

Update on the Worsening Particle Radiation Environment Observed by CRaTER

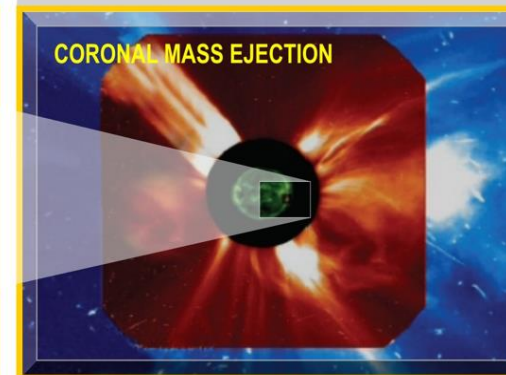
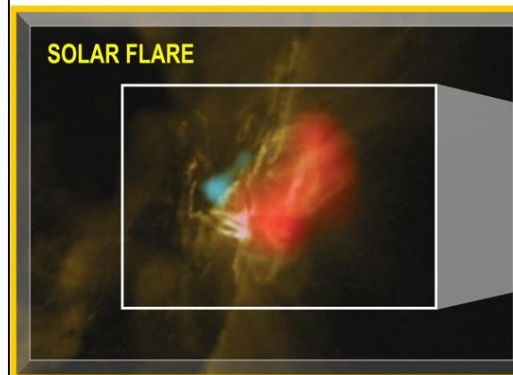
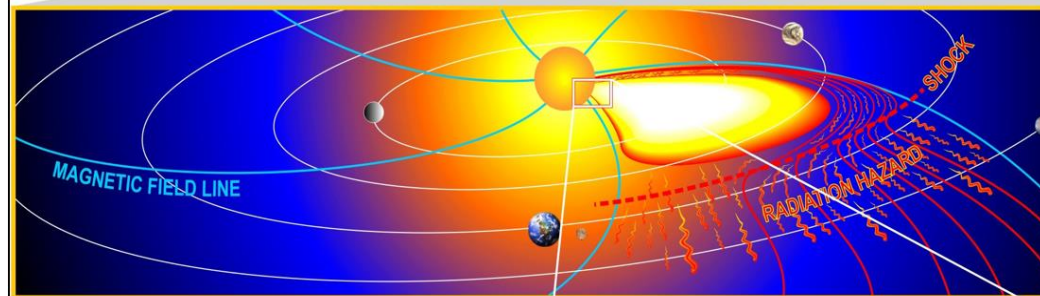
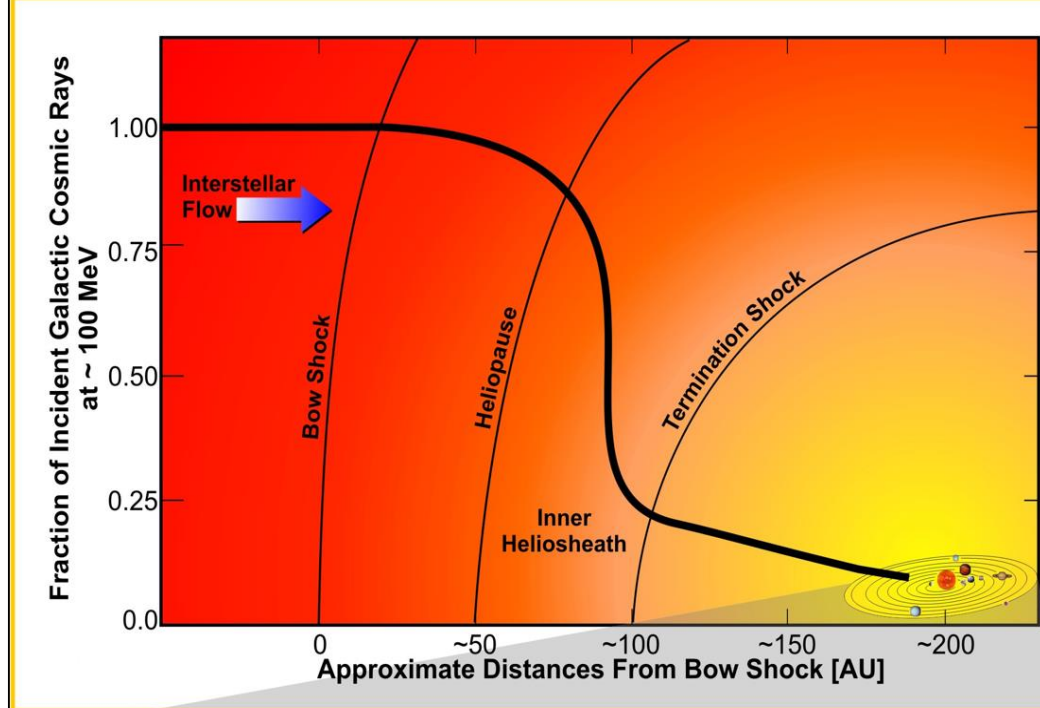


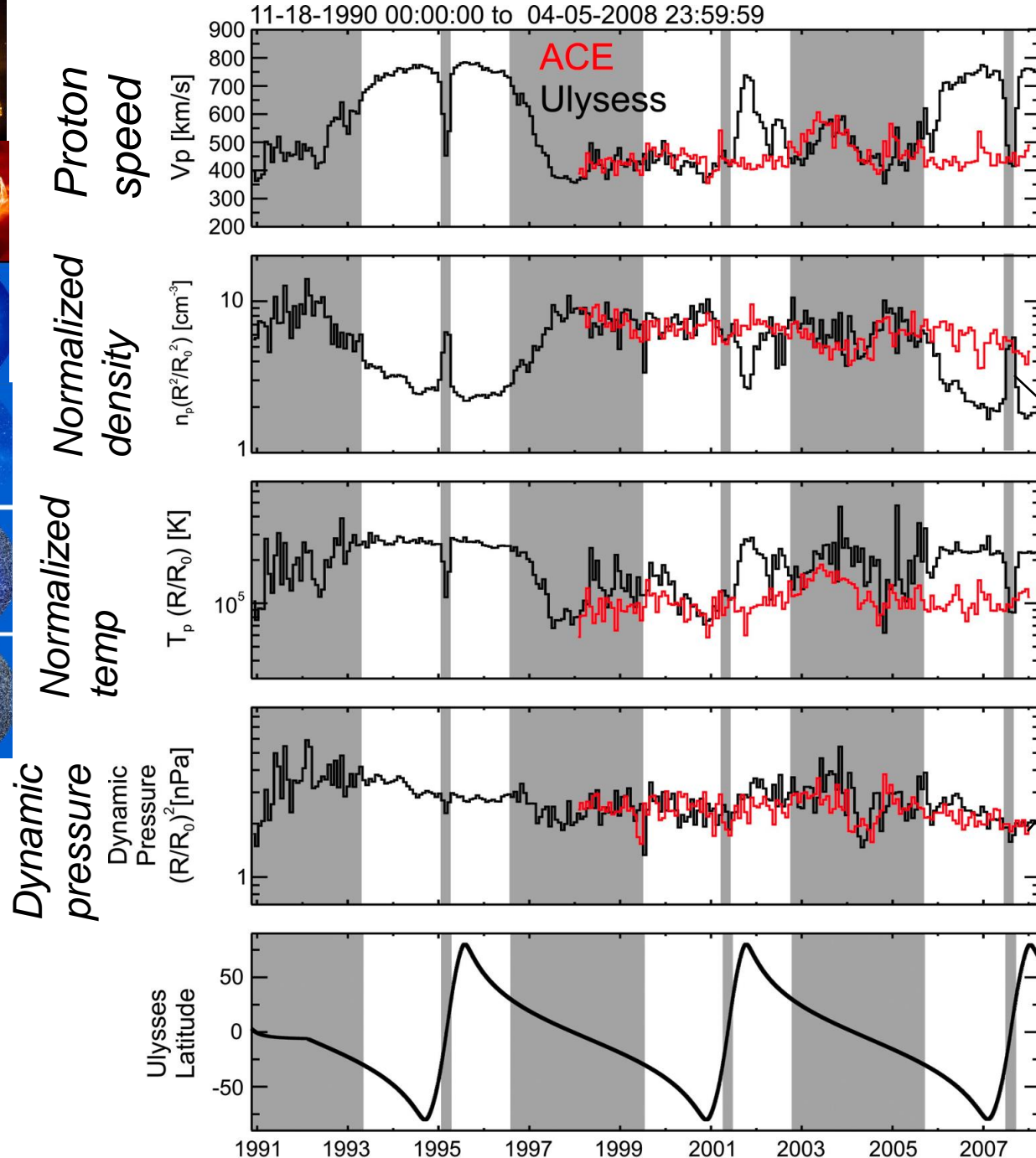
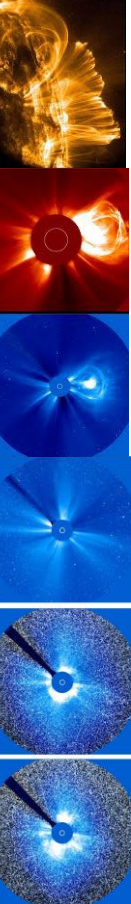
N A Schwadron, F Rahmanifard, J. Wilson, A P Jordan,
H E Spence, C J Joyce, J B Blake, A W Case, W d Wet,
W M Farrell, J C Kasper, M D Looper, N Lugaz, L Mays,
J E Mazur, J Niehof, N Petro, C W Smith, L W
Townsend, R Winslow and C Zeitlin



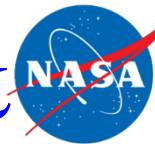
Radiation Hazards, Interactions

- Galactic Cosmic Rays (GCRs)
 - Steady Background
 - Career limit in ~ 1-3 years
- Solar Energetic Particles (SEPs)
 - Acute Sources
 - SEPs versus impulsive component
 - Time-dependent response



