Implications of the Worsening GCR Radiation Environment

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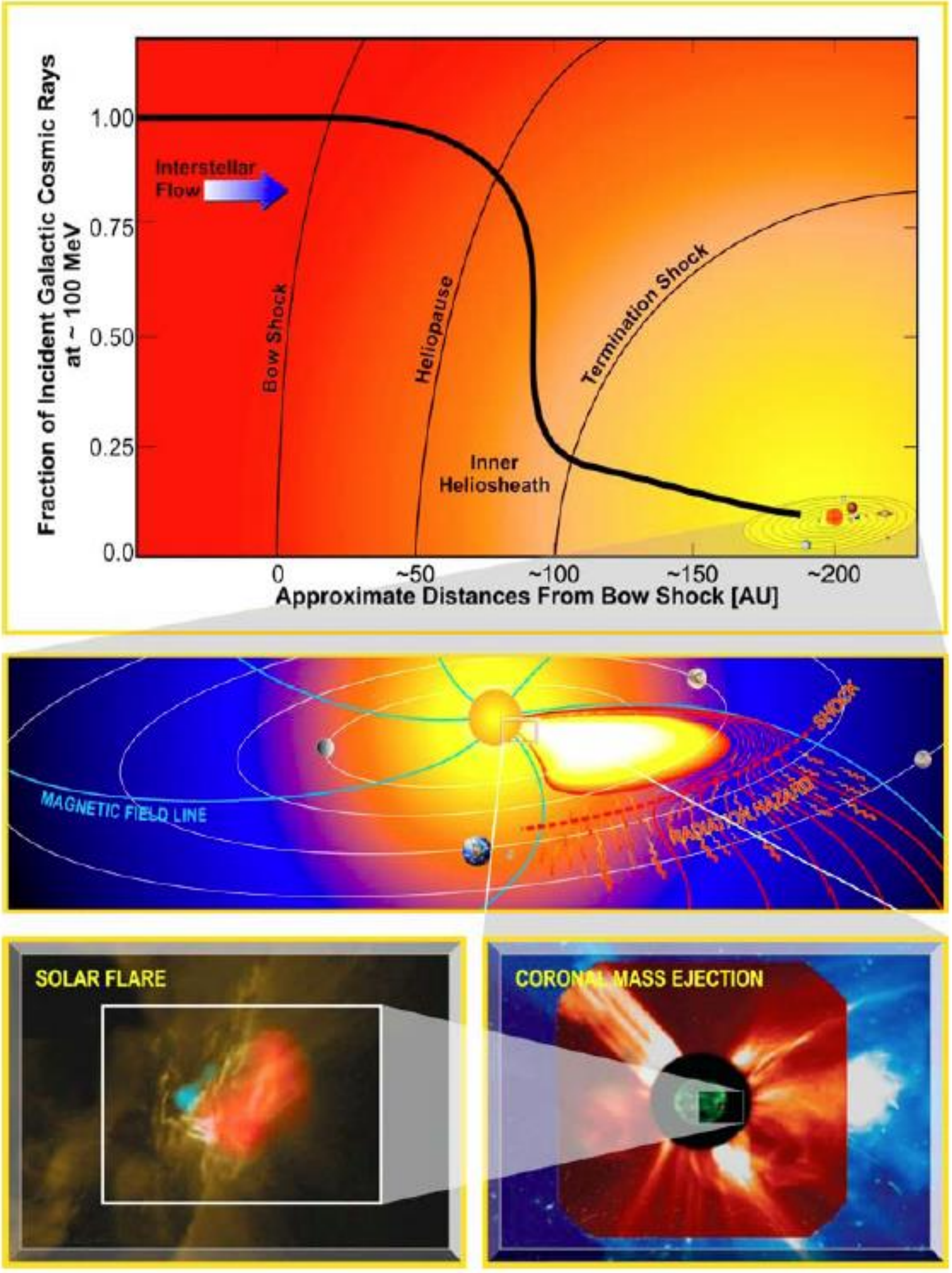
- GCRs from the Galaxy and Beyond

- SEPs from Flares and CMEs



AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE

10.1002/2014SW001084

Special Section:
The Crater Special Issue of Space Weather: Building the Observational Foundation to Deduce Biological Effects of Space Radiation

Key Points:

- GCR radiation is increasingly hazardous
- Radiation limited duration for missions in deep space
- Timing during solar cycle of missions remains a critical factor

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Does the worsening galactic cosmic radiation environment observed by CRaTER preclude future manned deep space exploration?

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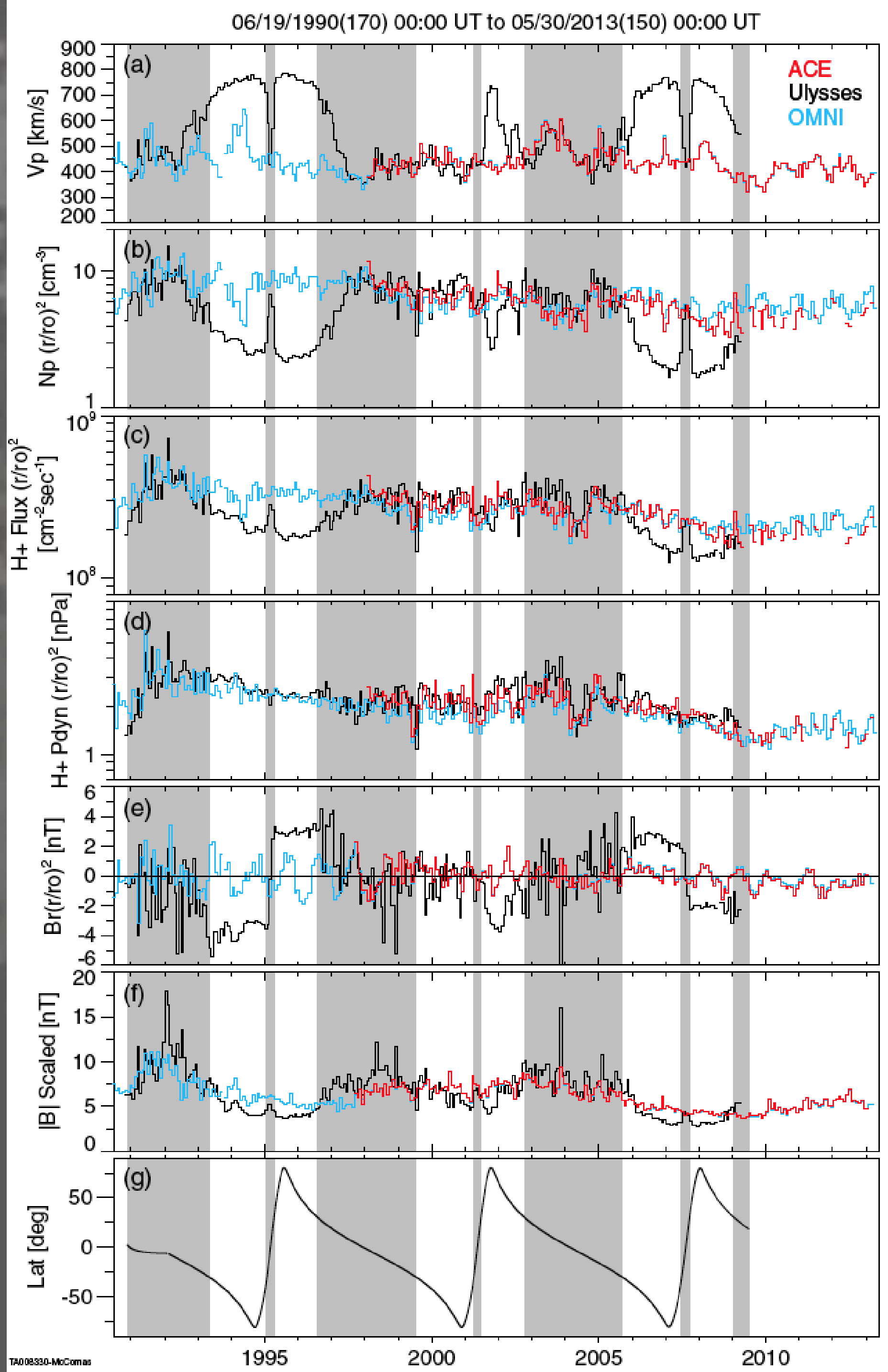
Abstract The Sun and its solar wind are currently exhibiting extremely low densities and magnetic field strengths, representing states that have never been observed during the space age. The highly abnormal solar activity between cycles 23 and 24 has caused the longest solar minimum in over 80 years and continues into the unusually small solar maximum of cycle 24. As a result of the remarkably weak solar activity, we have also observed the highest fluxes of galactic cosmic rays in the space age and relatively small solar energetic particle events. We use observations from the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) on the Lunar Reconnaissance Orbiter to examine the implications of these highly unusual solar conditions for human space exploration. We show that while these conditions are not a show stopper for long-duration missions (e.g., to the Moon, an asteroid, or Mars), galactic cosmic ray radiation remains a significant and worsening factor that limits mission durations. While solar energetic particle events in cycle 24 present some hazard, the accumulated doses for astronauts behind 10 g/cm^2 shielding are well below current dose limits. Galactic cosmic radiation presents a more significant challenge: the time

Protracted Min (23) and Mini Max (24)

