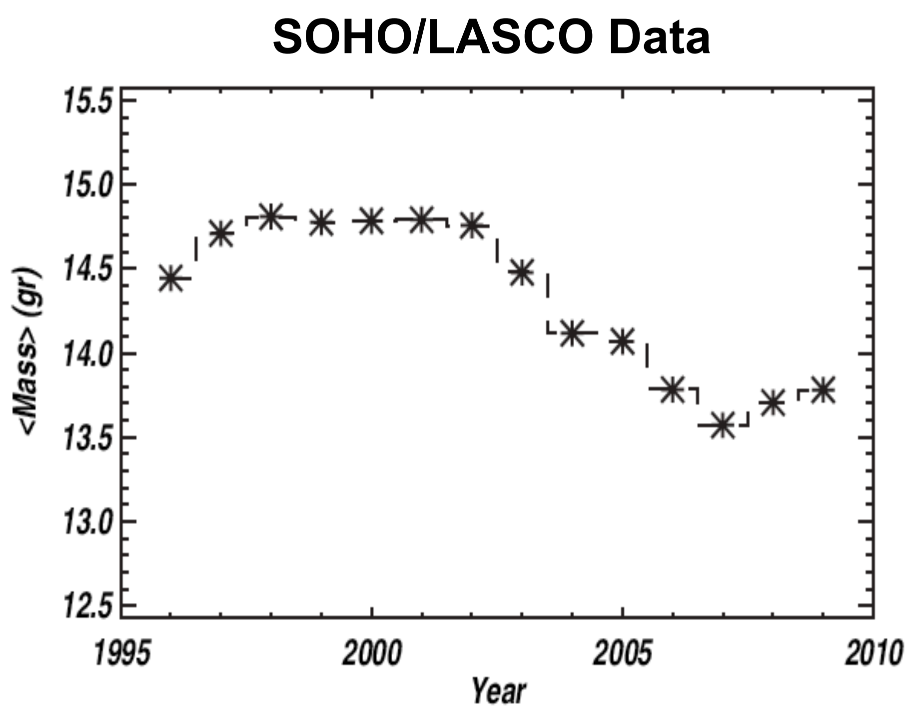
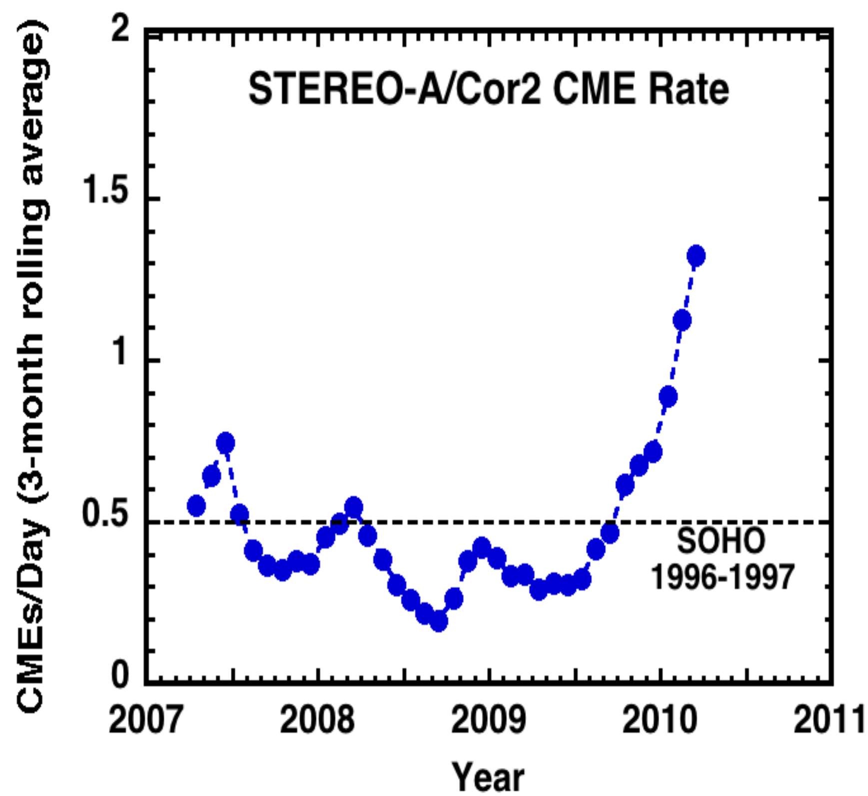
Solar/Interplanetary Parameters affecting cosmic ray intensity:

5) 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**

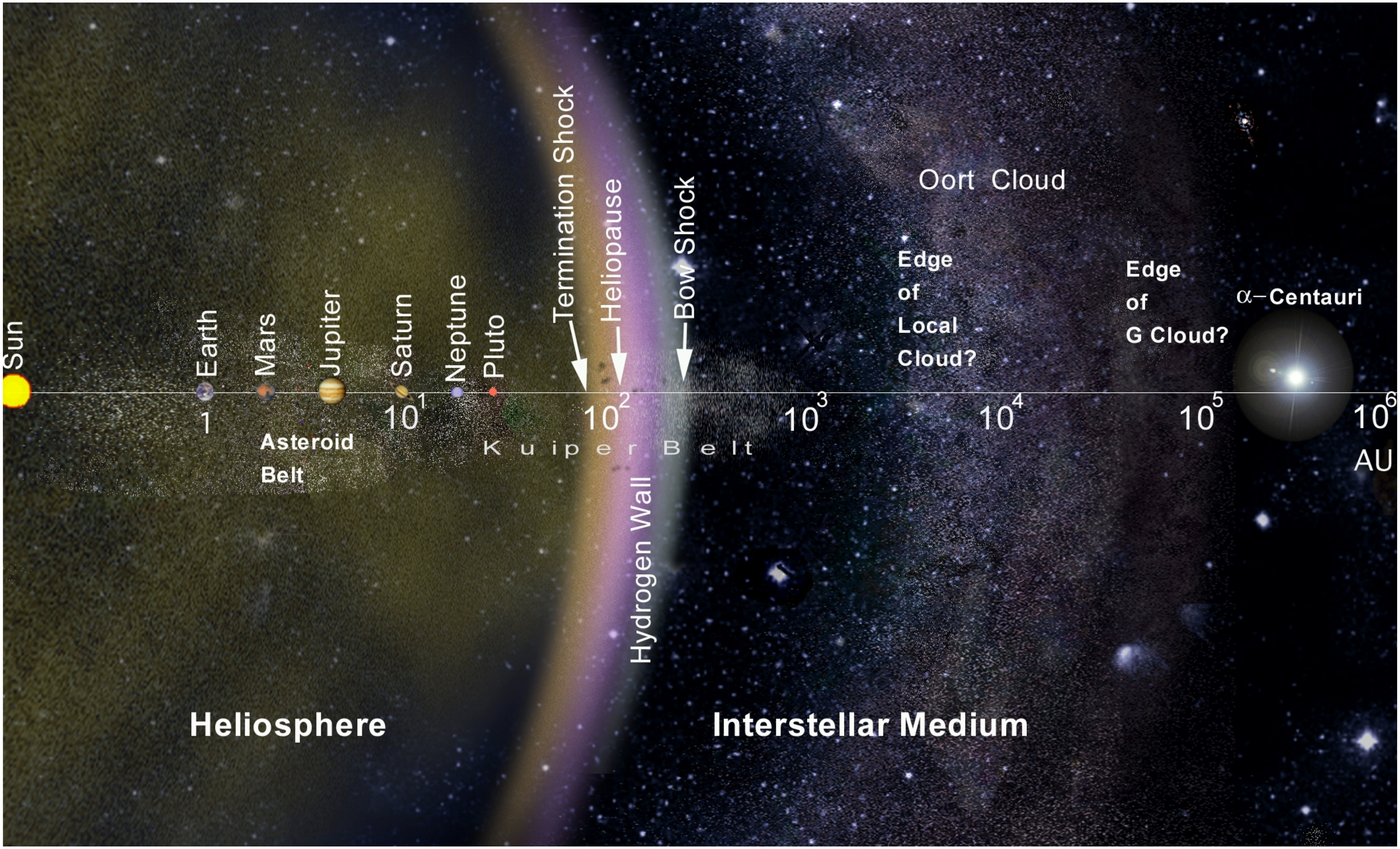


Vourlidas et al. (2010)