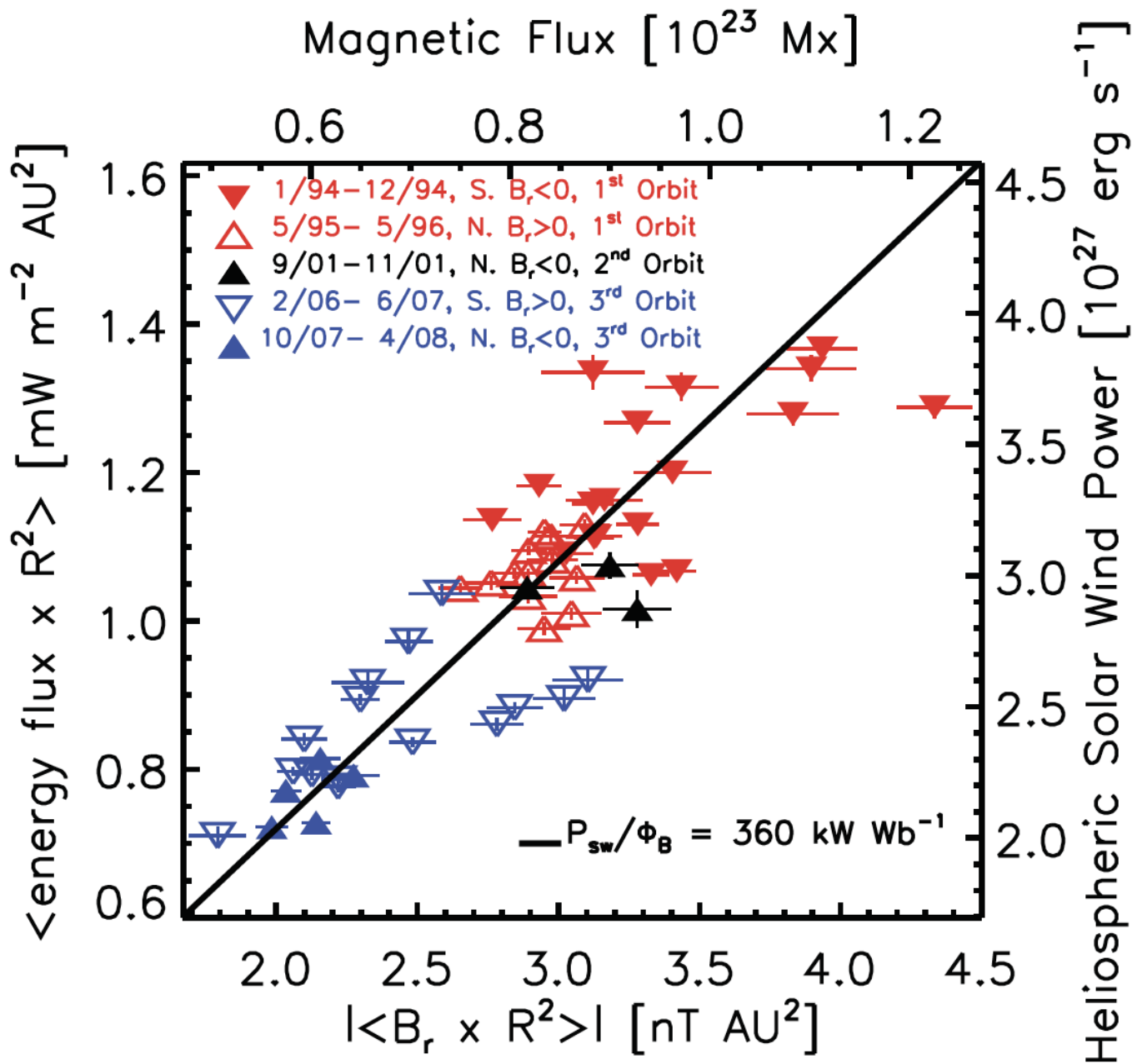
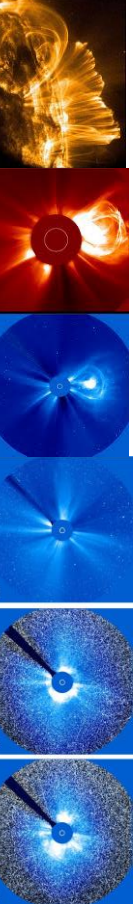


ACE & Ulysses Comp.



Reduced Density and Dynamic Pressure

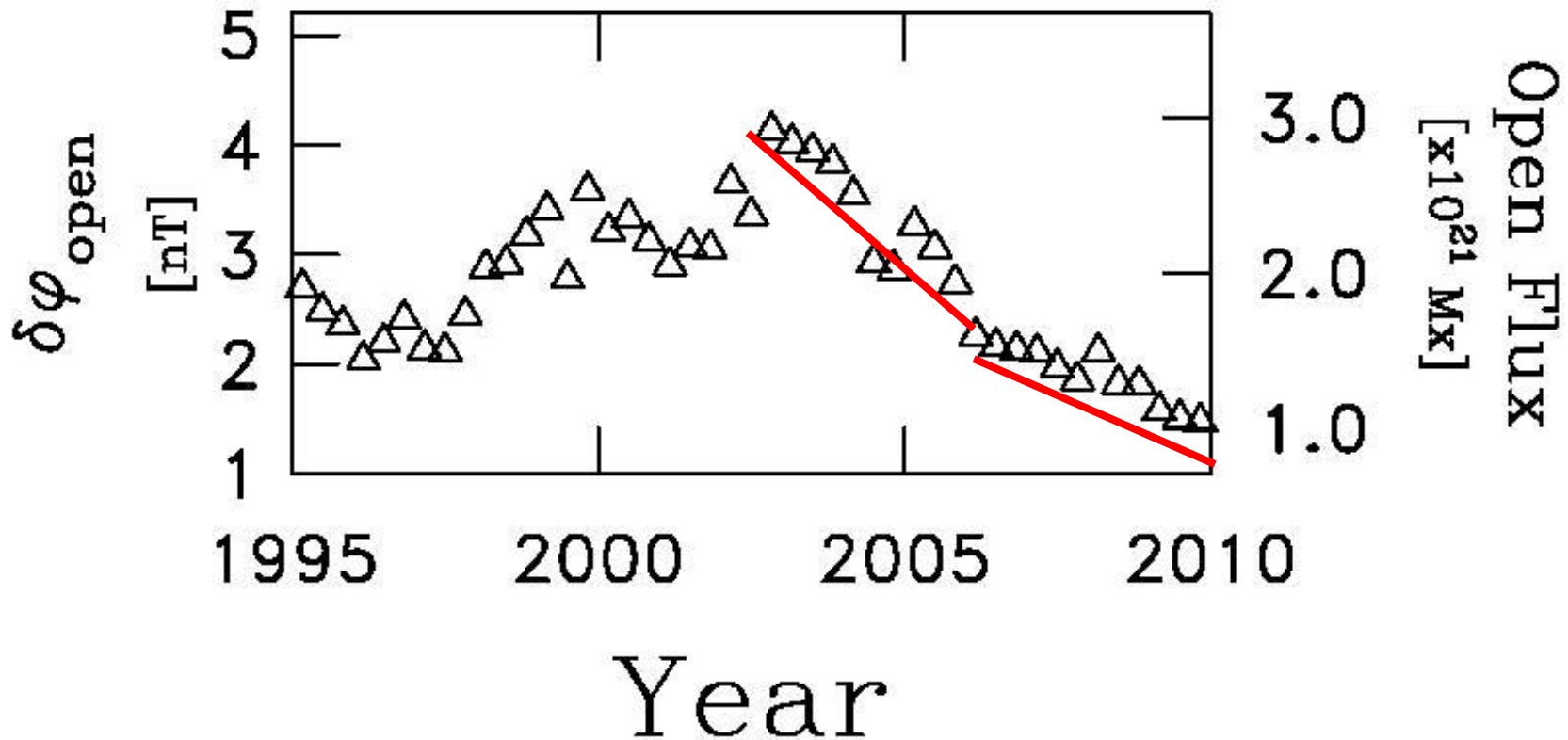
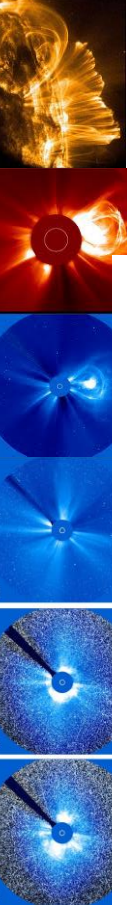




Schwadron and McComas, 2008



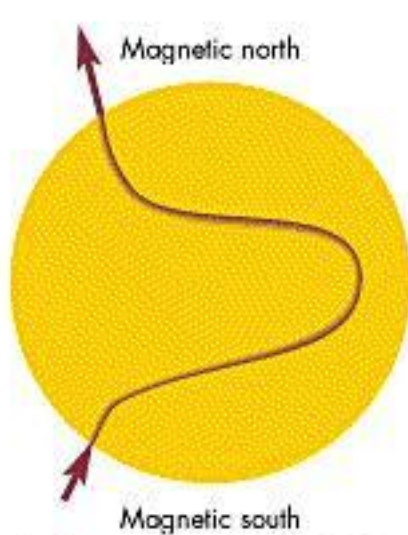
Open Flux Depletion



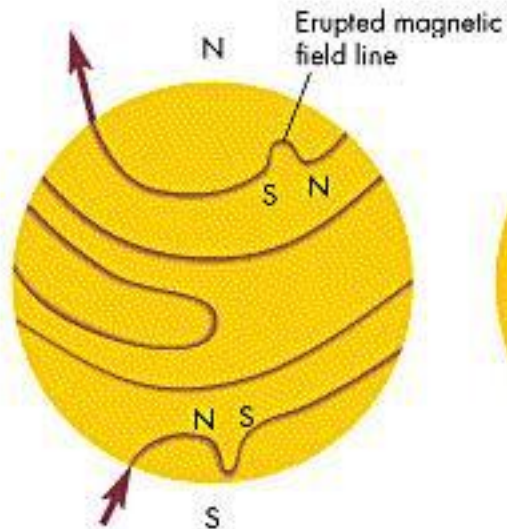
There is a 2-phase depletion of open field lines: first during the “normal phase” of solar min when ICME activity is small, and then later when ICME activity is virtually zero.

Connick et al., Astrophys. J., 2011

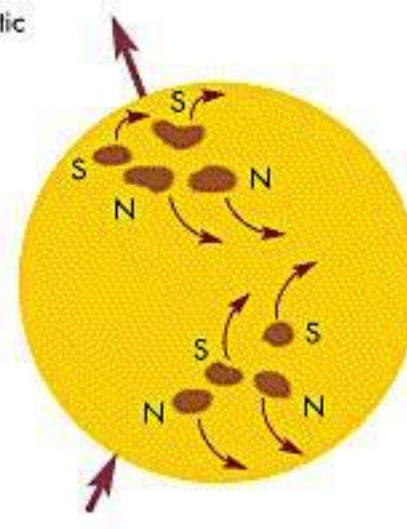




A Sunspot minimum: The Sun's rotation begins to stretch and distort magnetic field lines

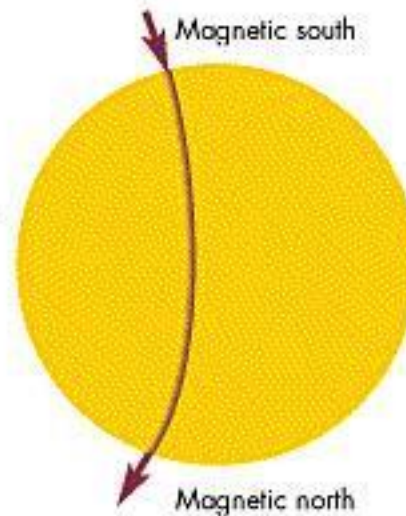


B The magnetic field lines become so twisted that they erupt through the Sun's surface