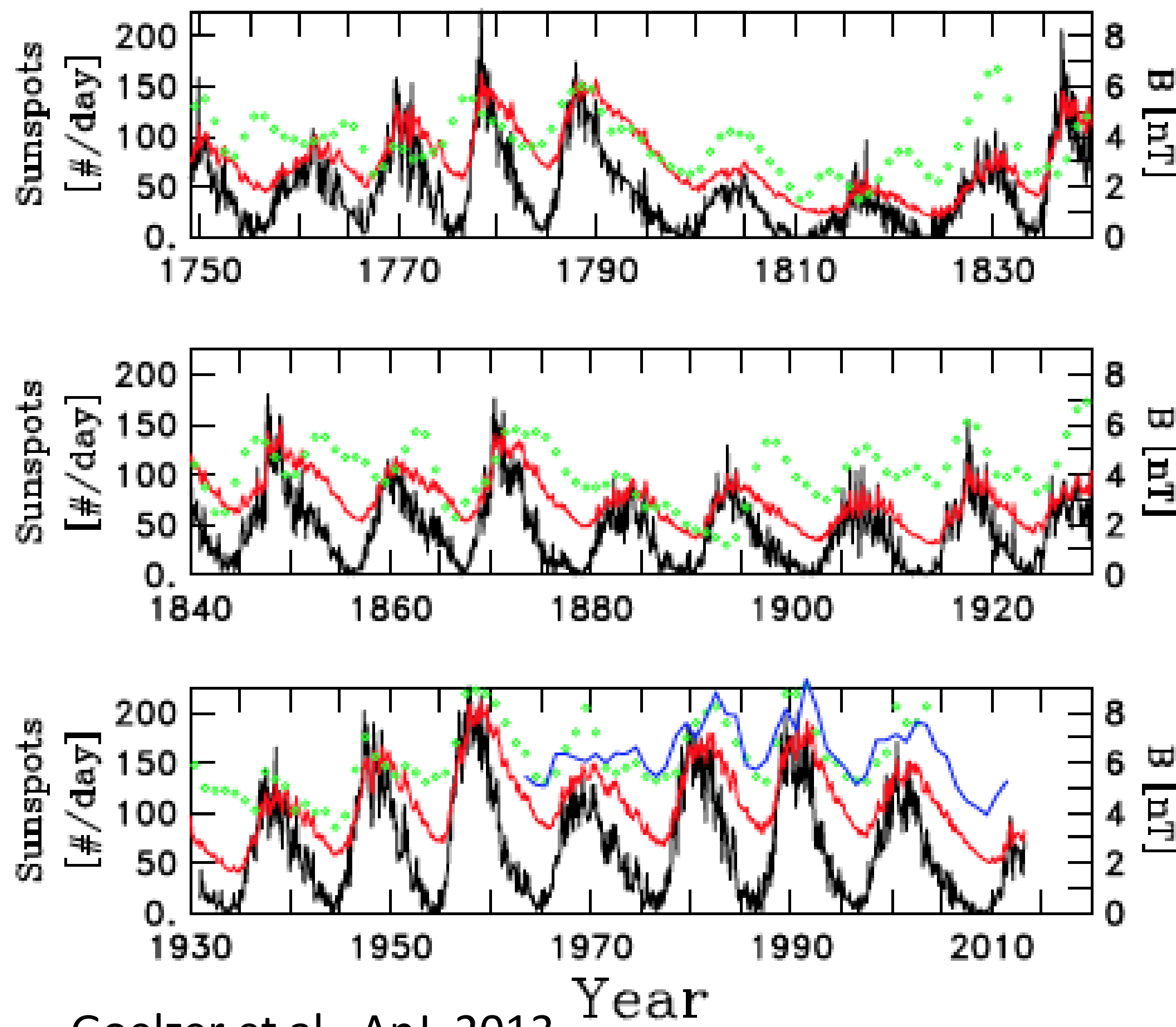
- Dropping solar wind
  - Flux
  - Pressure
  - Magnetic Field
- Continues trend observed by Ulysses

McComas et al., ApJ, 2013



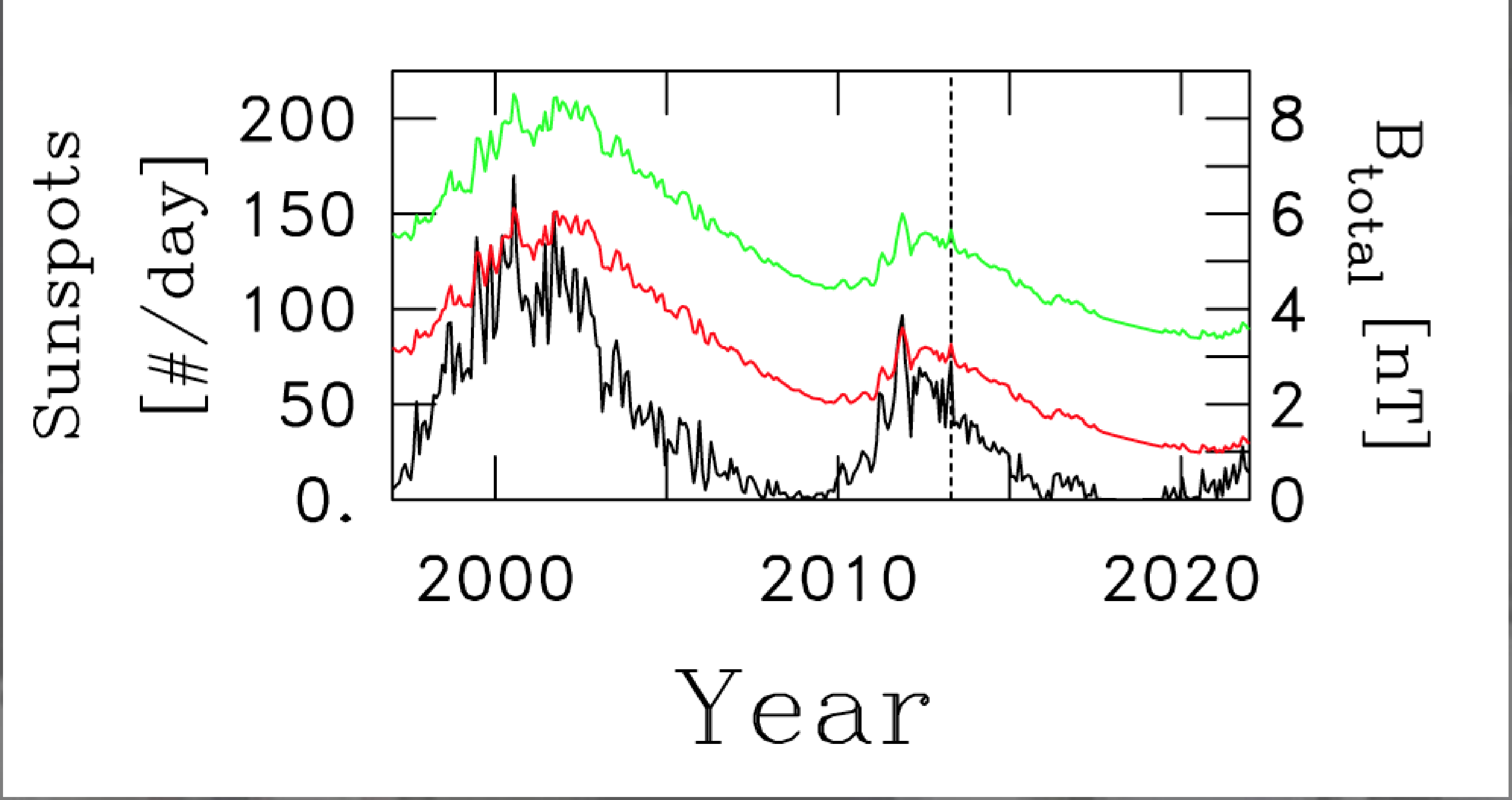
Long-term Record of Magnetic Field & SSN

- SSN (black)
- Predicted (red)
- OMNI (blue)
- ^{10}Be (green)
- Magnetic Flux Balance (Schwadron et al.,, 2010)



