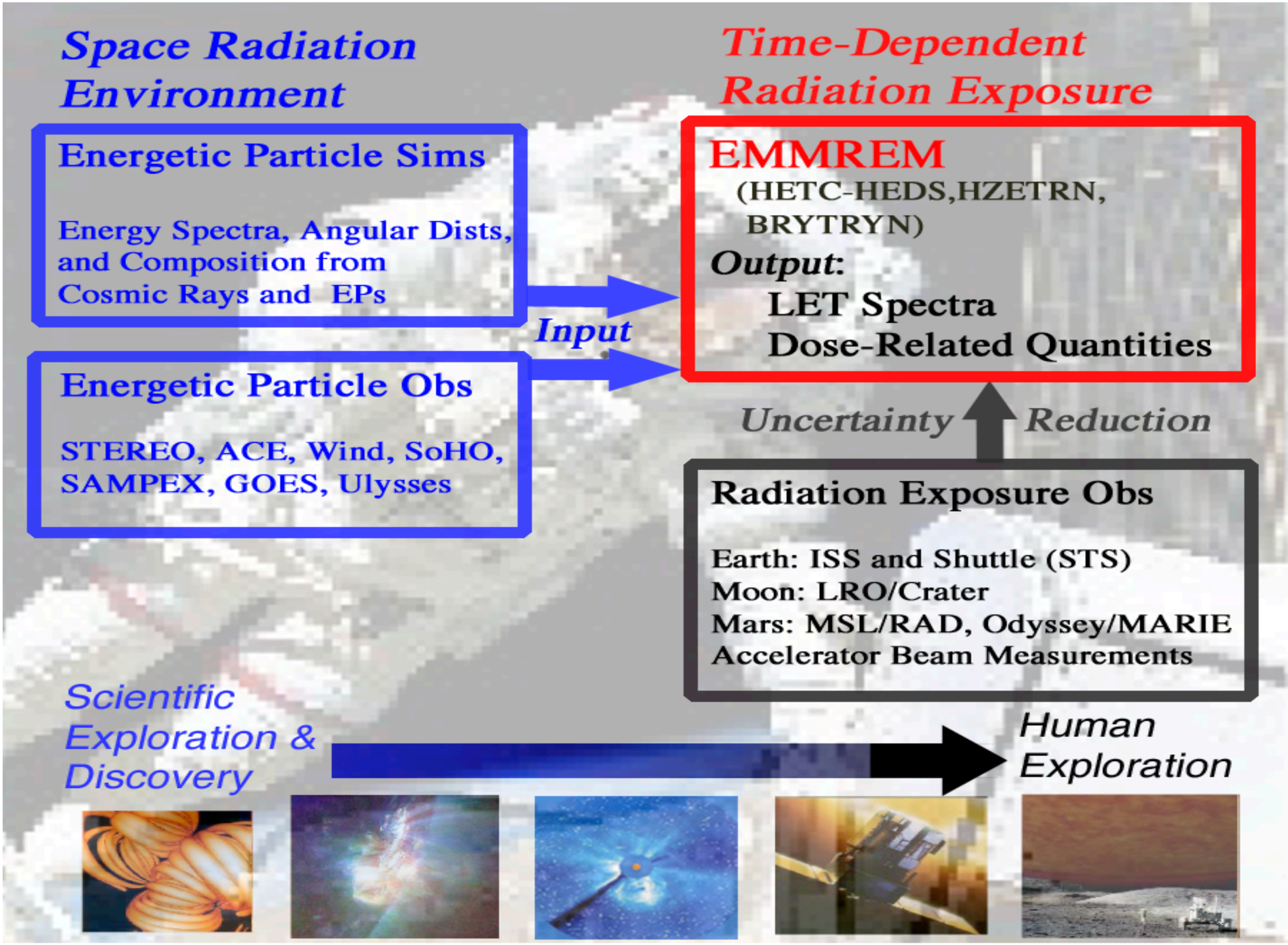
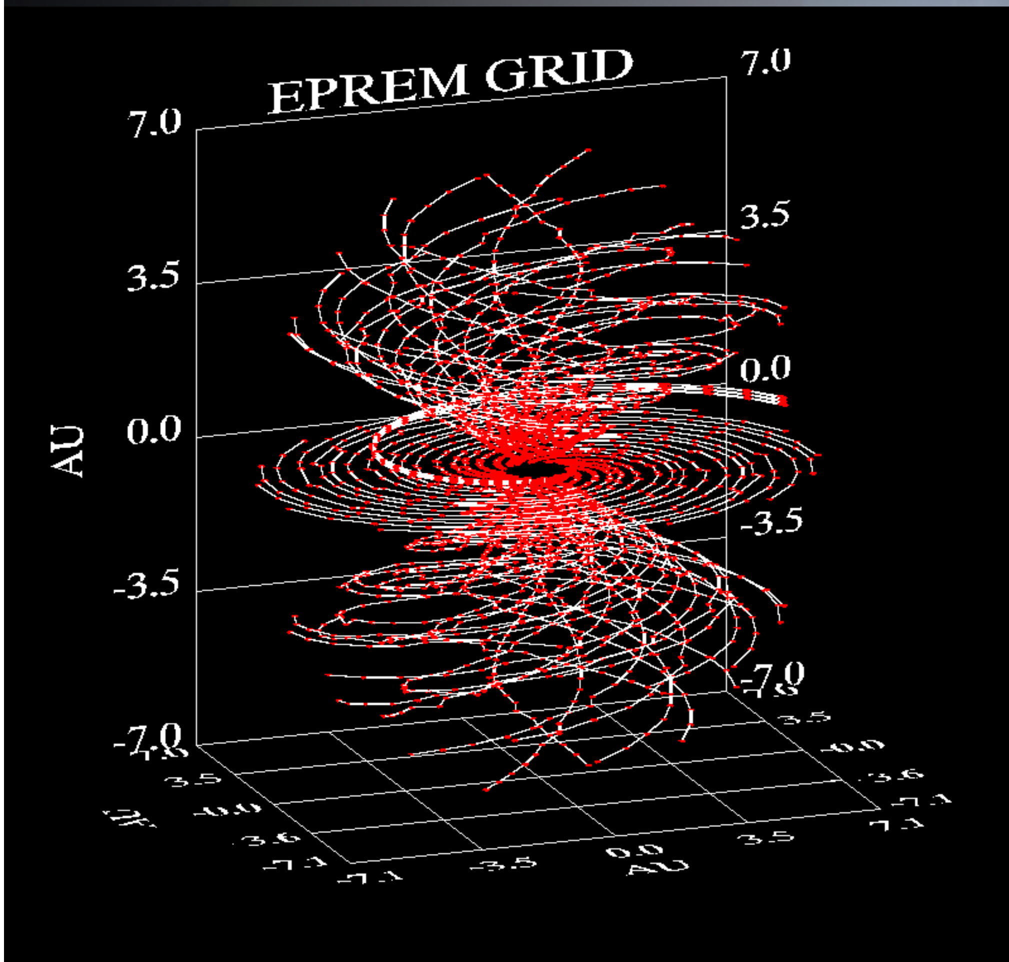
Earth-Moon-Mars Radiation Environment Model, PREDICCS, the Genesis of SEPs (C-SWEPA)