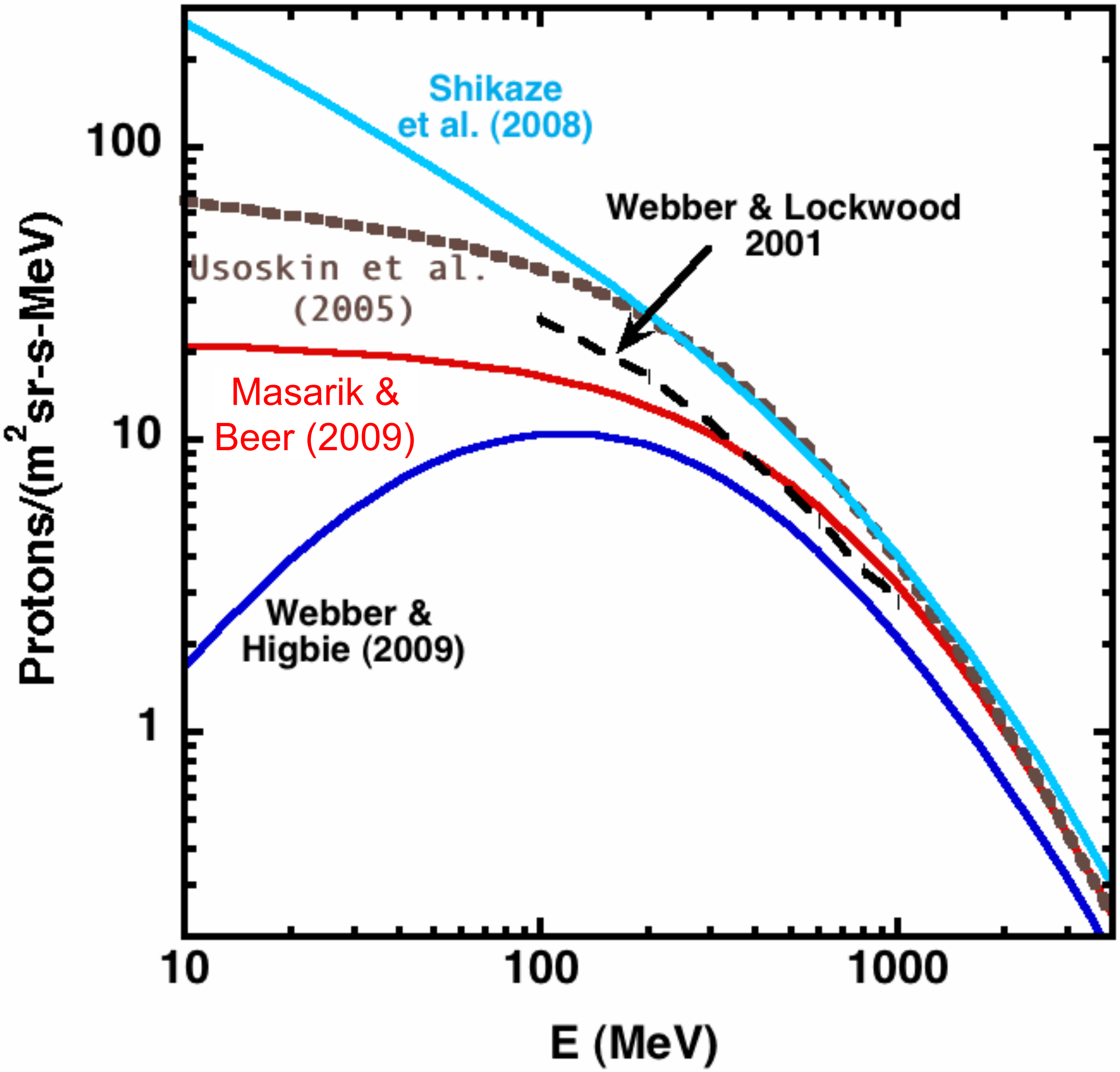


(Robbrecht et al.2009; St. Cyr, 2009)