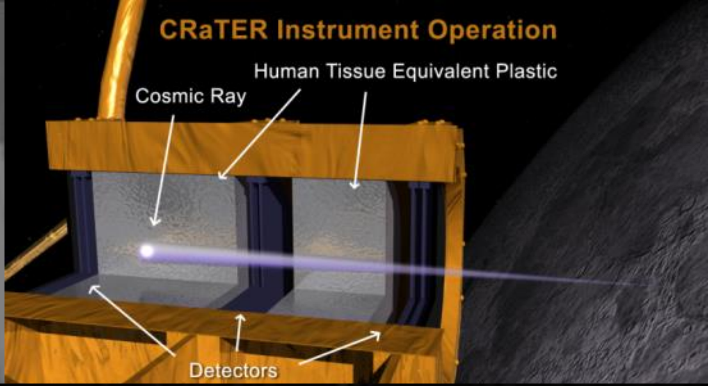
Goelzer et al., ApJ, 2013

Continued Decay of Magnetic Flux in the Dalton-like Minimum



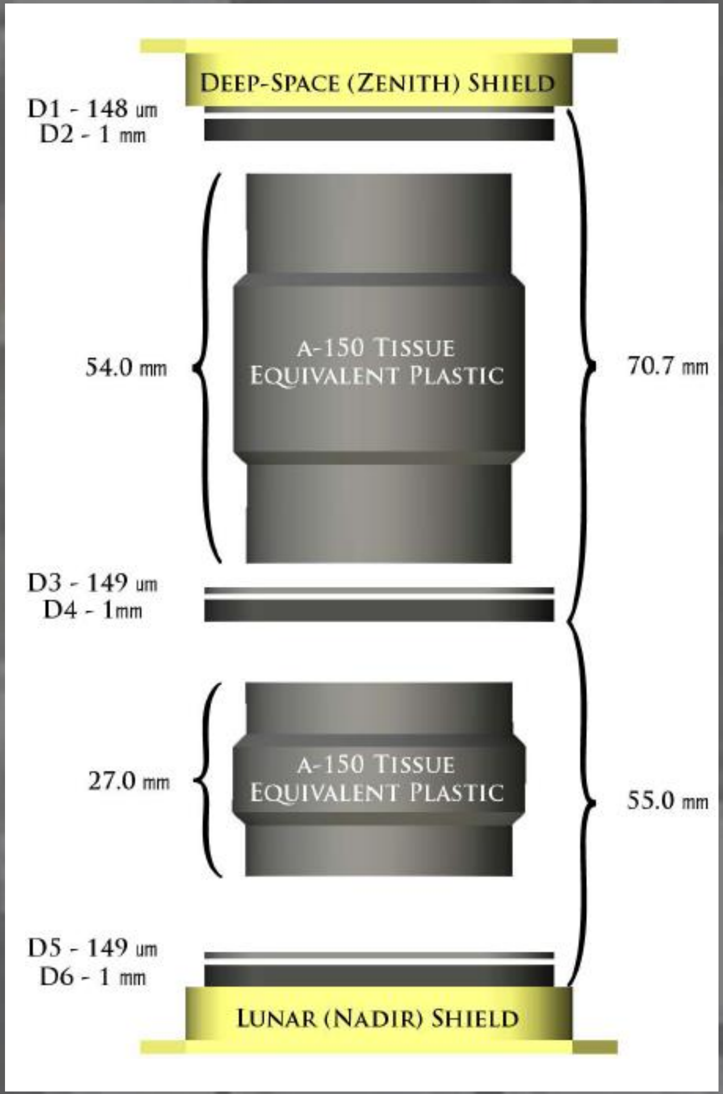
Goelzer et al., ApJ, 2013

CRaTER Concept of Operations



Quick CRaTER Overview

- Measures > 12 MeV/nuc particles
- 6 detectors (D1-D6) with Tissue Equivalent Plastic (TEP) between pairs of detectors
  - Thick and thin detectors with different gains allow a large range of Linear Energy Transfer (LET) to be sampled
  - TEP mimics absorption of energy by human tissue as radiation passed through telescope
- Senses particles from zenith and nadir directions
- Any energy deposit in any detector triggers an 'event', in which all energy deposits from all detectors are recorded
- Data products are in terms of LET, the amount of energy deposited per path-length ($\Delta E/\Delta x$) as a particle transits through detector



Slab Turbulence Model for Modulation of Galactic Cosmic Rays

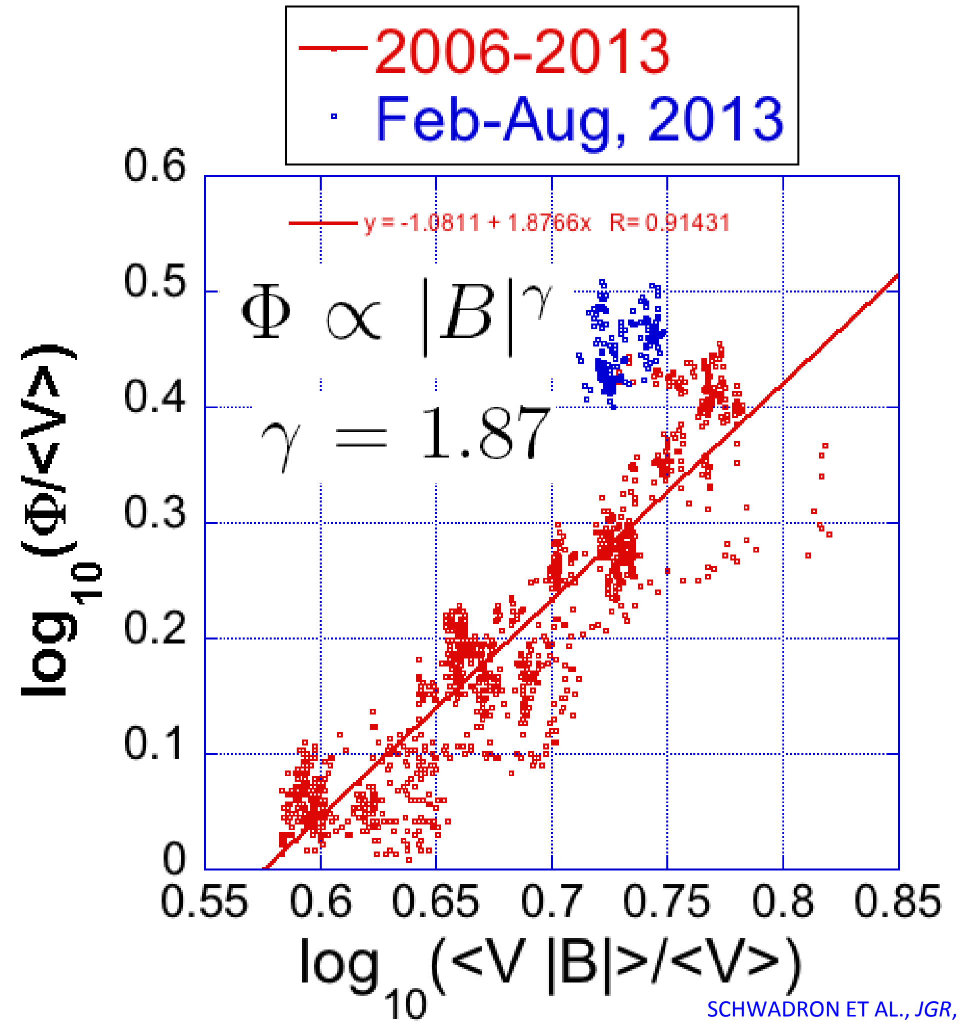
- Modulation Potential characterizes evolution of GCRs fluxes (protons & heavy ions)

$$\Phi = |Ze|\phi(r)$$

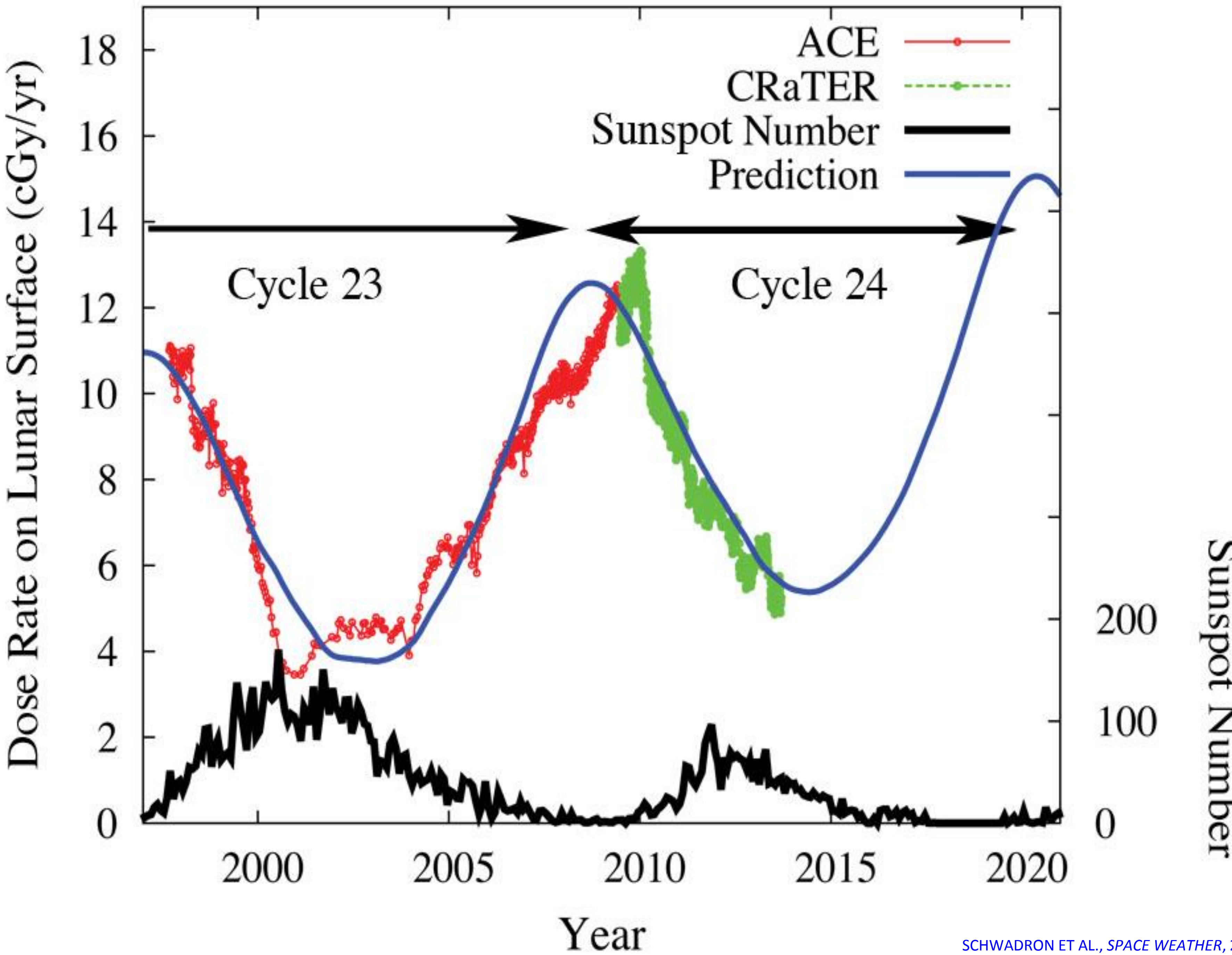
$$\phi(r) = \int_r^{R_b} dx \frac{V(x)}{3\kappa_1(x)}$$