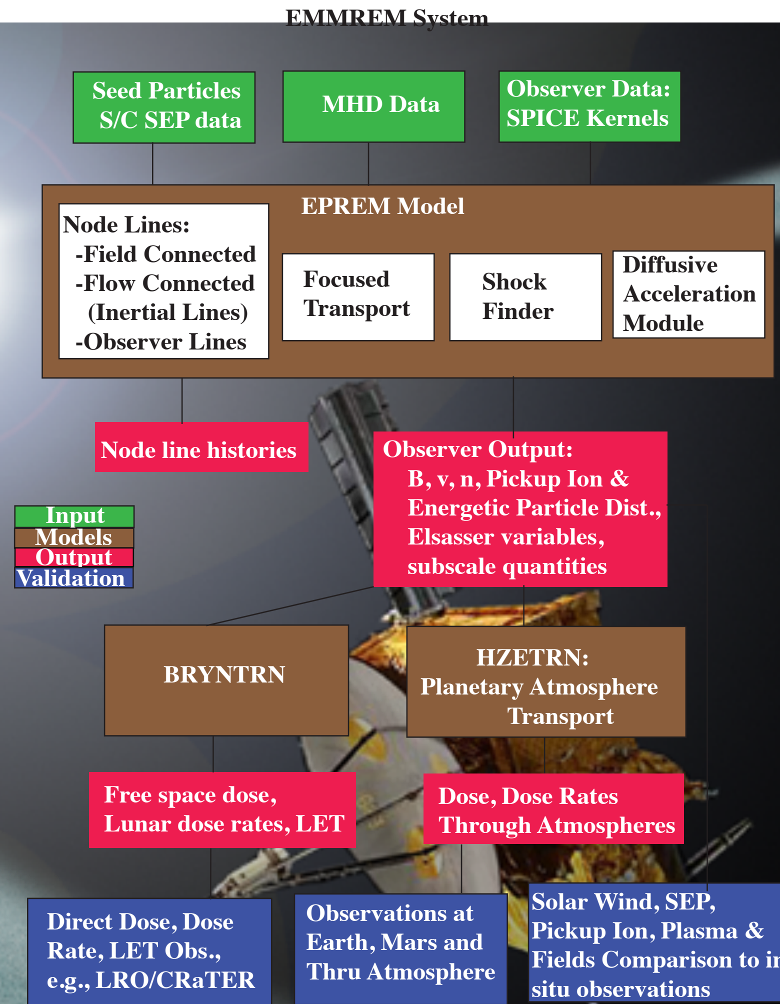
N. A. Schwadron, K. Kozarev, L. Townsend, M. Desai, M. A. Dayeh, F. Cucinotta, D. Hassler, M. Gorby, H. Spence, M. Pourars, E. Wilson, K. Korreck, X. Ao, G. Zank and MANY OTHERS ..