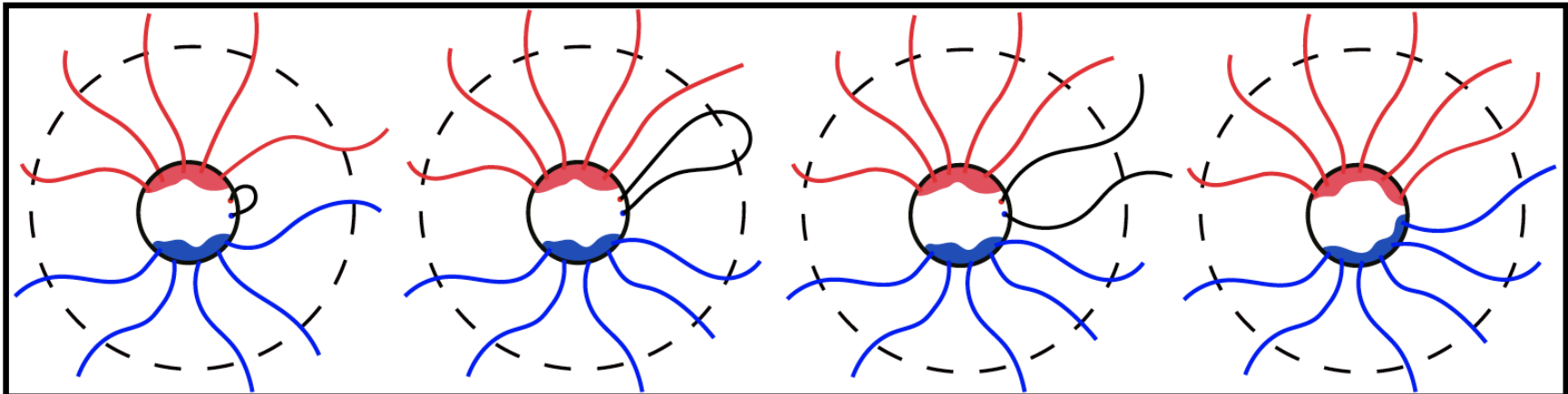
C Nearing the end of the cycle

D End of the cycle: The polarity of the magnetic field is opposite what it was at the beginning of the cycle **(A)**

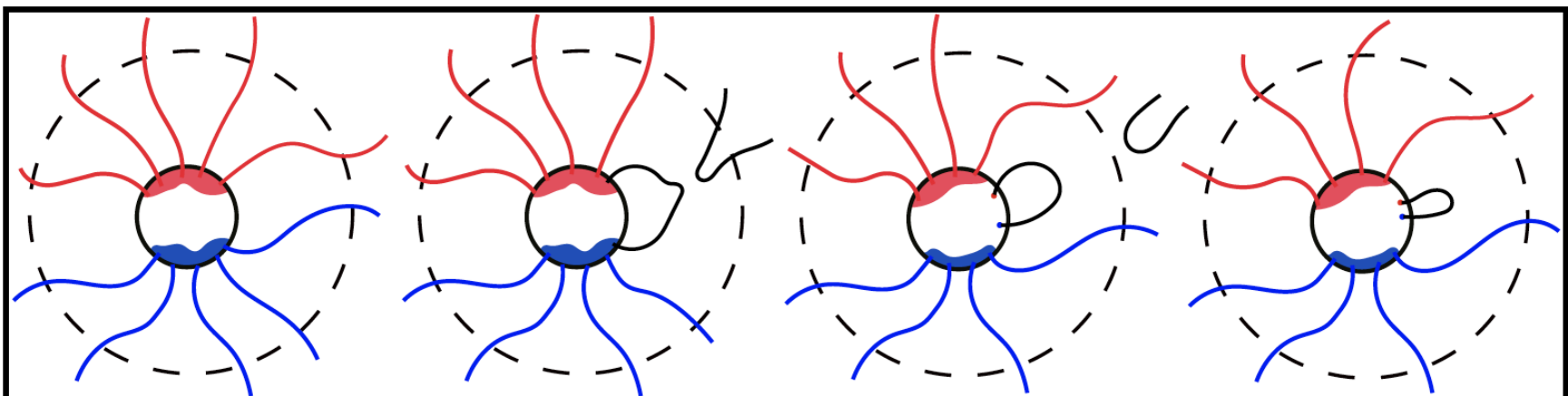




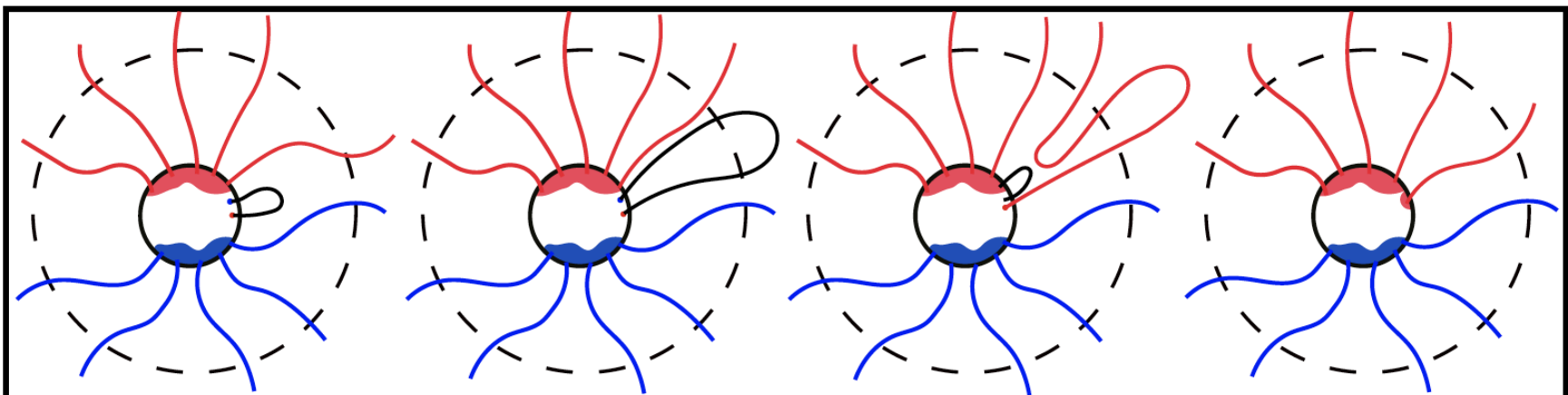
Conversion



Loss



Interchange
Reconnection

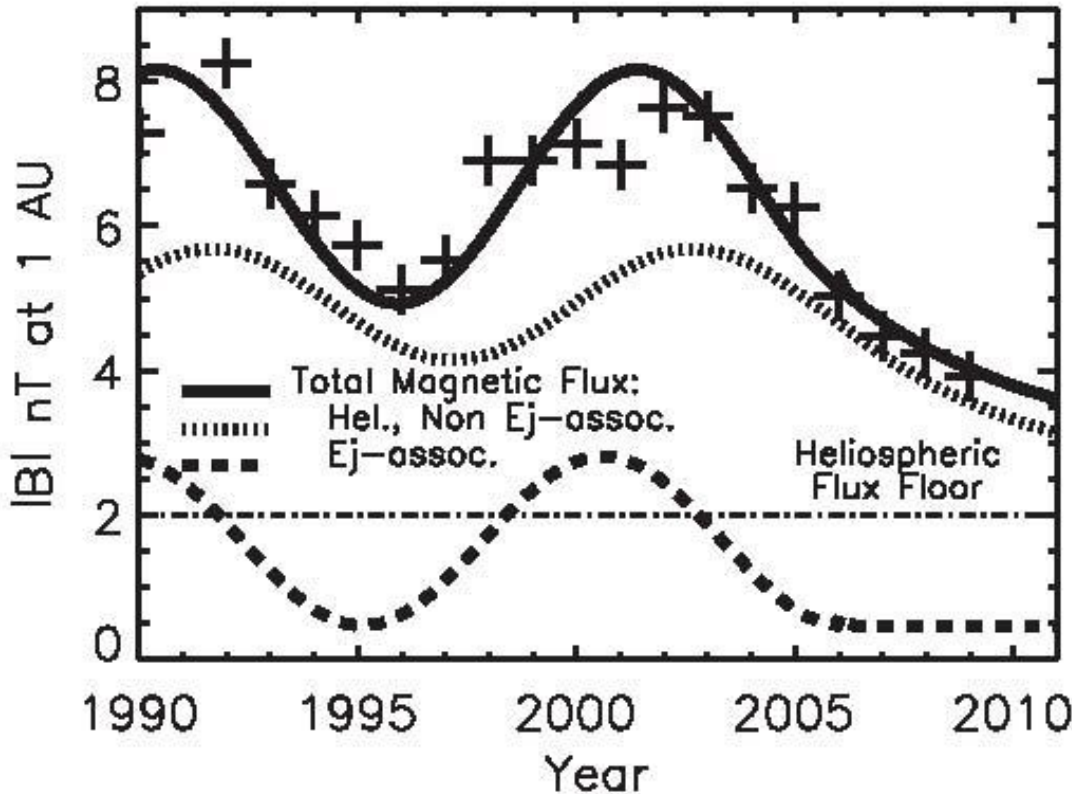


Time

Rahmanifard et al., 2016



Integration into Heliospheric Models



$$|B| = \sqrt{2} \Phi / 4\pi R_1^2 \text{ where}$$

$$R_1 = 1 \text{ AU};$$

$$\phi_{ICME} = 1 \times 10^{13} \text{ Wb};$$

$$D = 1/2;$$

$$\tau_{ic} = 40 \text{ days};$$

$$\tau_0 = 2.5 \text{ years};$$

$$\tau_d = 4.4 \text{ years};$$

$$F_{lo} = 0.5 \text{ day}^{-1};$$

$$f_{hi} = 3 \text{ day}^{-1};$$

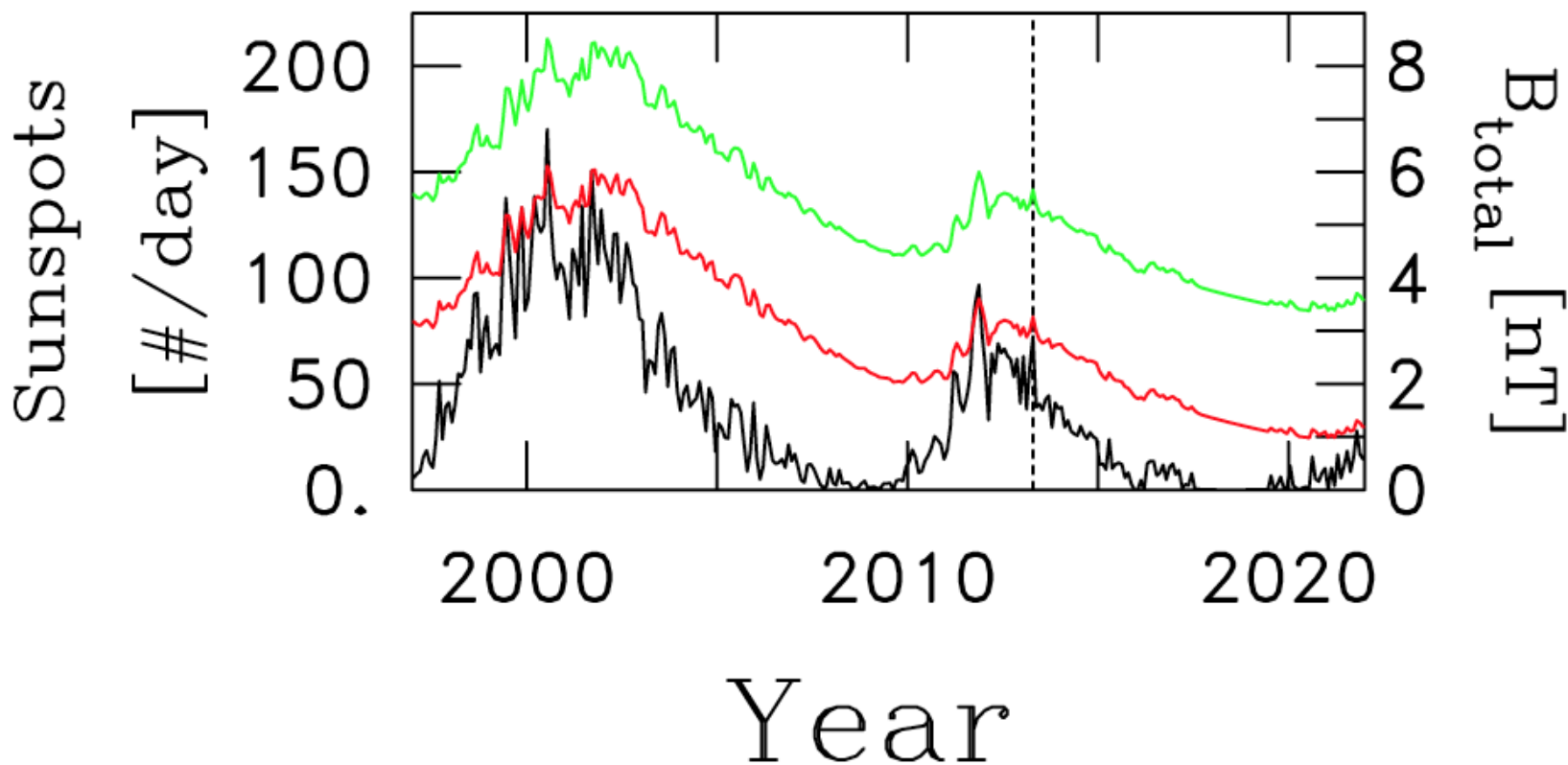
$$\Phi_{flr} = 4 \times 10^{14} \text{ Wb } (|B| = 2 \text{ nT}).$$

More recent theoretical considerations are predicting a lower flux floor.