$$\kappa_{||} \propto r_g^2/F^2 \quad F = \delta B/B$$

$$\Phi \propto B^2$$



SCHWADRON ET AL., *JGR*, 2012

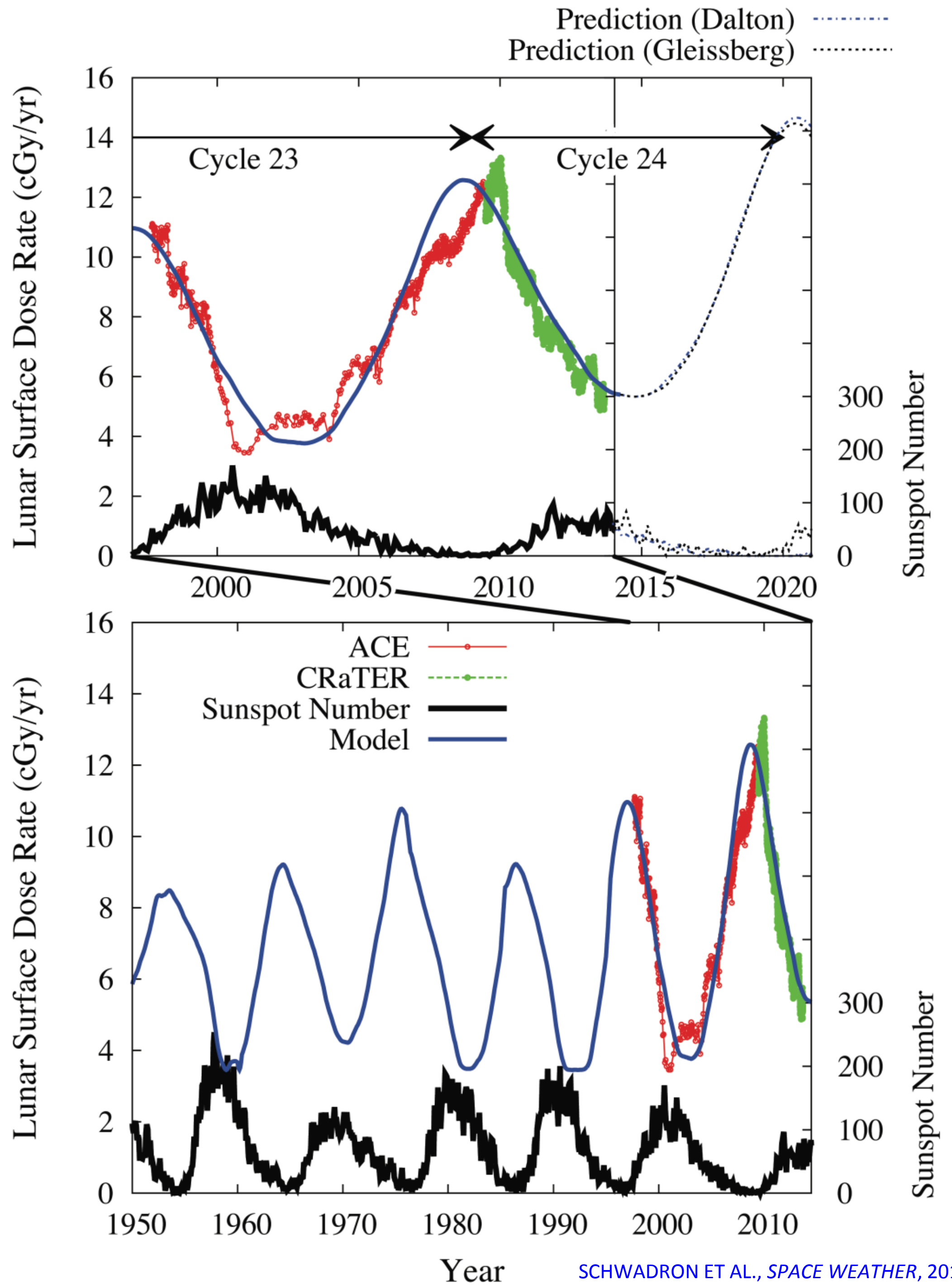


SCHWADRON ET AL., *SPACE WEATHER*, 2014a

Details about the Modeling

- GCR fluxes modeled using slab-turbulence + force-free model
  - Similar model as Badhwar O'Neill, however modulation potential scaled differently based on observations
- Utilize a three-layer version of HZETRN 2005 and HZETRN 2010 for modeling doses, dose-equivalents, and effective dose

- Longer-term trend deduced from observed Heliospheric Magnetic field
- Continues trend observed by ACE and CRaTER



SCHWADRON ET AL., *SPACE WEATHER*, 2014a

3% Risk for Exposure Induced Death

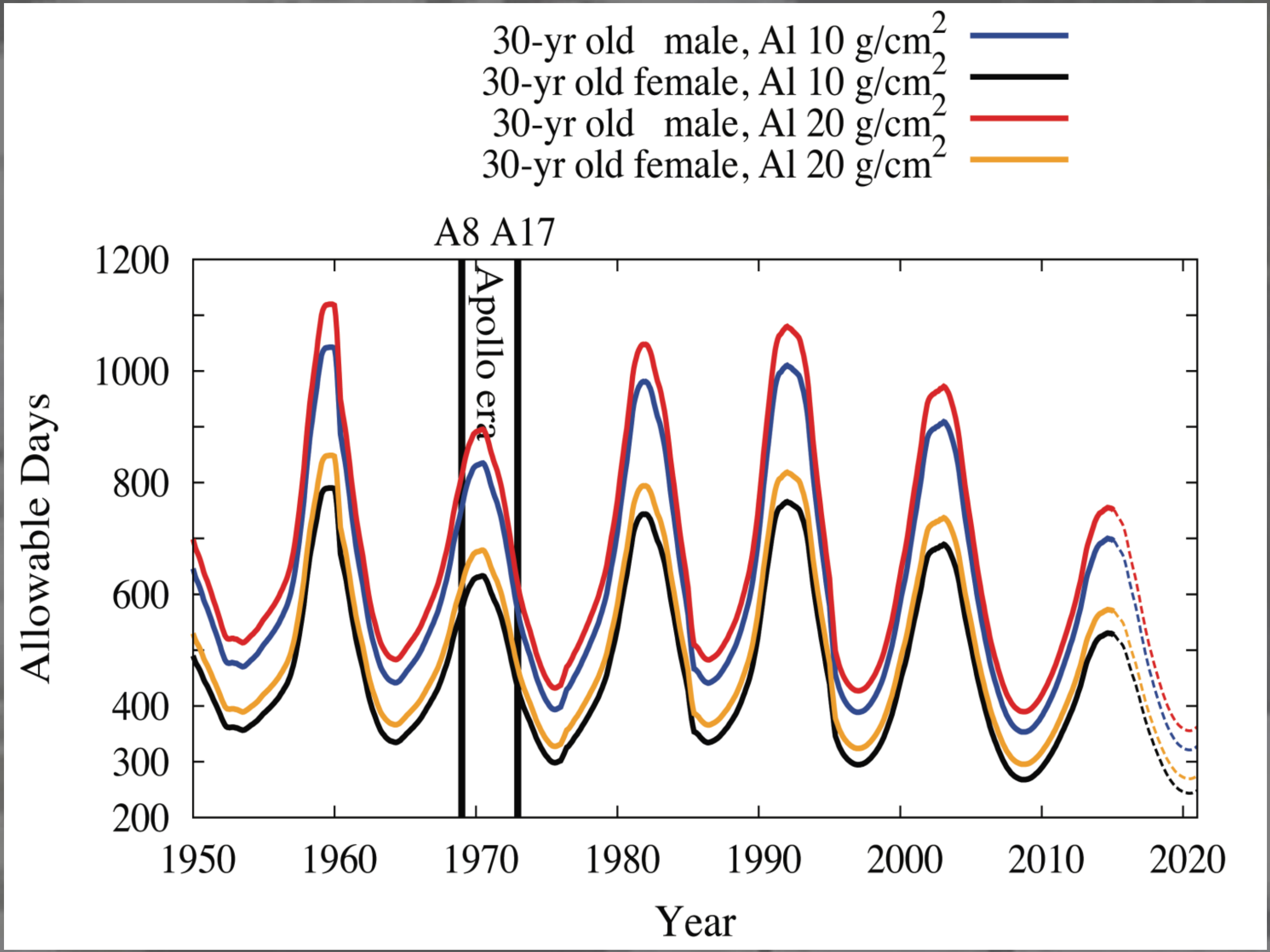
Age	3% REID Male E (cSv)	3% REID Female E (cSv)
30	62	47
45	95	75
55	147	112

Managing Space Radiation Risk in the New Era of Space Exploration
Committee on the Evaluation of Radiation Shielding for Space Exploration, National Research Council 2008

Note: E. Semones will present an updated approach to risk

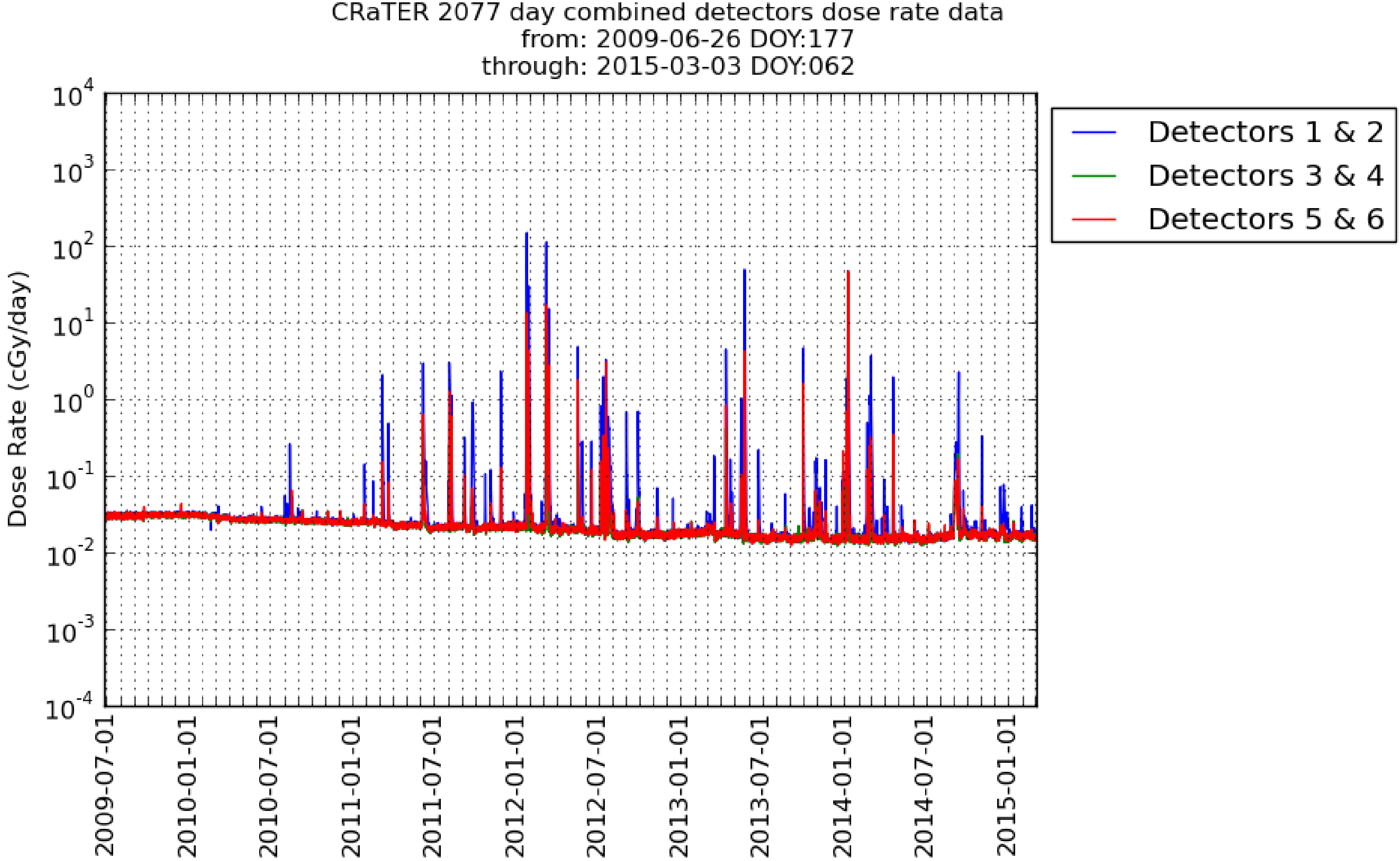
Implications of the Changing Space Weather Environment