Space Radiation Environment
Energetic Particle Sims
Energy Spectra, Angular Dists, and Composition from Cosmic Rays and EPs
Energetic Particle Obs
STEREO, ACE, Wind, SoHO, SAMPEX, GOES, Ulysses
Input
Time-Dependent Radiation Exposure
EMMREM
(HETC-HEDS,HZETRN, BRYTRYN)
Output:
LET Spectra
Dose-Related Quantities
Uncertainty Reduction
Radiation Exposure Obs
Earth: ISS and Shuttle (STS)
Moon: LRO/Crater
Mars: MSL/RAD, Odyssey/MARIE
Accelerator Beam Measurements
Scientific Exploration & Discovery
Human Exploration

Accomplishments

- *Radiation Biology*
  - Risk models
  - Radiation Transport
    - Interplanetary Space
    - Earth, Moon, Mars
- *EPREM*
  - Transport Particle Acceleration
  - Particle radiation throughout inner helioshere
  - Earth, Moon, Mars
- *EPREM-MHD*
  - Transport Effects
  - Particle Acceleration
- *Validation*
  - Marie
  - CRaTER
  - MSL/Rad
- *PREDICCS*
  - Near Real-time Space Radiation Awareness
- *Extended Solar Minimum Science*
- *EMMREM Special Section (Spaceweather Journal; currently, 12 papers)*
- *Approaching 45 accepted papers using EMMREM & EPREM directly*
- *PREDICCS & EMMREM a significant component of LRO/ CRaTER special issue*





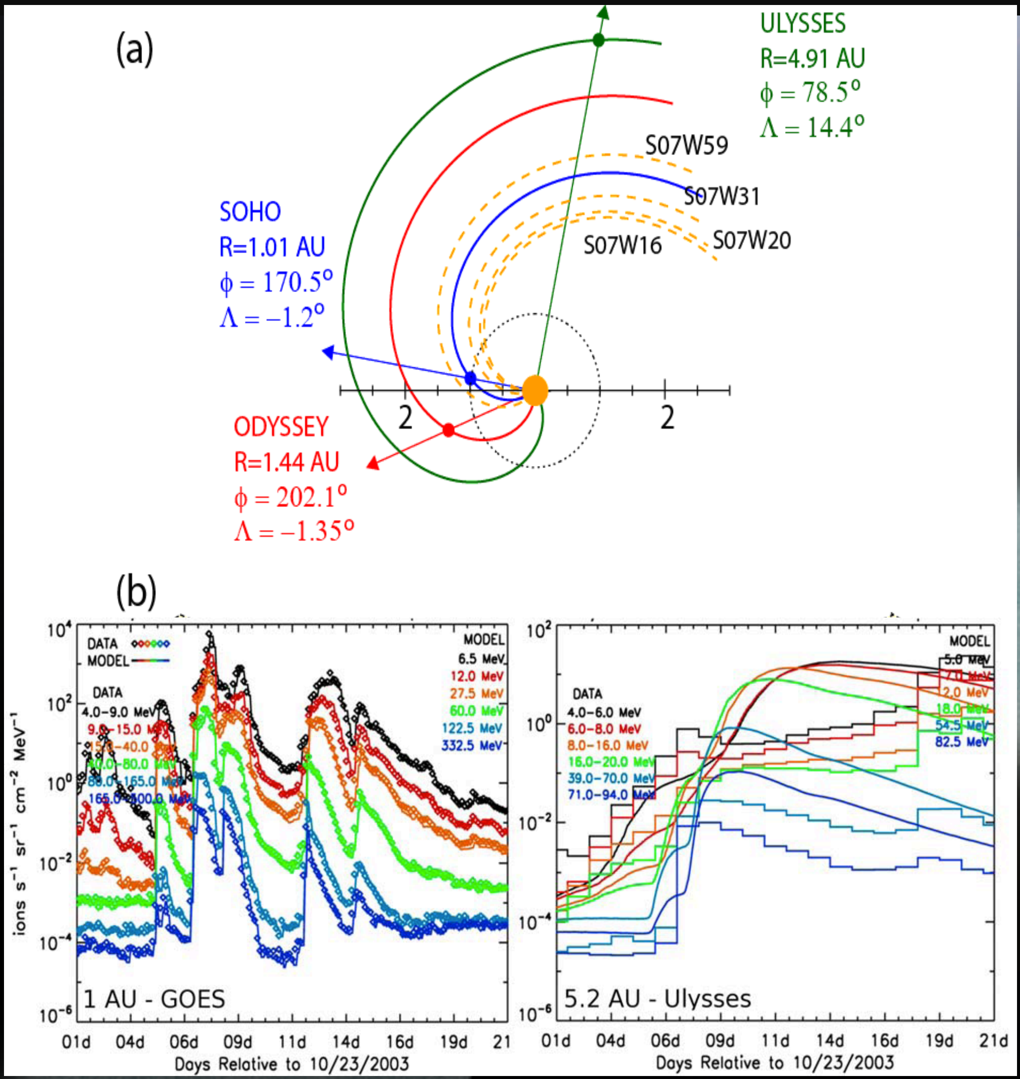
Focused Transport in Lagrangian Frame (Kota, 2005)