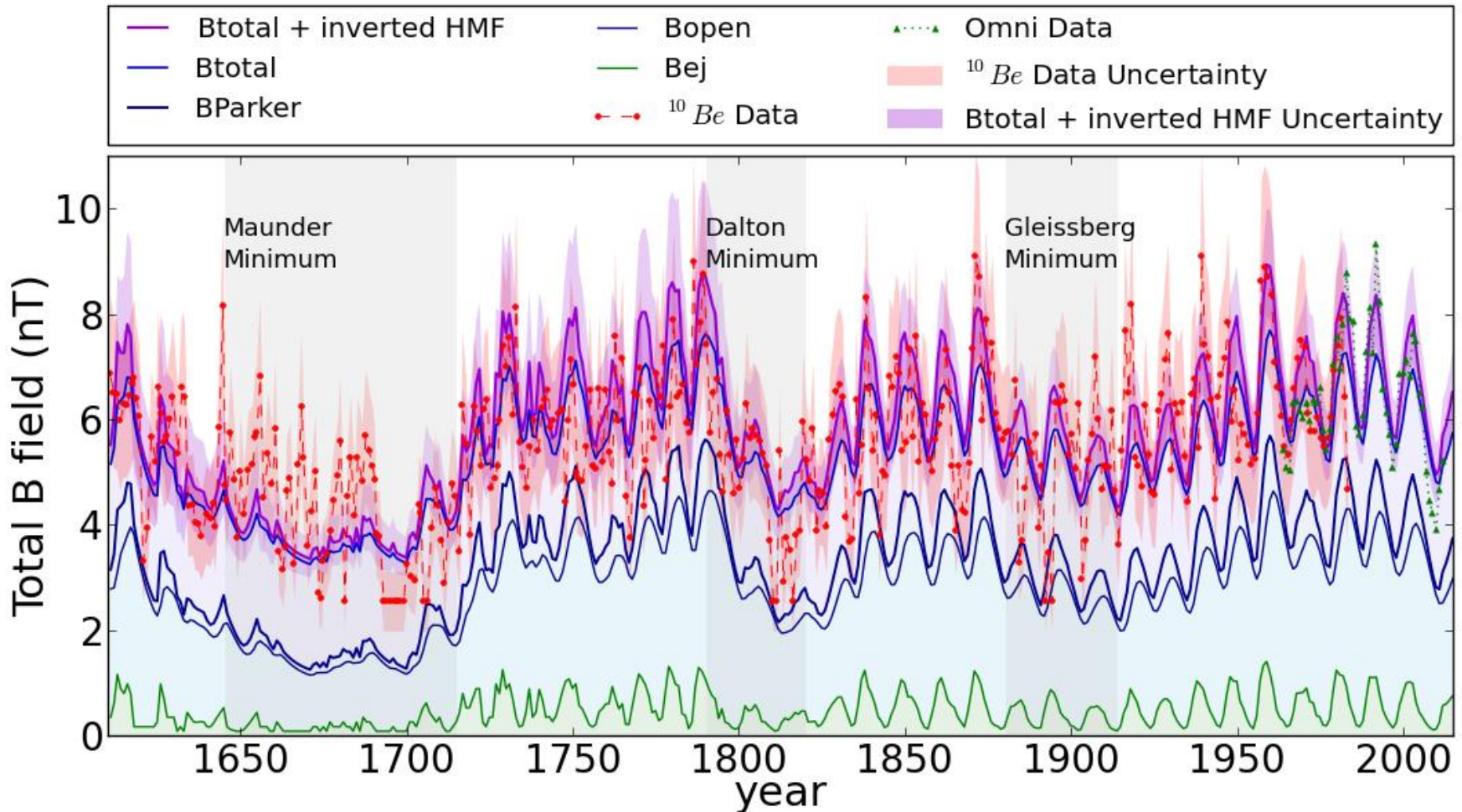
Continued Decay of Magnetic Flux in the Dalton-like Minimum



Goelzer et al., ApJ, 2013

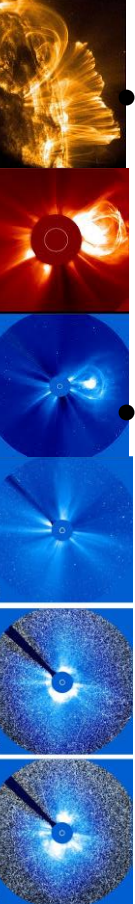


Strong Reduction in Field Possible – Much Higher GCR Flux



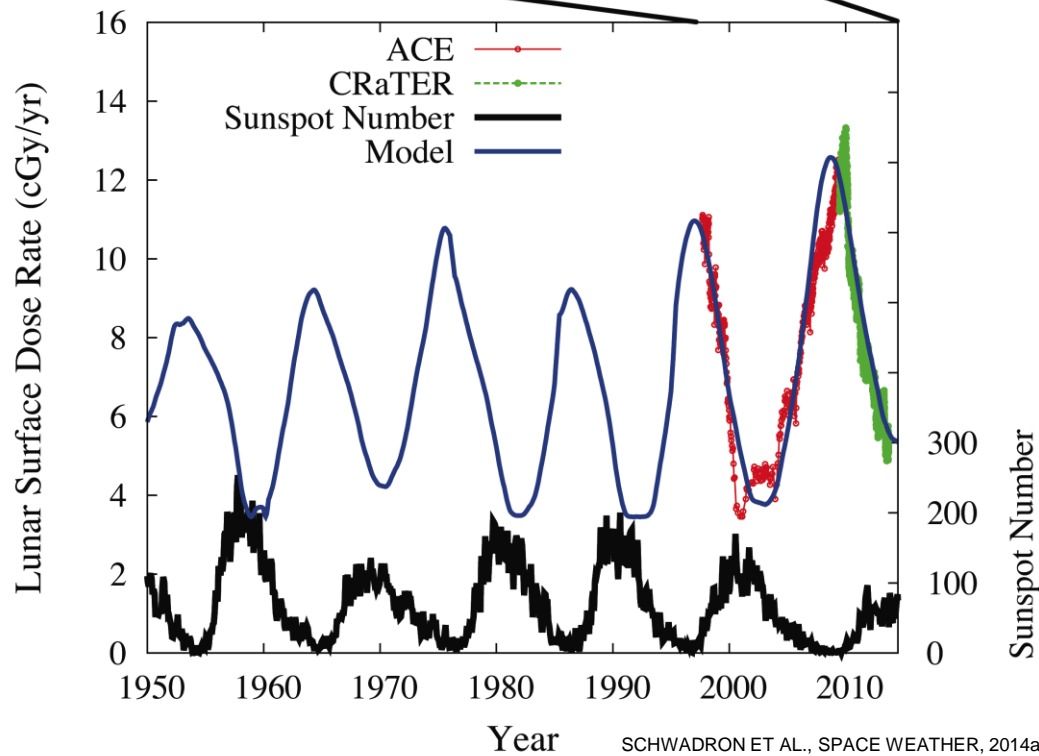
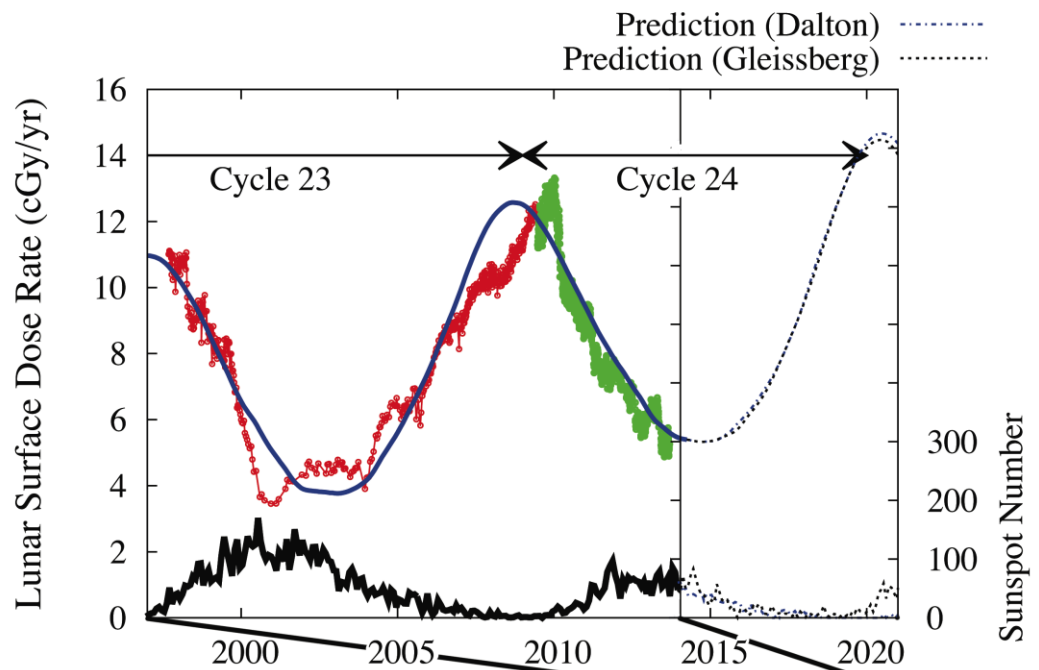
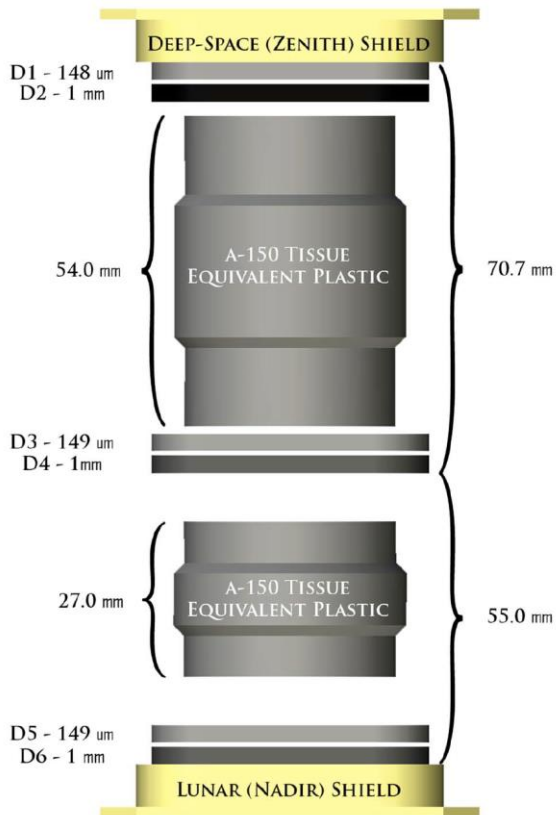
Rahmanifard et al., 2016