- HZETRN used to derive effective dose rate
- "Allowable days" simply the effective dose limit/effective dose rate



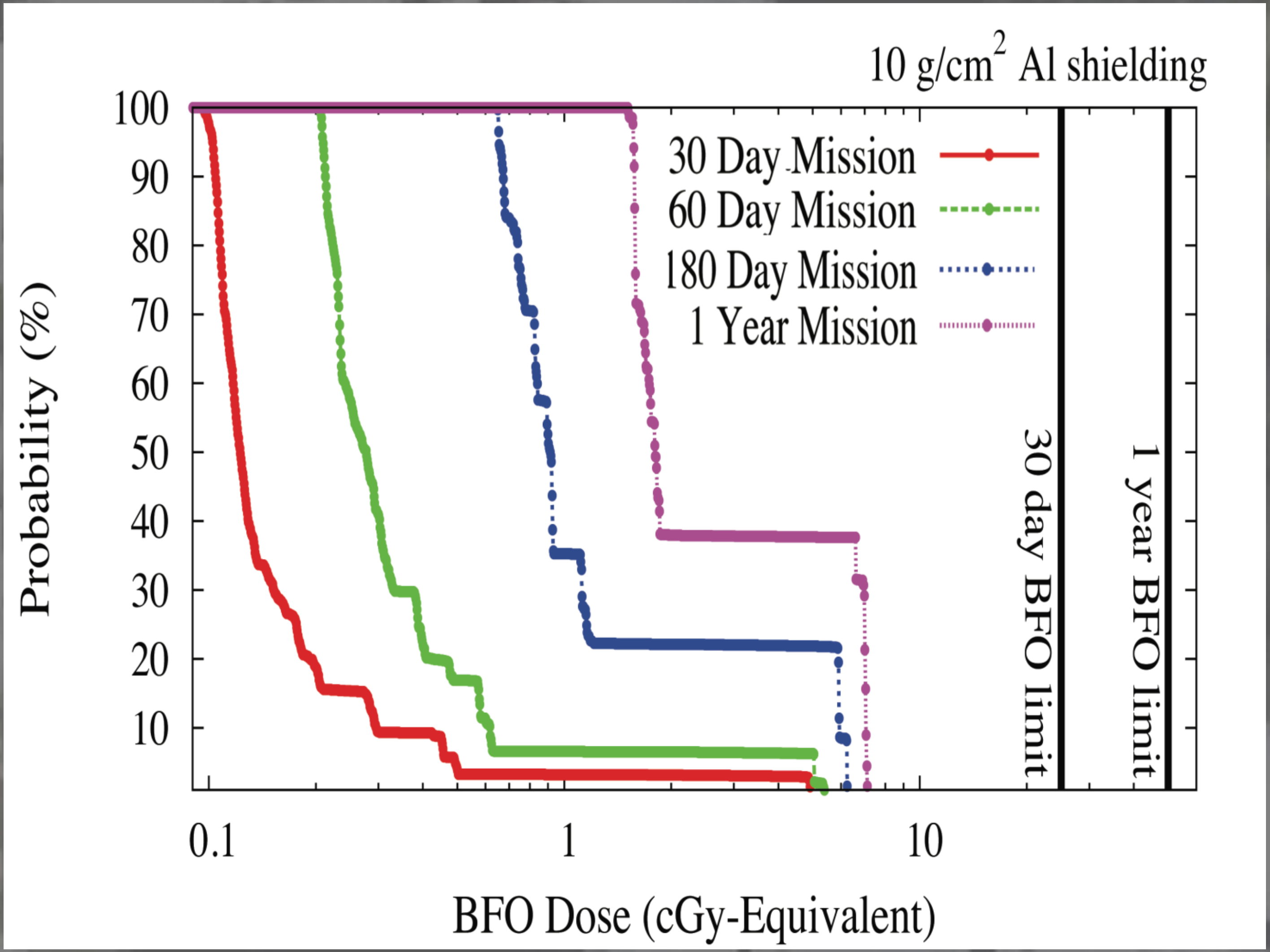
SCHWADRON ET AL., *SPACE WEATHER*, 2014a

CRaTER – the complete record



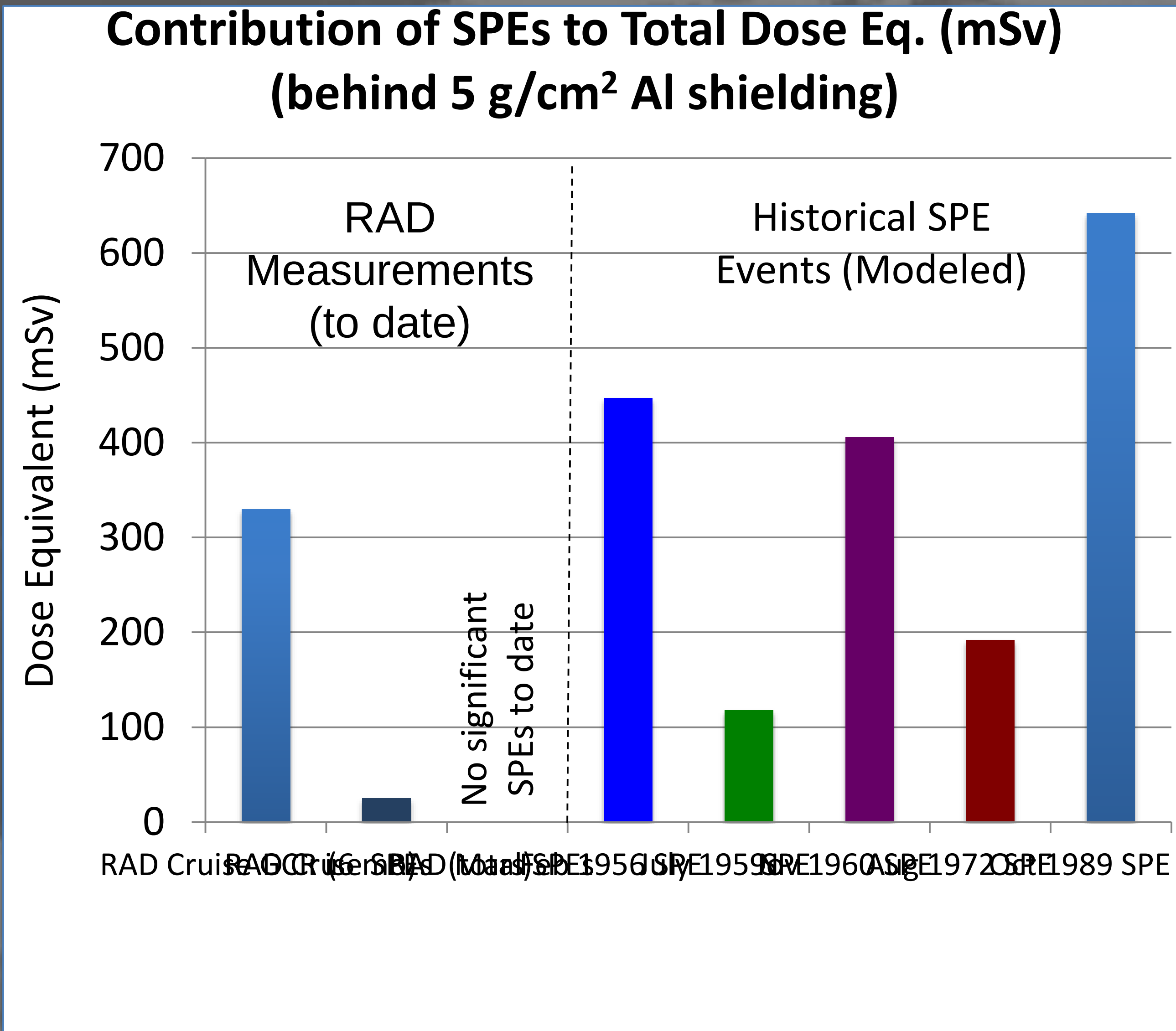
PREDICCS Data Showing Low Probability of SEP events in cycle 23-24

- PREDICCS - Predictions of radiation from REleASE, EMMREM, and Data Incorporating CRaTER, COSTEP, and other SEP measurements
- On-line system to specify radiation environment through interplanetary space



SCHWADRON ET AL., *SPACE WEATHER*, 2014a

Comparison of Total Radiation Dose Equivalent measured by RAD to modeled Historic SPE Events



*SPE Dose Equivalent values modeled behind 5 g/cm2 Aluminum by M.-H. Kim, F. Cucinotta, et al. (AGU, 2012).