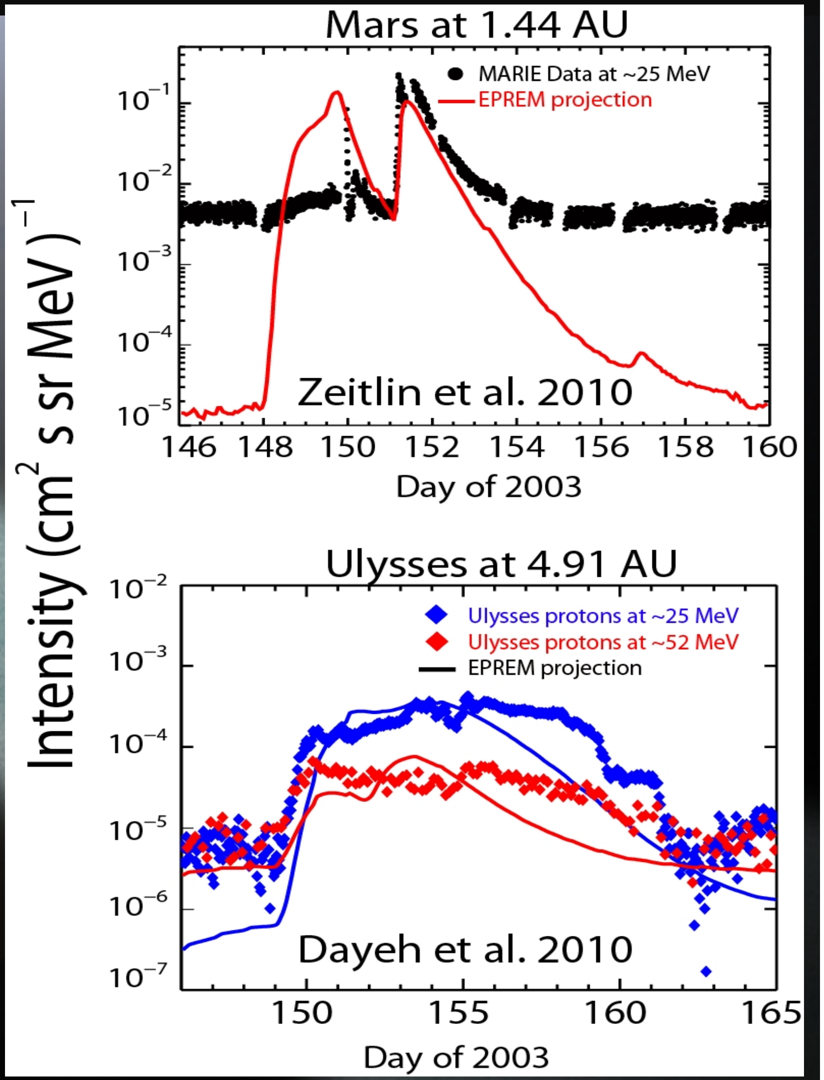
$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial\ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial\mu}+$$

$$\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial\ln p}=\frac{\partial}{\partial\mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\right)+S$$

- Cross-field Diffusion
- Drift

EMMREM has proved very successful at predicting SEP spectra and radiation dose estimates at different distances 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.