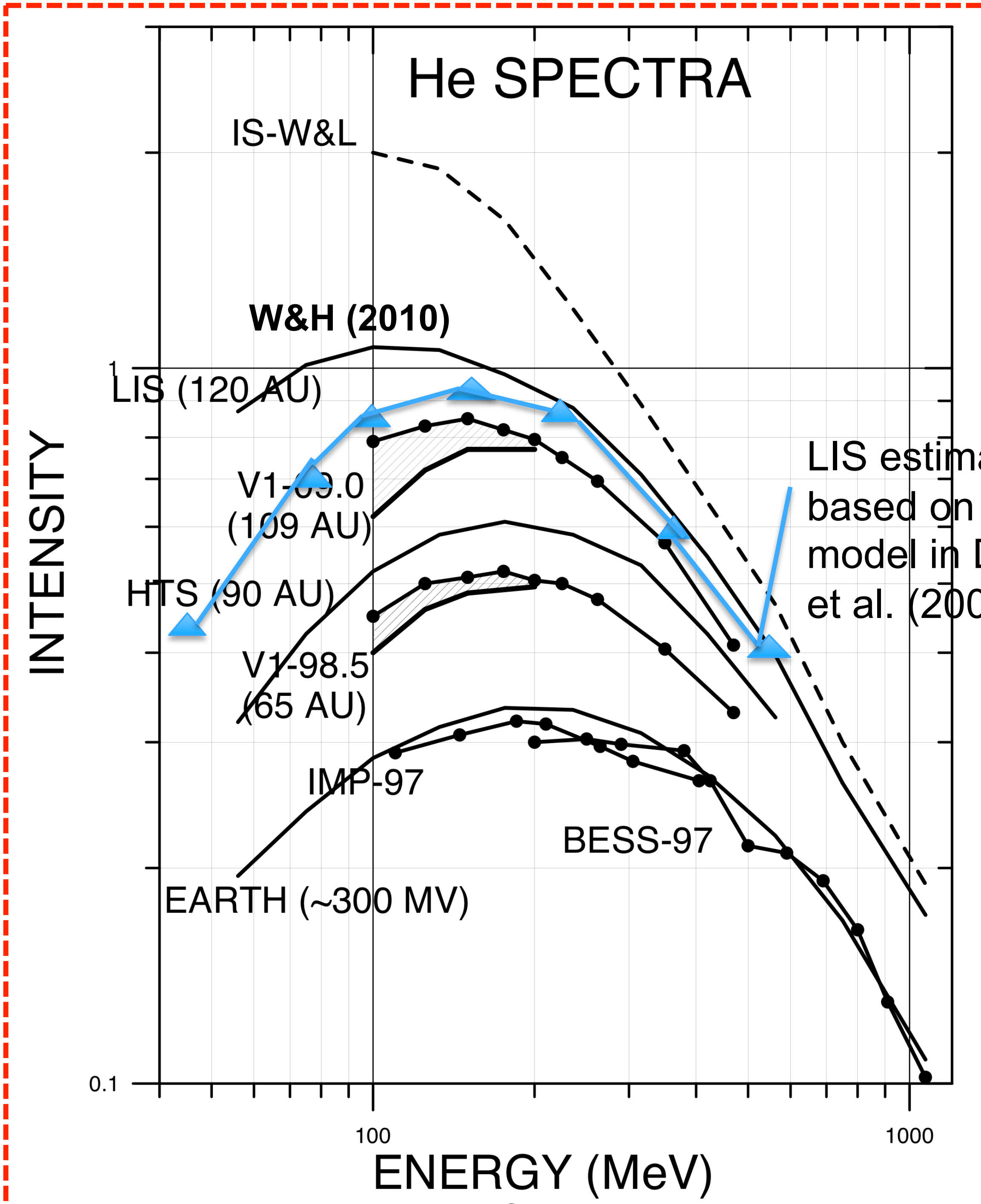
In the next few year Voyager-1 will enter our nearby galactic neighborhood where it may measure local-interstellar GCR spectra



Comparison of LIS Spectra for Hydrogen



Voyager may distinguish between these and other possibilities.



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

Summary

- The current solar minimum created "perfect storm" conditions for "super-fluxes" of cosmic rays at 1 AU.
  - weakened <B>
  - reduced <δB>
  - reduced CME rate, mass, and kinetic energy
  - slower solar wind
  - 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

Key Questions:

What are the local interstellar spectra (LIS)? They will reveal the maximum GCR intensity in the past (and the future). They could potentially limit the interpretation of ^{10}Be in ice cores

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