RAD cruise measurements from Jan-July 2012.

Nov. 60 SPE includes contributions from 2 events.

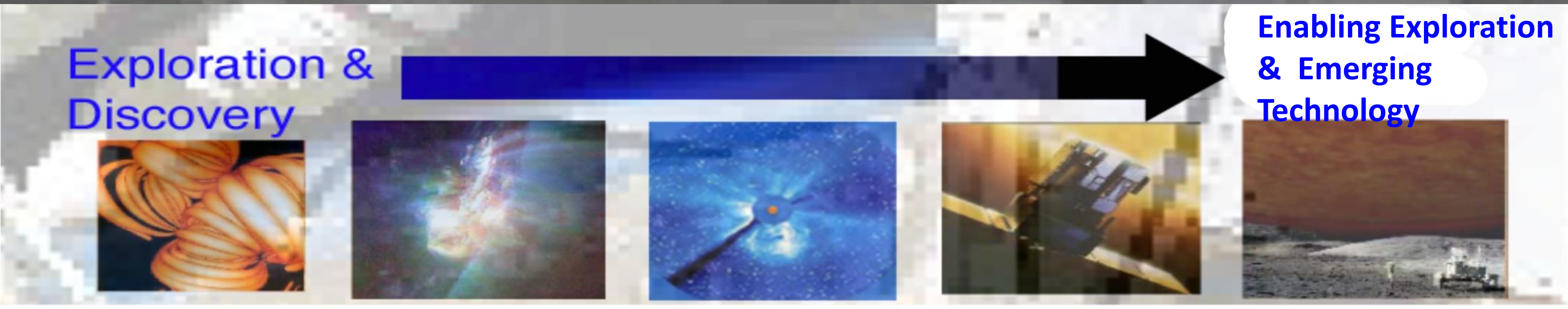
Oct. 89 SPE includes contributions from 5 events over 1 month.

Approach, Assumptions

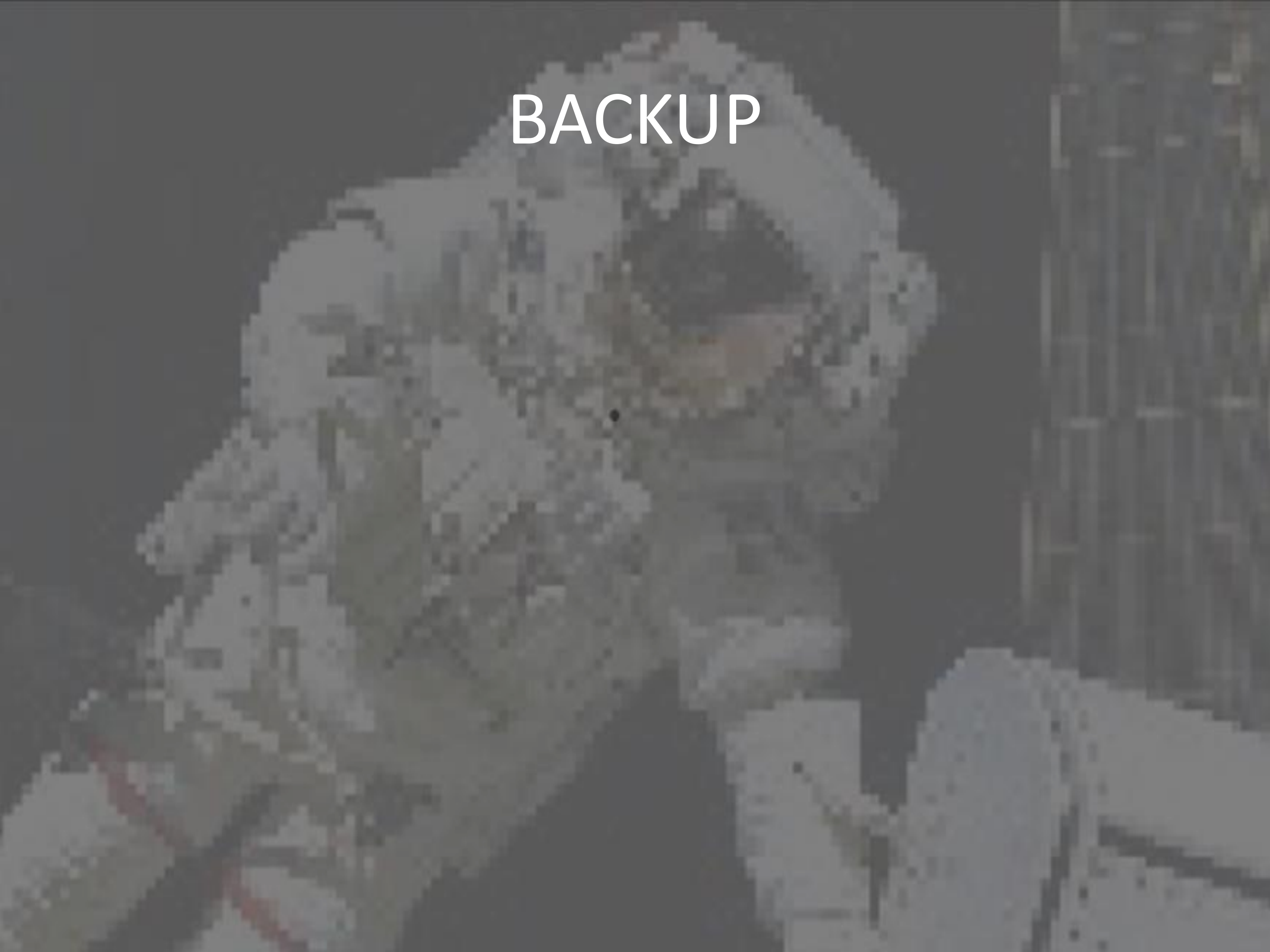
- Direct observations critical for validating models!!!
- GCR fluxes modeled using slab-turbulence + force-free model
  - Modulation potential scaled with observed magnetic field strength
  - Dose-rate validated with ACE and CRaTER
- Three-layer version of HZETRN 2005 and HZETRN 2010 for modeling doses, dose-equivalents, and effective dose
  - LET spectra from HZETRN validated with CRaTER

Implications of the Worsening GCR Radiation Environment

- Direct observations (e.g., from LRO/CRaTER and MSL/Rad) critical!
- Deepest Solar Minimum and Weakest Maximum more than 80 years
  - Increased GCR radiation intensity, particularly in solar minima
  - Reduced allowable time in deep space for astronauts
  - Lower probability of SEP events
- Need Improved Understanding/Predictability of SEPs
  - Probability of Extreme Events
  - Resolve physics and predictability of extreme events