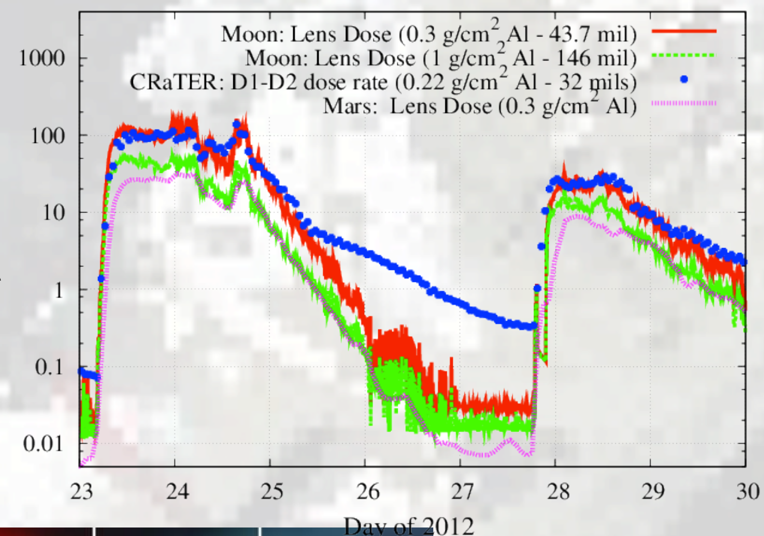


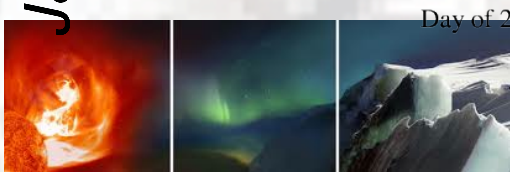
Validation with CRaTER

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*

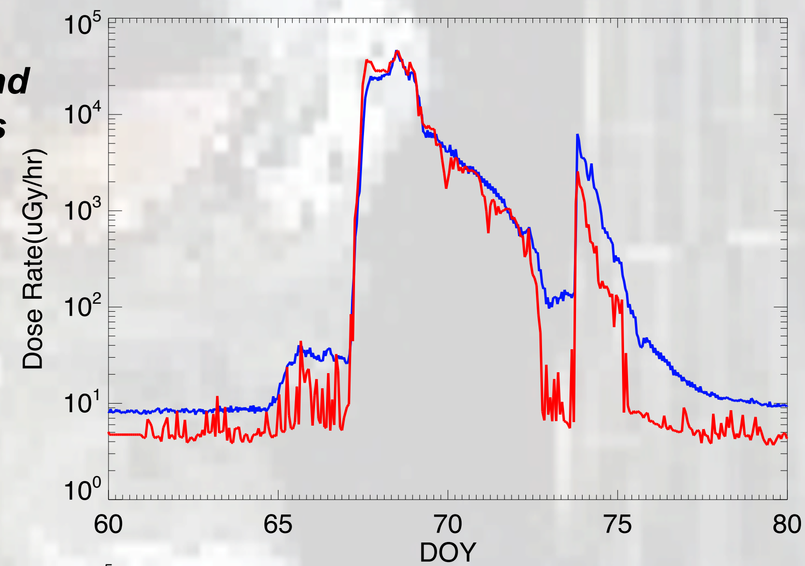
Jan. 23rd, 2012 Event



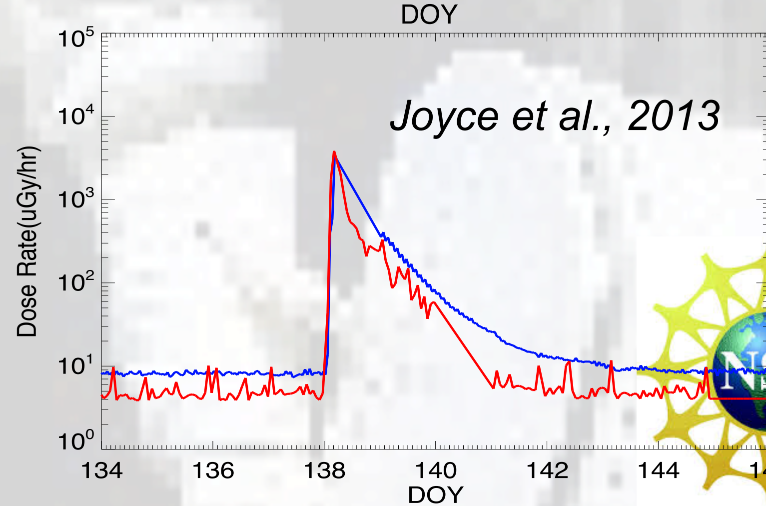