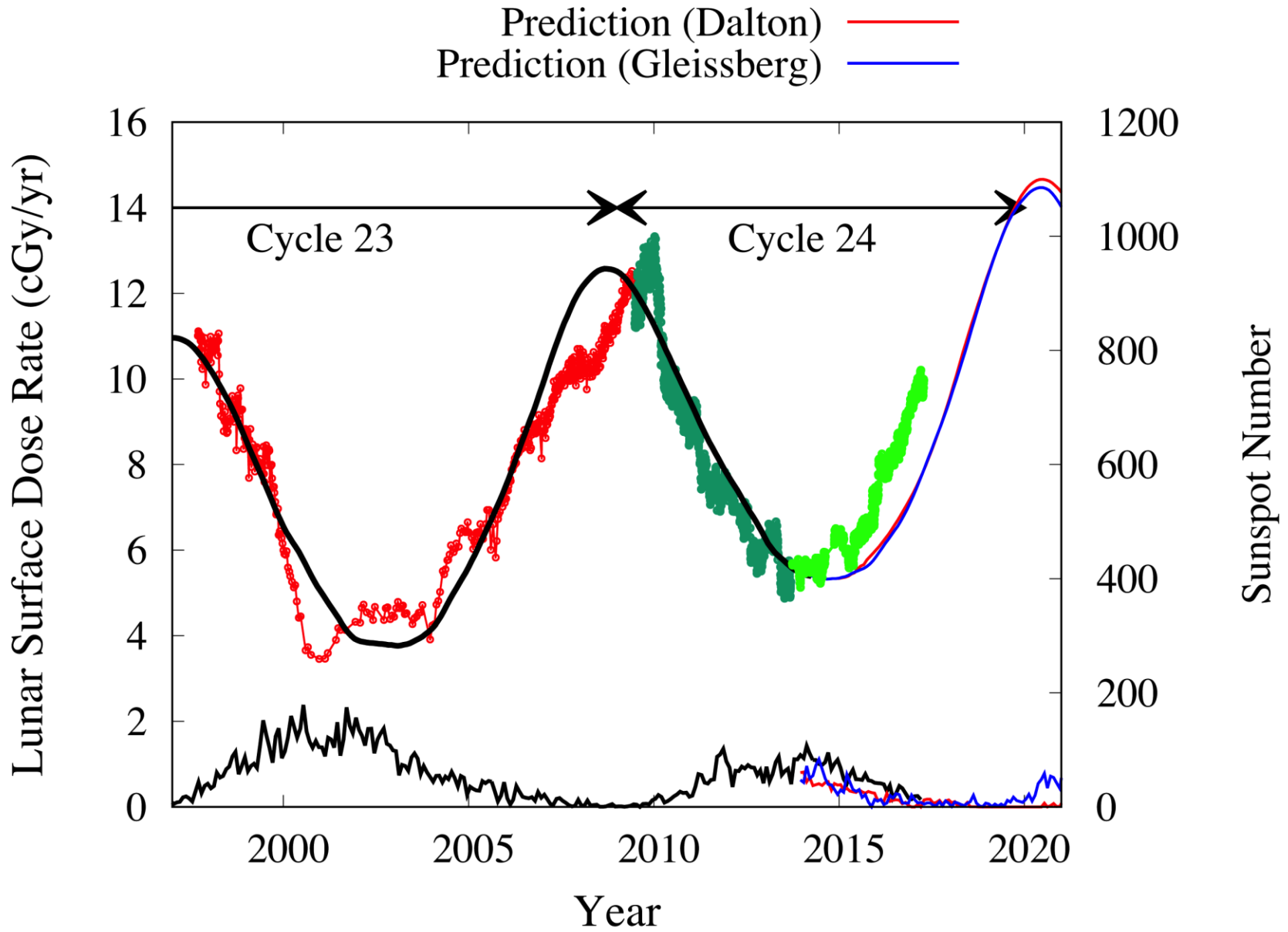
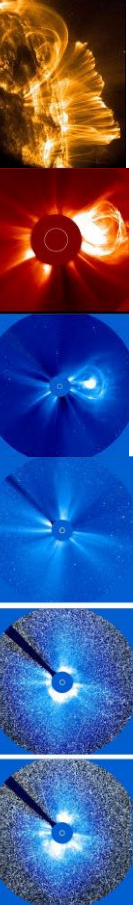




Highest GCR doses
in space age in
recent cycle 23 solar
minima

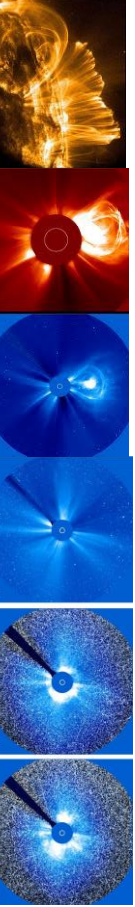
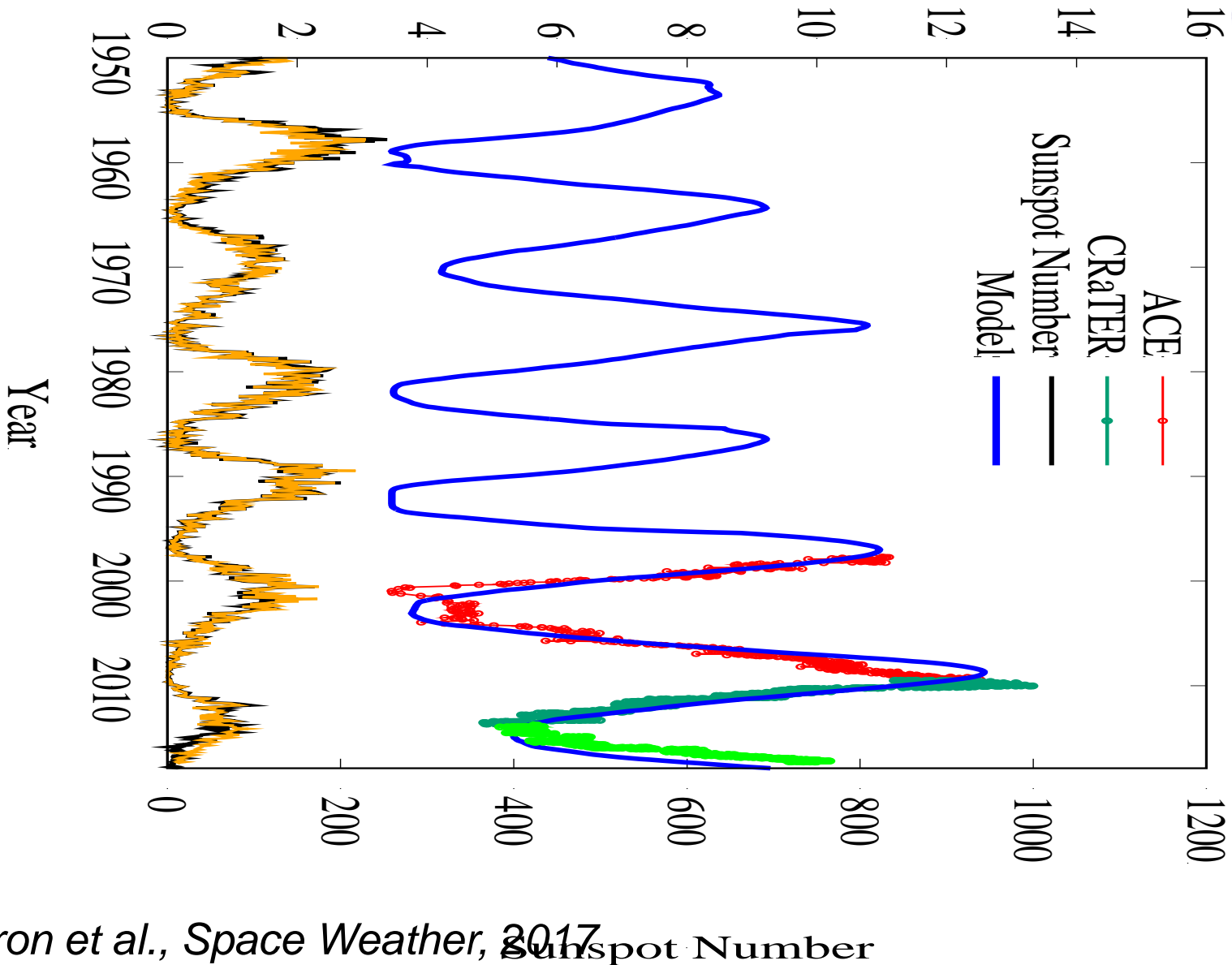
Continues trend
observed by
Ulysses, ACE







Lunar Surface Dose Rate (cGy/yr)



Solar Proton Model Prediction/Validation

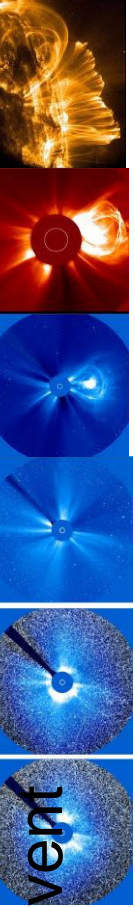
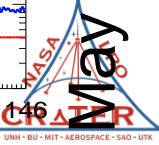