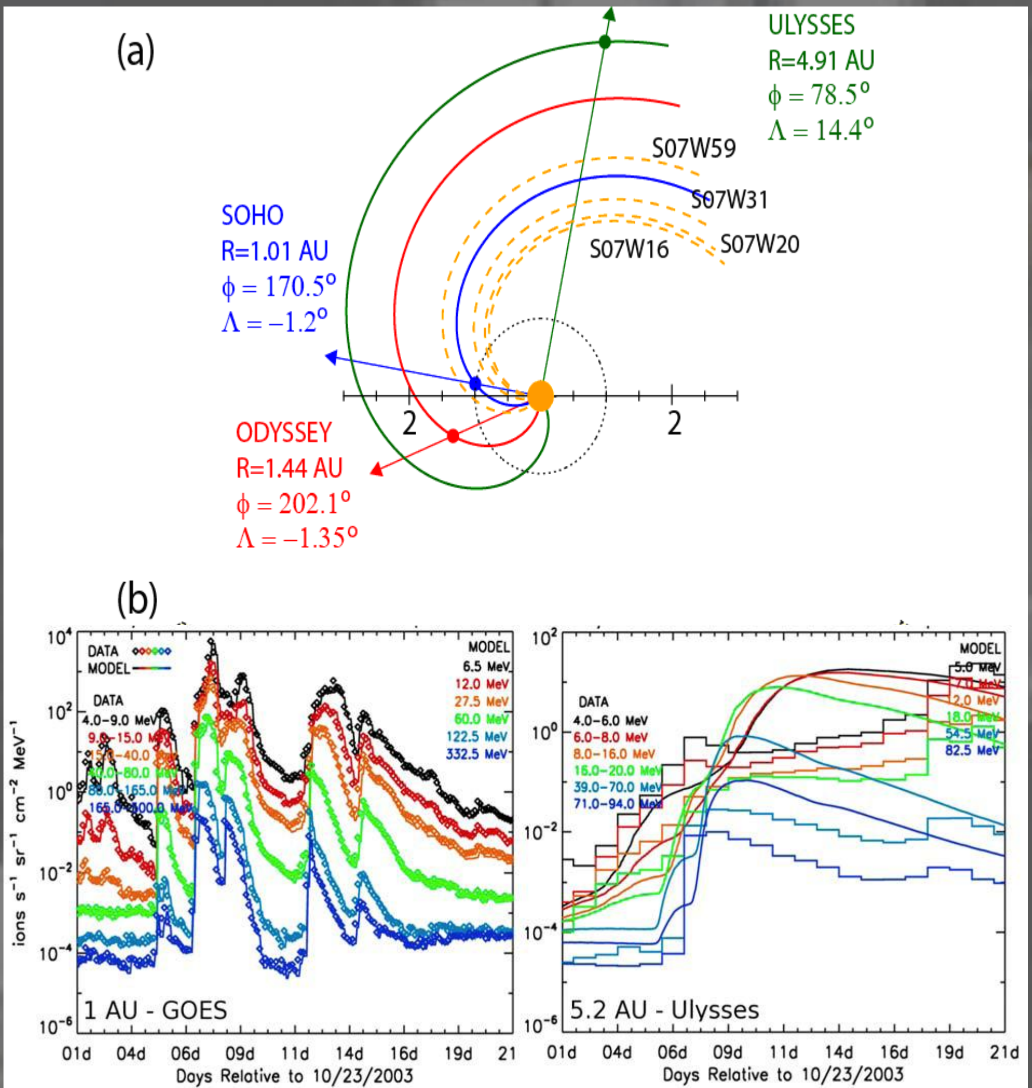


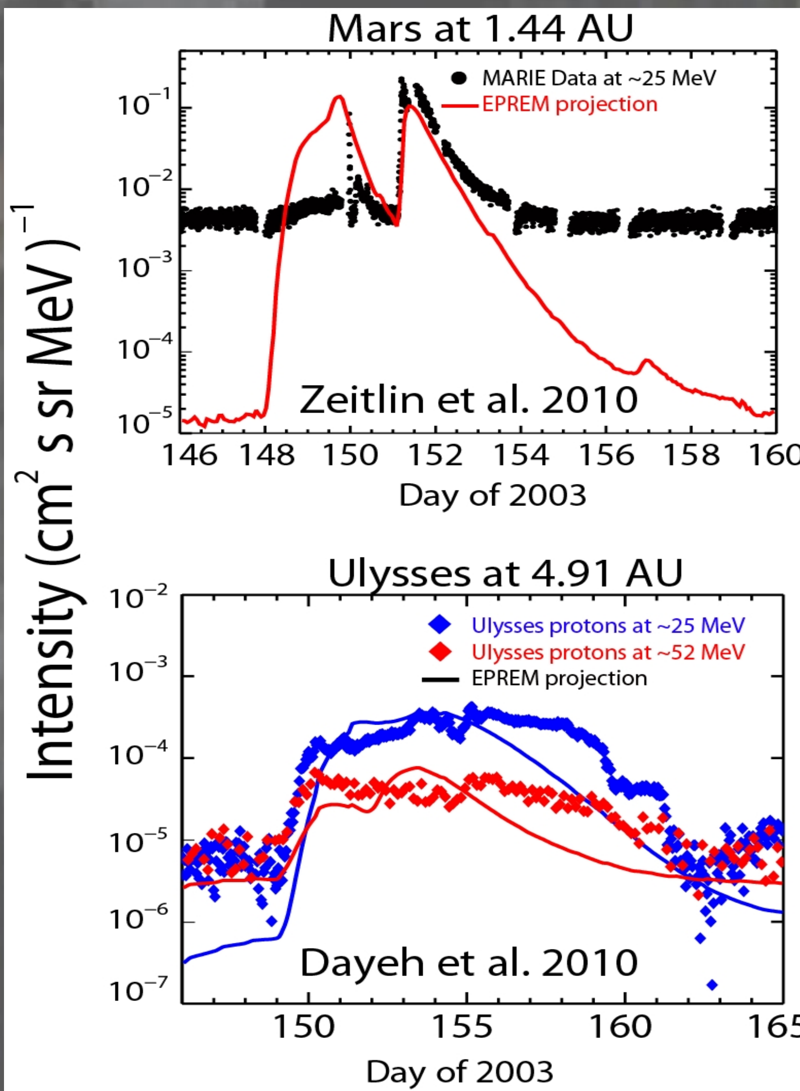
BACKUP



Connecting Events Through the Heliosphere

Power of Distributed Observers: *Broad Longitudinal extent of SEP events has proved very useful for predicting SEP spectra and radiation doses at different locations in the inner heliosphere. Figures below show two recent papers by which SEP time profiles, onset, and radiation estimates were successfully predicted at Mars (Odyssey) and Ulysses located at 1.44 AU and 4.91 AU, respectively. 1 AU measurement from ACE, SoHO, and GOES*

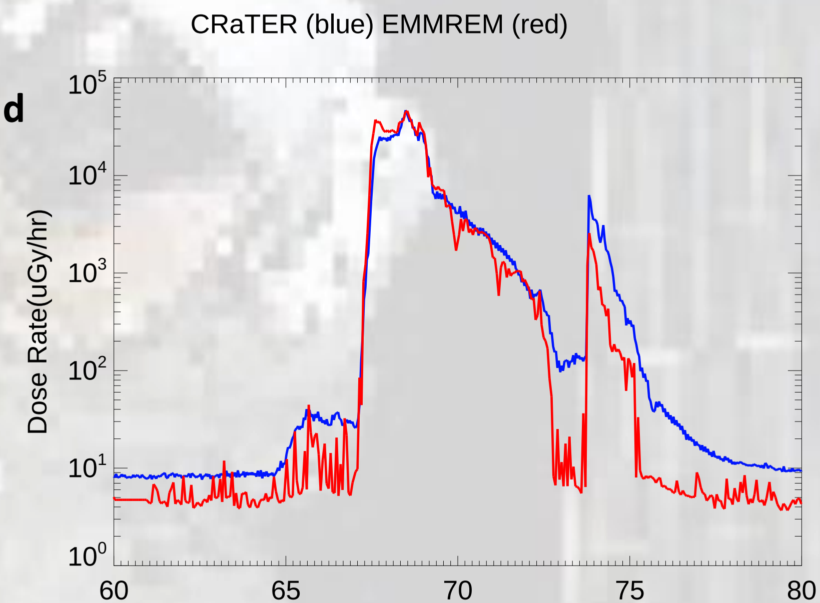




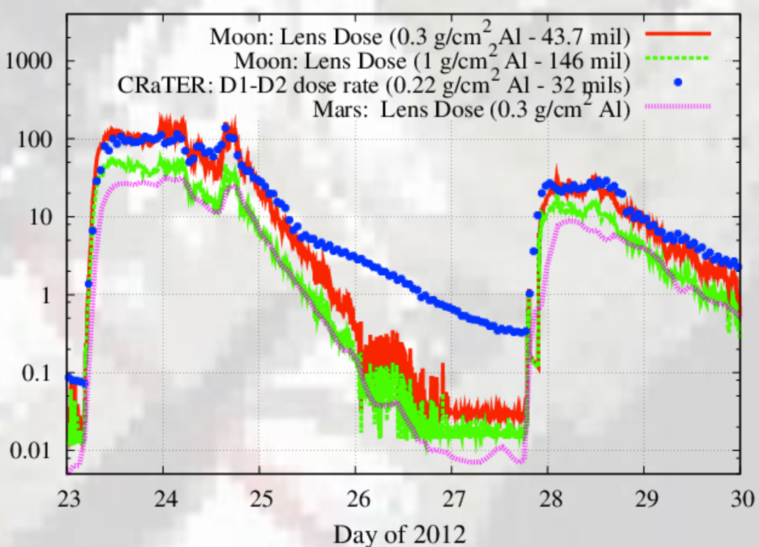
SEP events with PREDICCS

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

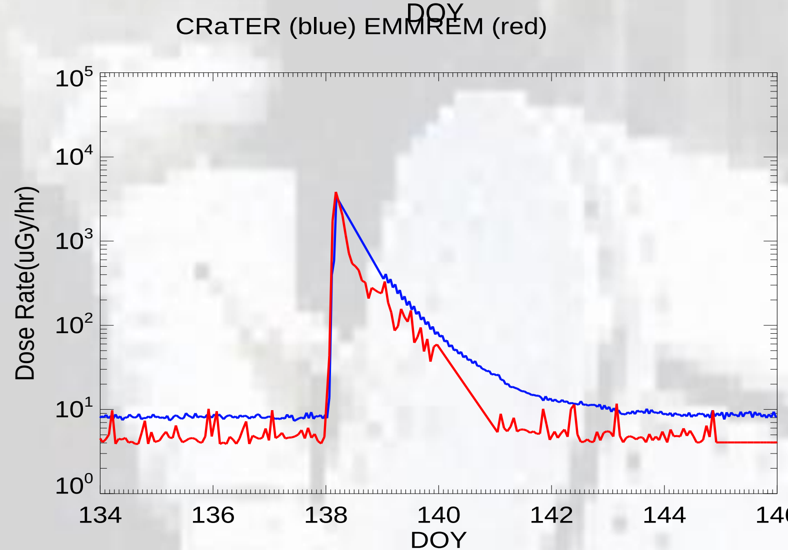
- **Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and prediccs predictions (red and green).**
- **Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER**