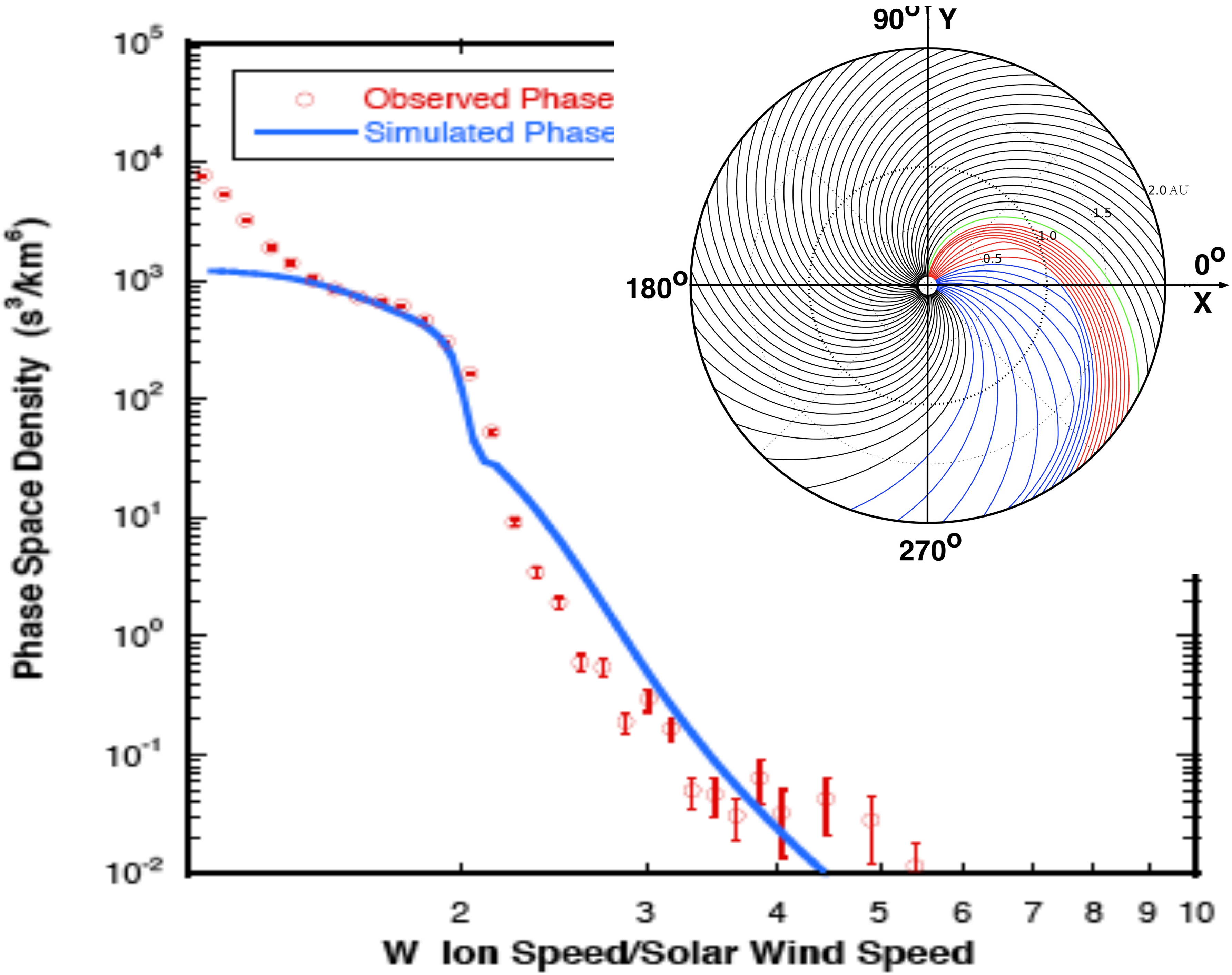
Schwadron et al., 2013

Mar 7, 2012 Event



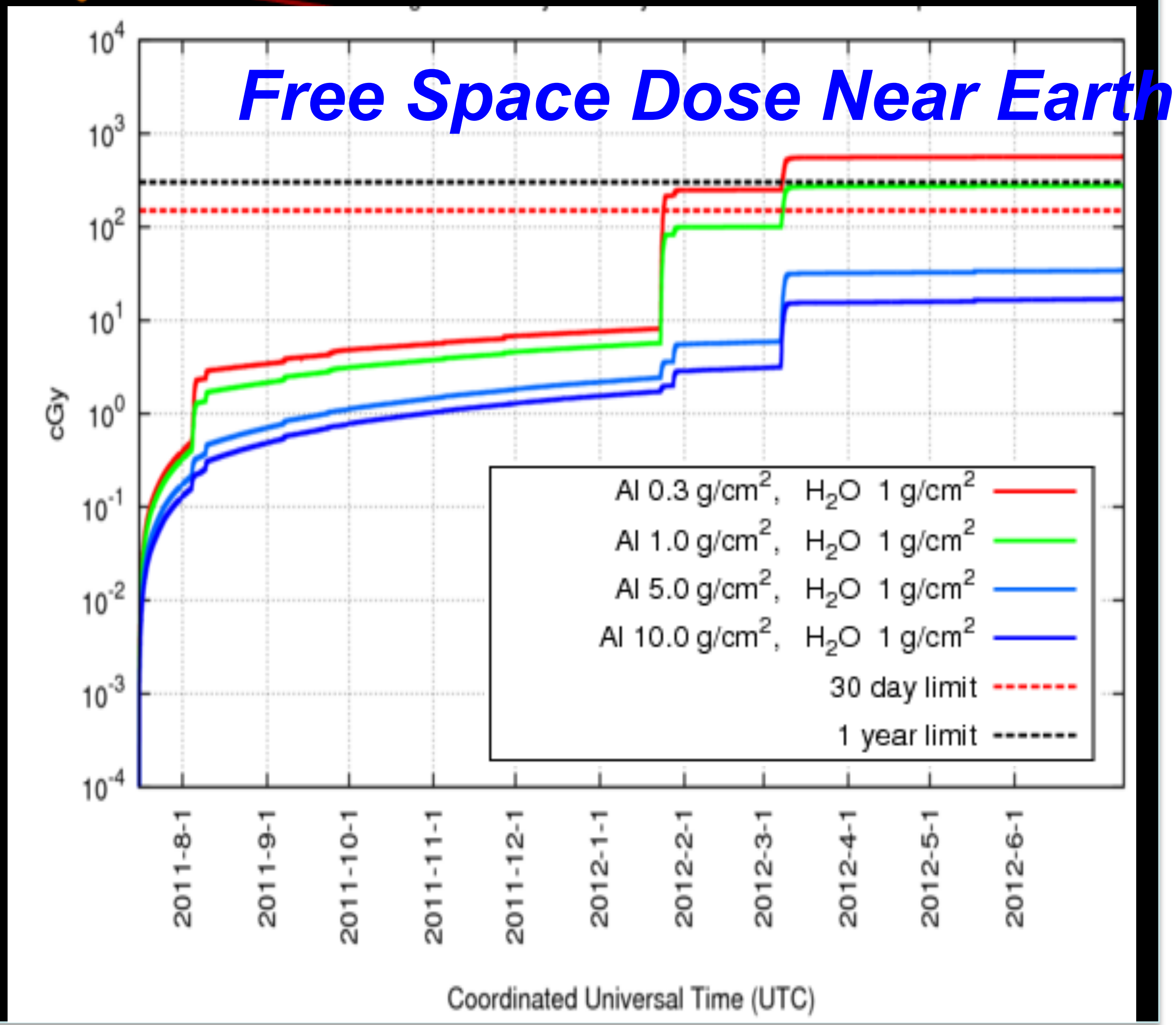
May 16, 2012 Event



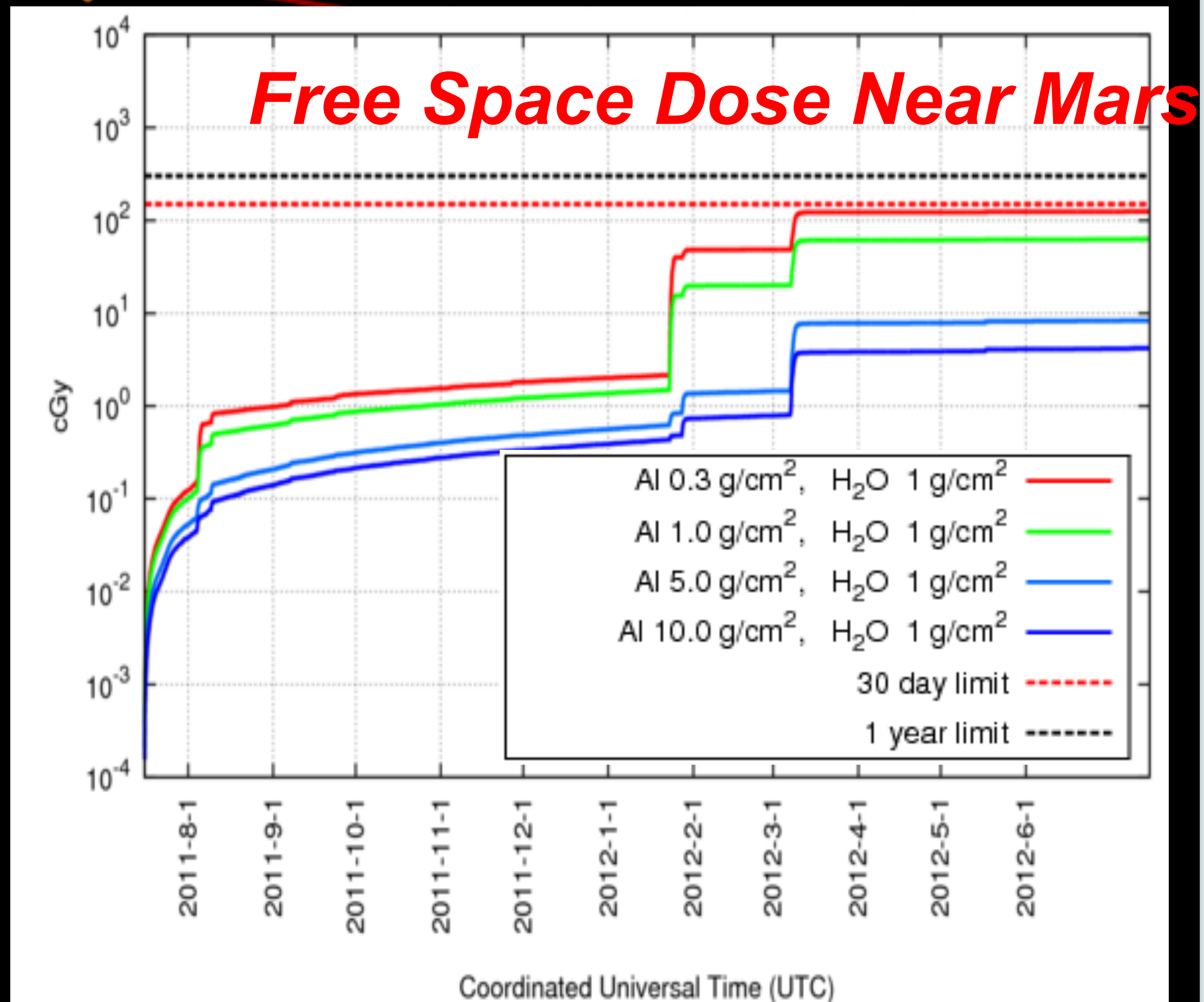


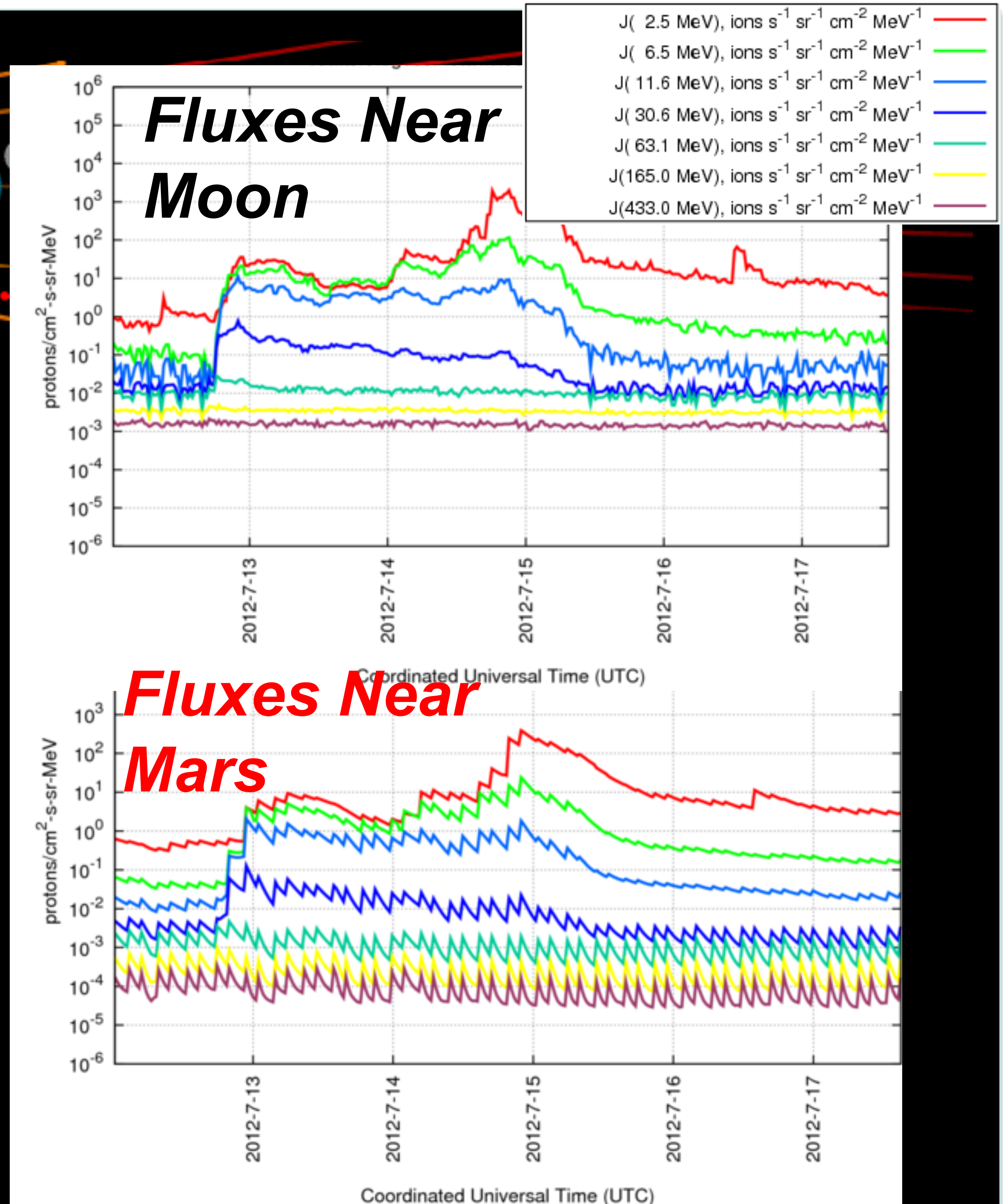