After Schwadron et al., 2012



Mar 7, 2012 Event

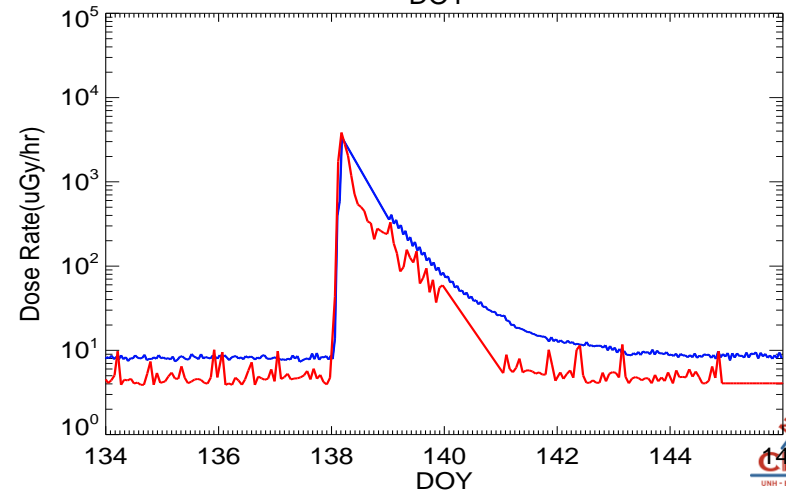
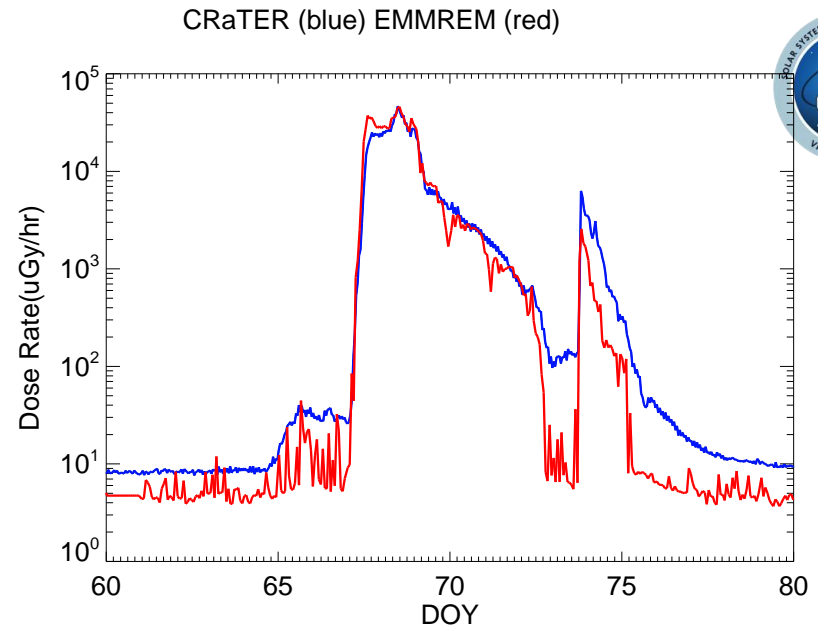
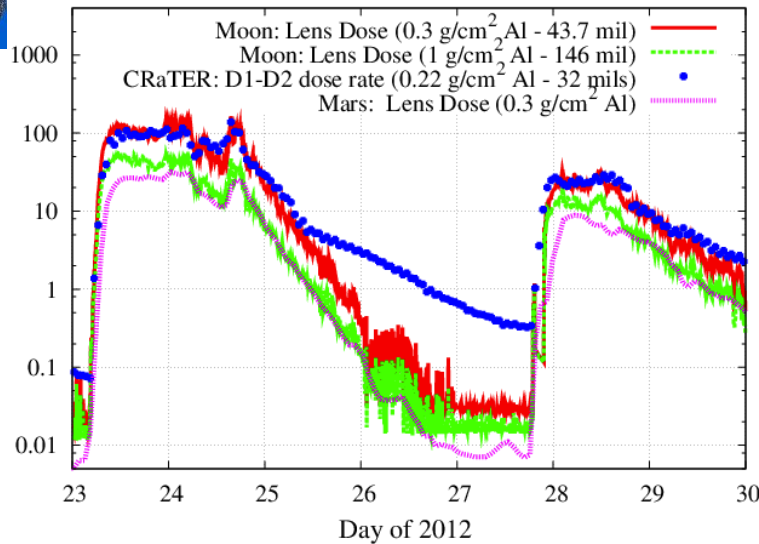
May 16, 2012 Event

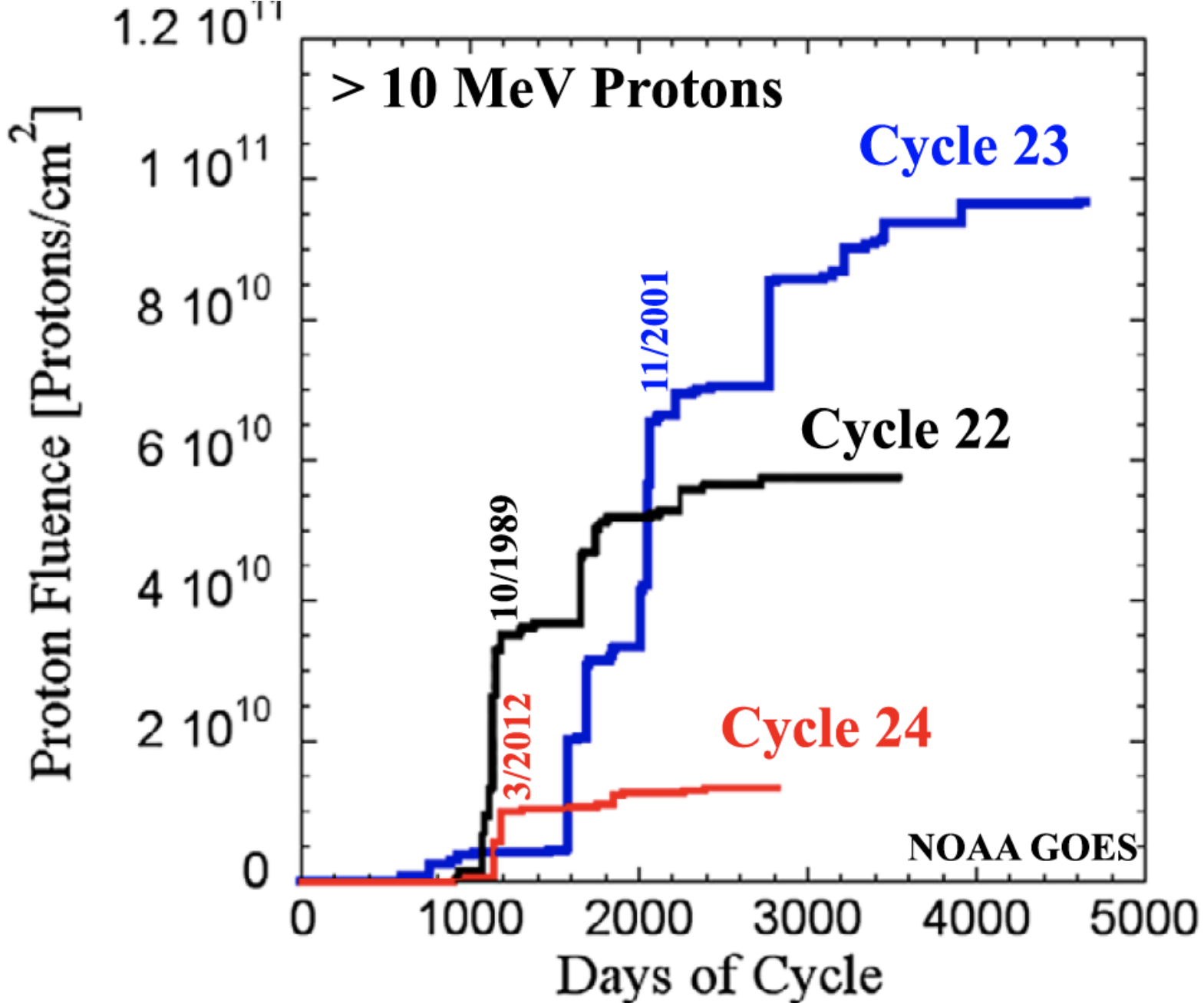
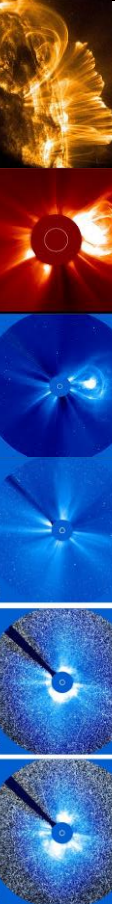


Jan. 23rd, 2012 Event

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 predicc predictions (red and green).
- Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER