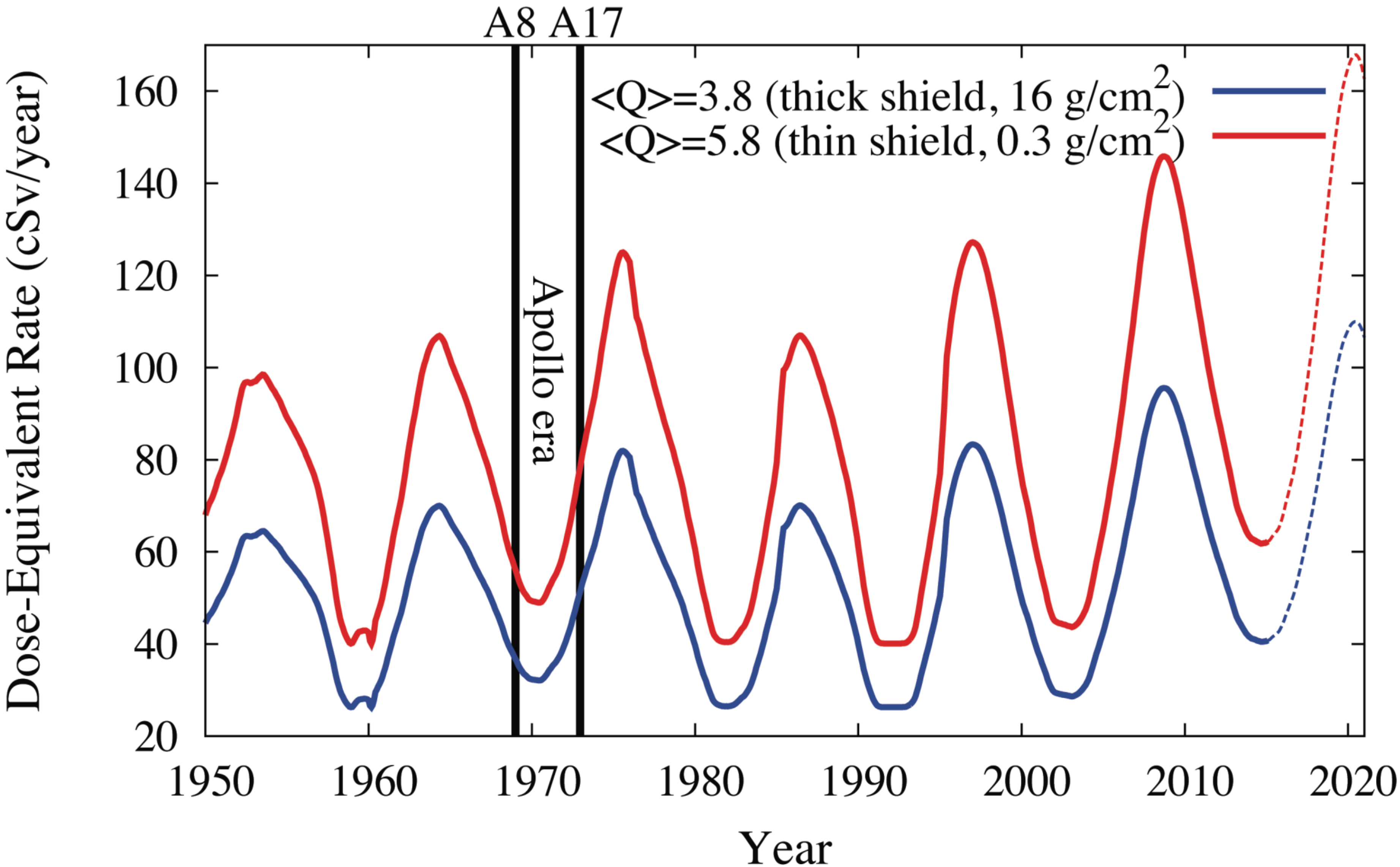
Mar 7, 2012 Event



Jan. 23rd, 2012 Event

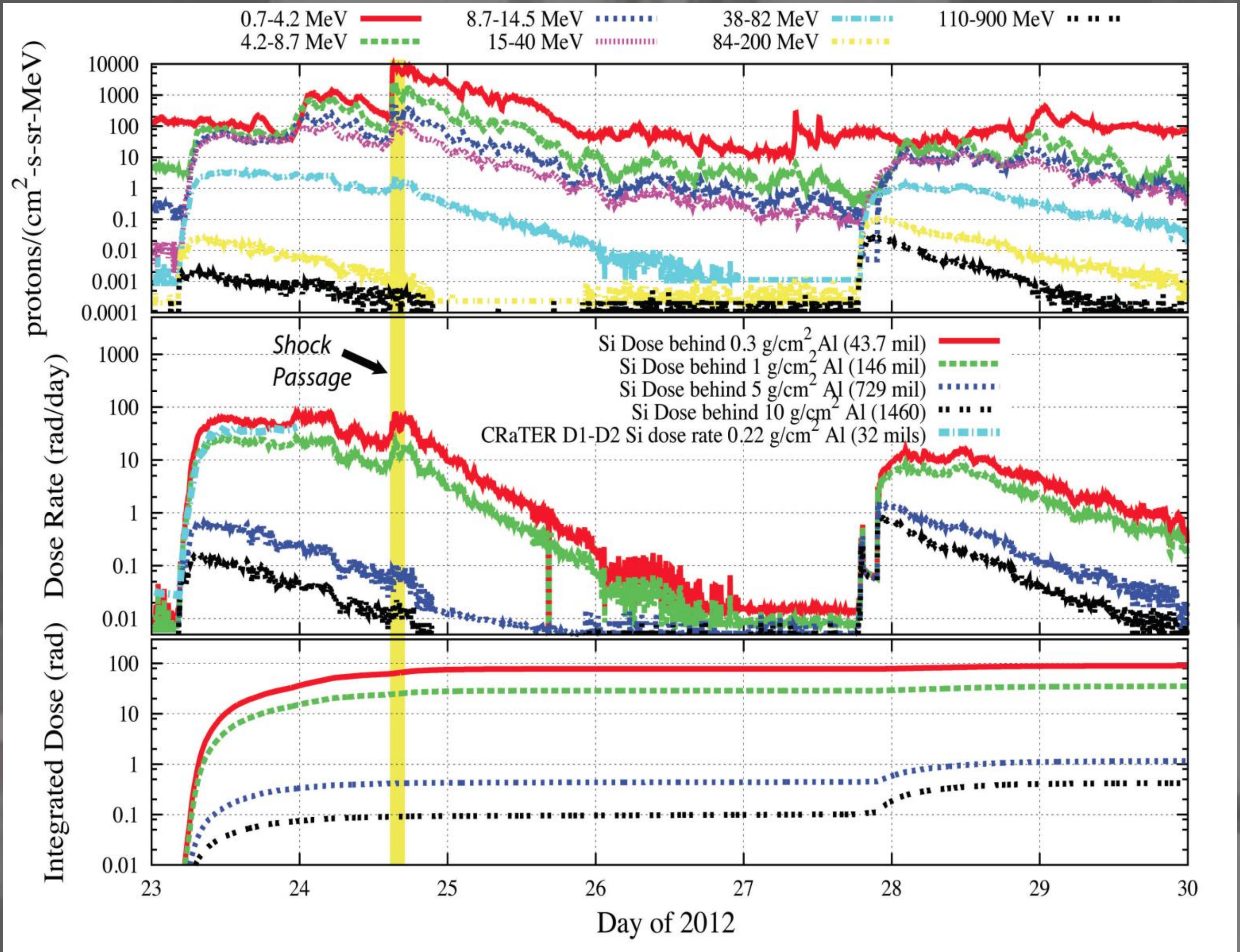


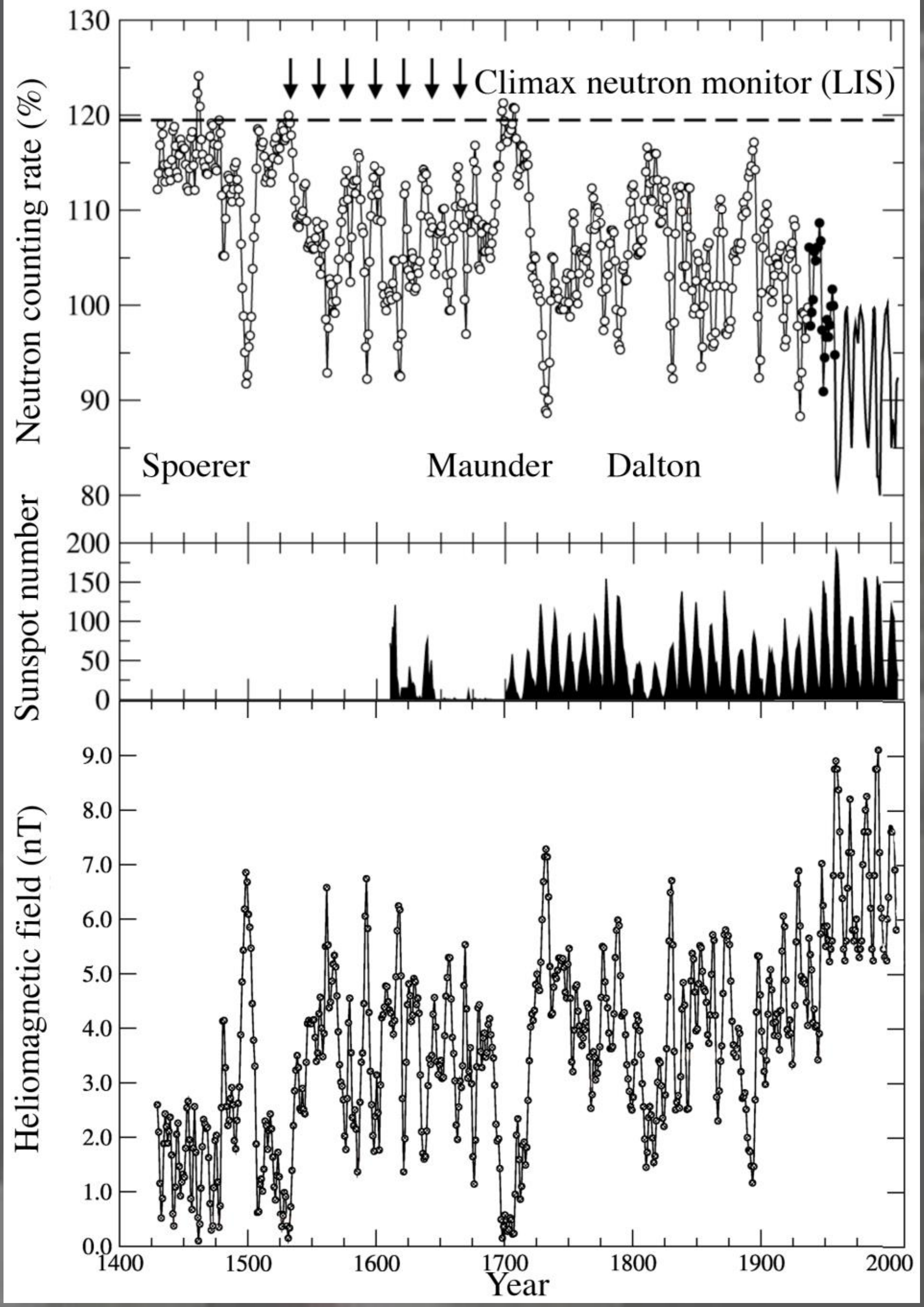
May 16, 2012 Event



A8 A17
<Q>=3.8 (thick shield, 16 g/cm2)
<Q>=5.8 (thin shield, 0.3 g/cm2)
Apollo era
Dose-Equivalent Rate (cSv/year)
Year
160
140
120
100
80
60
40
20
1950
1960
1970
1980
1990
2000
2010
2020

Jan 23rd 2012 Event





McCracken and Beer, 2007

- Galactic Cosmic Ray Record from Be10 in Ice Core (product of spallation)
- Do recent solar changes suggest larger changes in store?

Halloween 2003 Storms