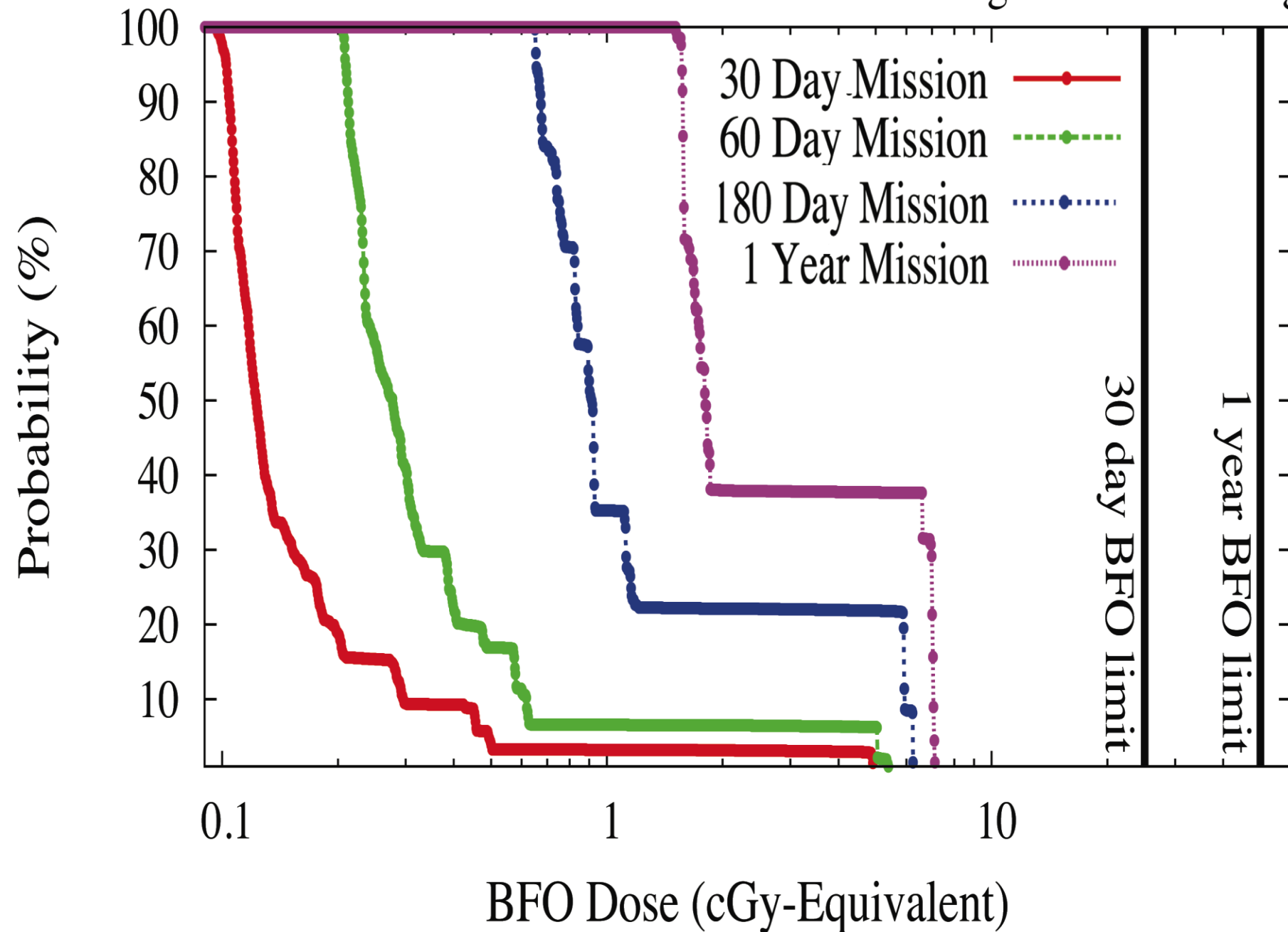


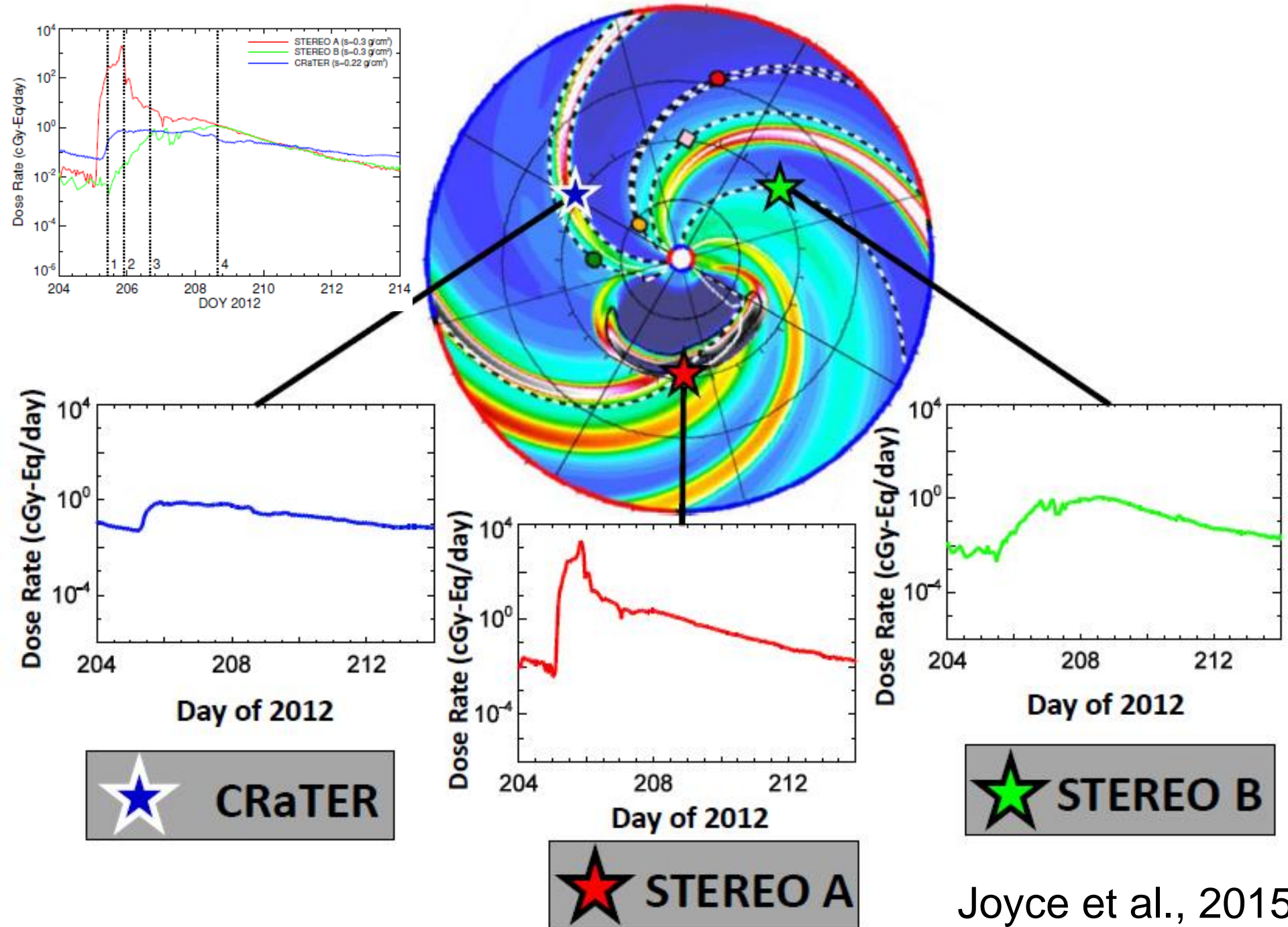


MeWaldt et al., 2015

Schwadron et al., 2017

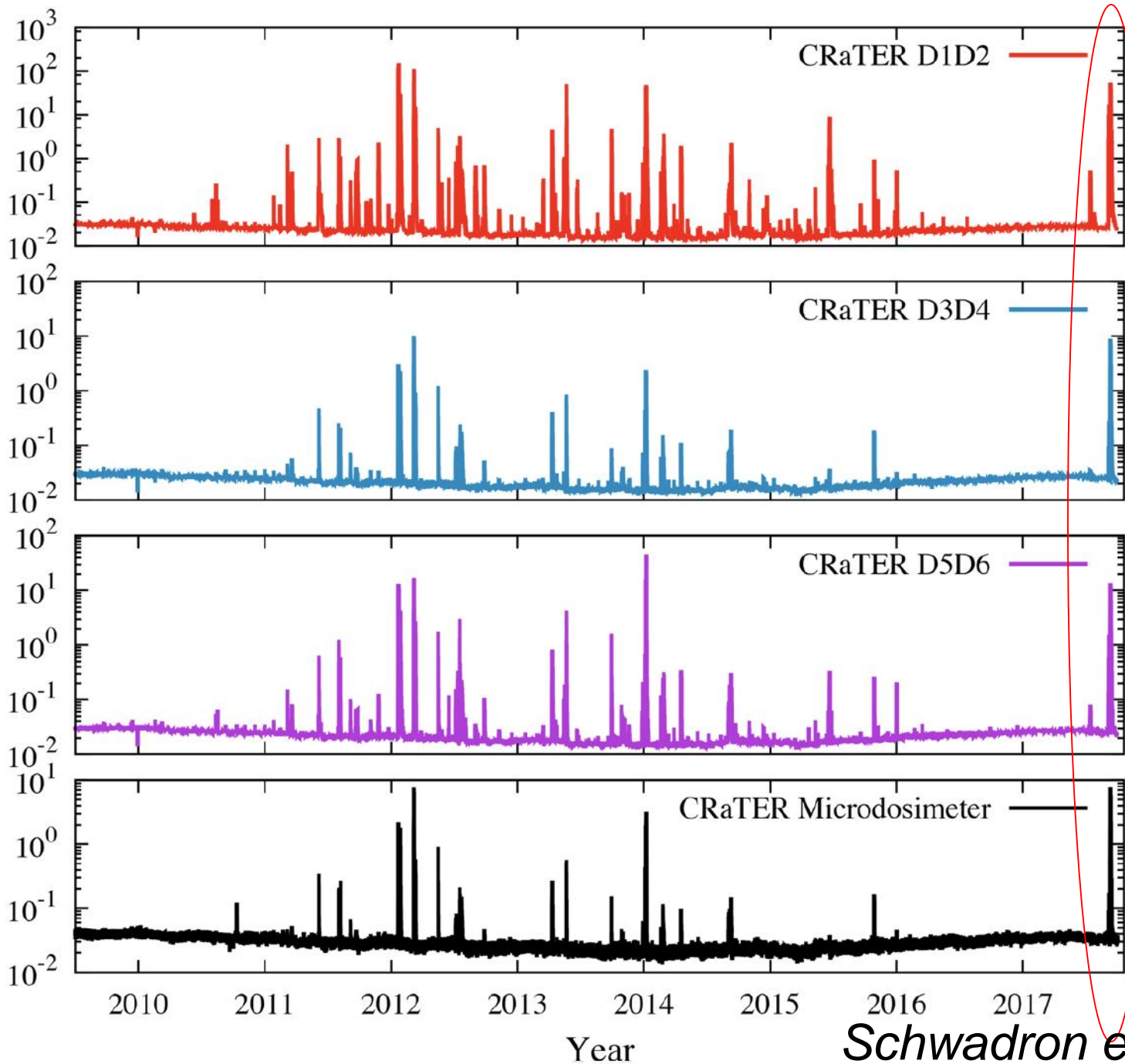






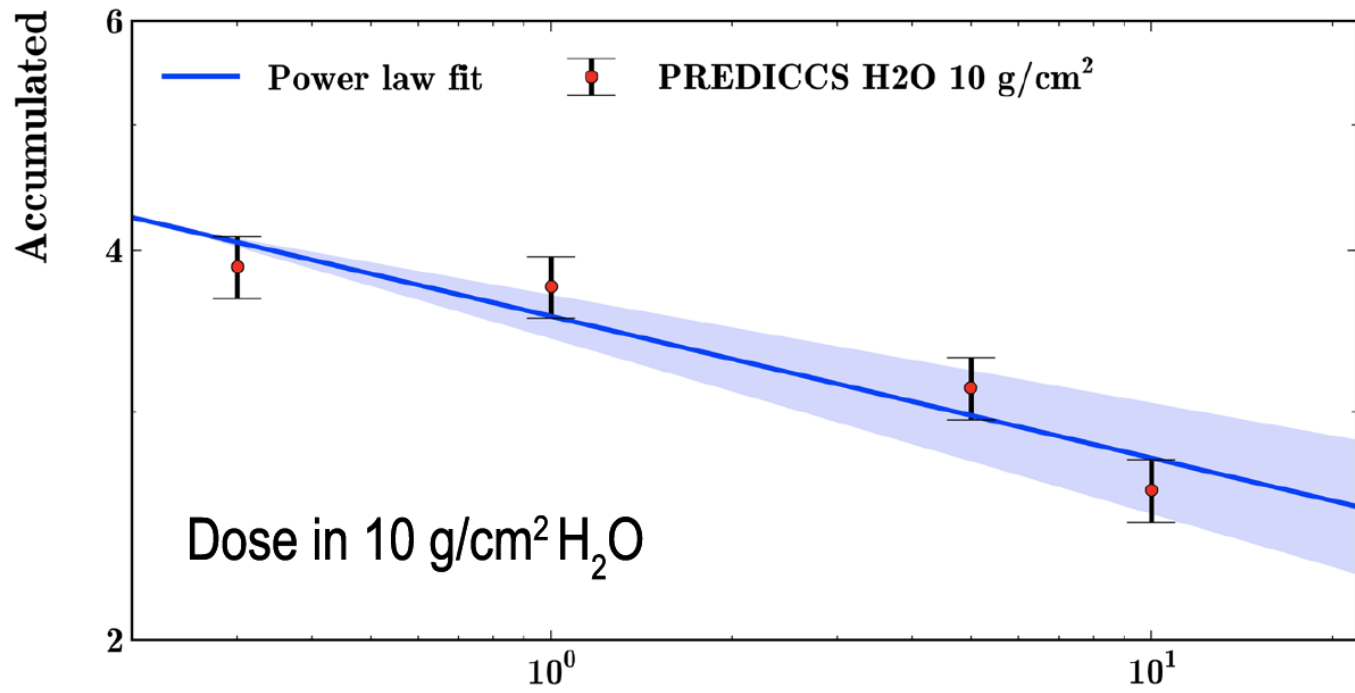
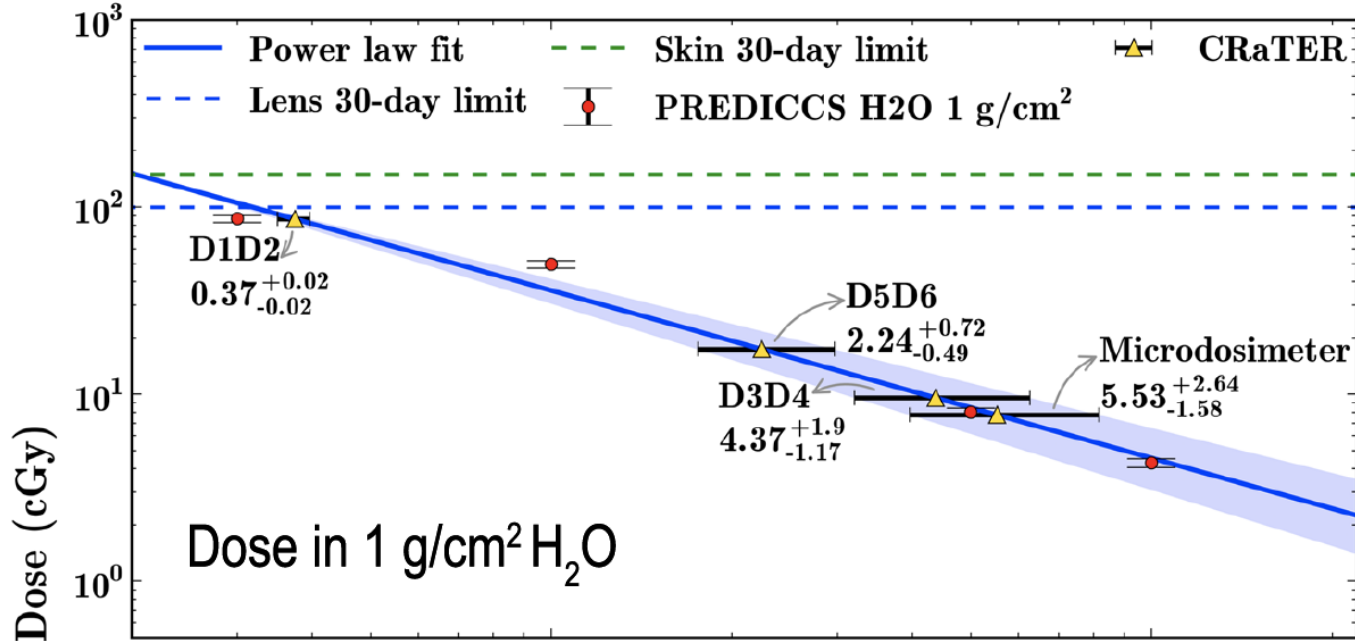
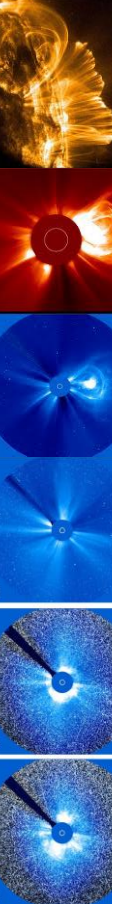
Joyce et al., 2015

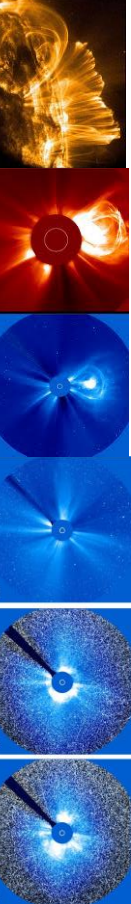
Lunar Dose Rate (cGy/day)



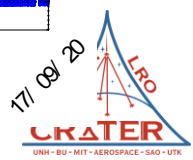
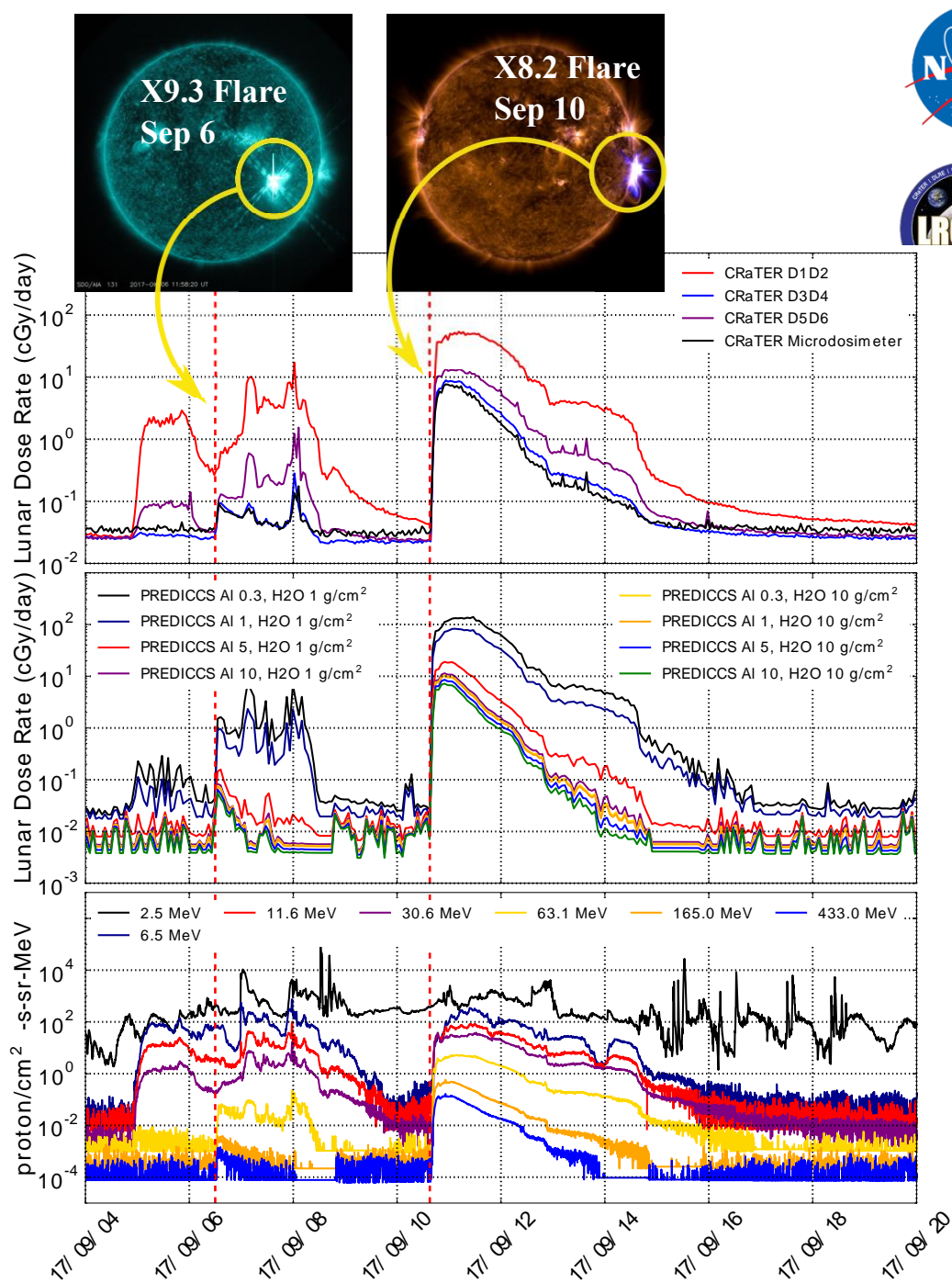
Schwadron et al., 2017



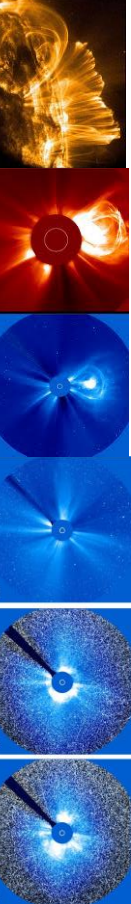




- Example of a large event during decline of cycle 24
- Note importance of seed population

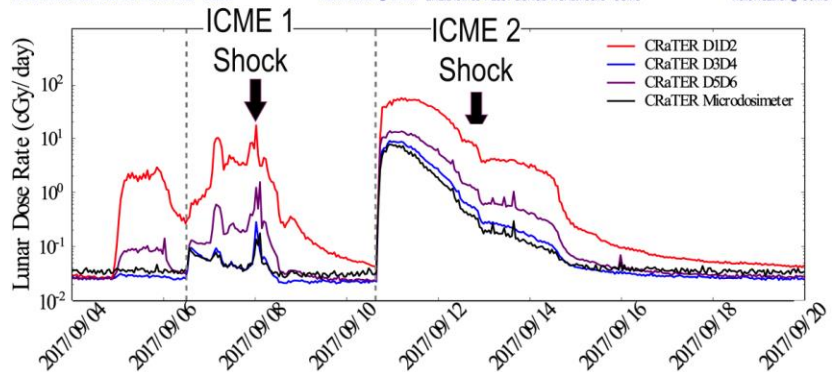
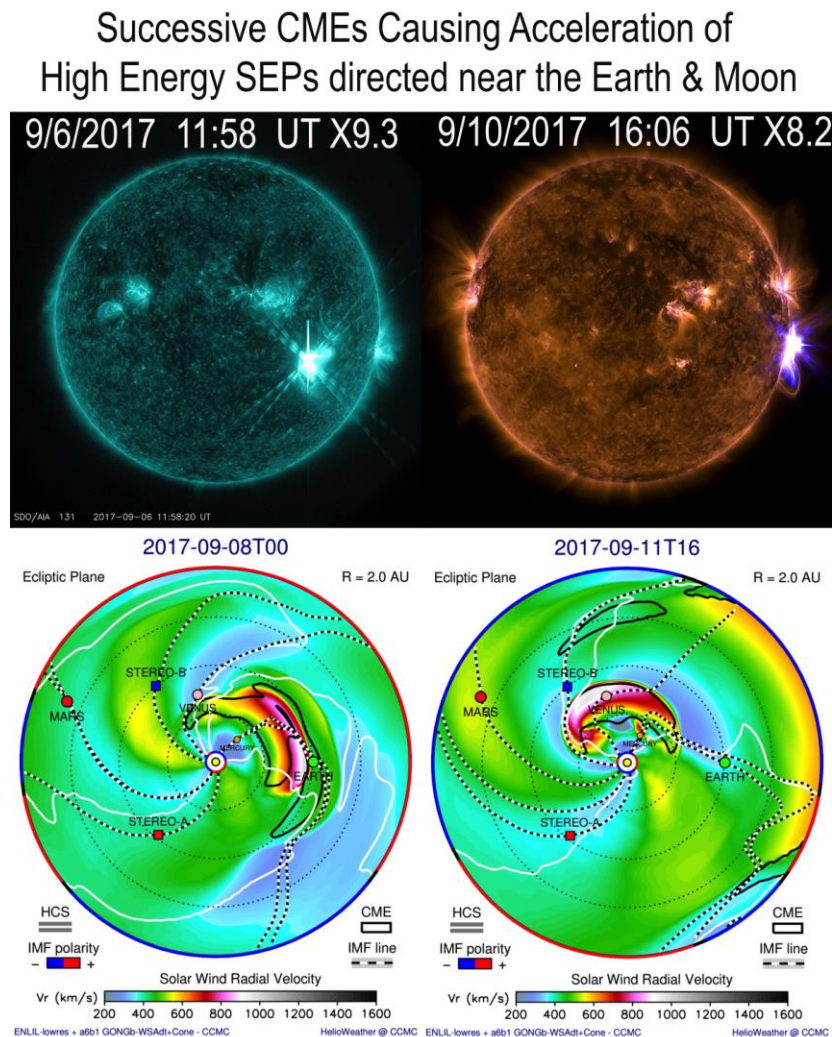


Schwadron et al., 2017



- First event had clear shock, and ESP
- Second event shows prompt acceleration

Schwadron et al., 2017



Conclusions

- Radiation levels continue to increase due to weakening solar activity
- Dose rates even higher than predicted in 2014
- Large events (Sep 2017) in decline of cycle 24 indicate that weak activity does not exclude large SEP events
- Overall, SEP event probabilities still quite low during cycle 24