Observed Phase
Simulated Phase
Phase Space Density (s³/km⁶)
W Ion Speed/Solar Wind Speed
90° Y
180°
0°
X
270°
2.0 AU
1.5
1.0
0.5

- System for Radiation Environment characterization (fluxes, doses, dose equivalents at Earth, Moon and Mars) on hourly thru yearly time frame
- Example: Snapshots of Current Yearly Doses at Earth and Mars
- Note: Exceeding 1-yr Free Space Dose Limits at Earth and Moon for < 1 g/cm² Al Shielding
- See more at http://prediccs.sr.unh.edu/

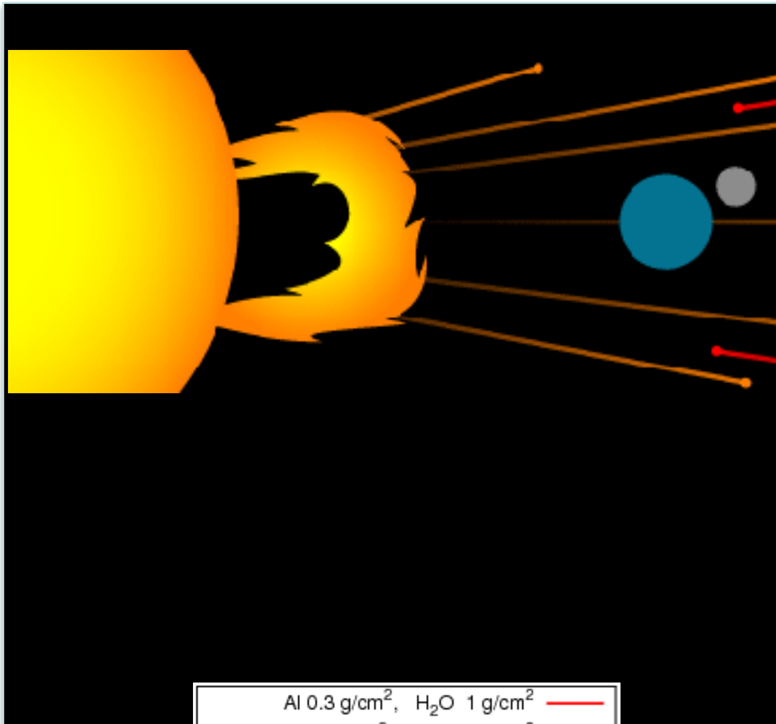


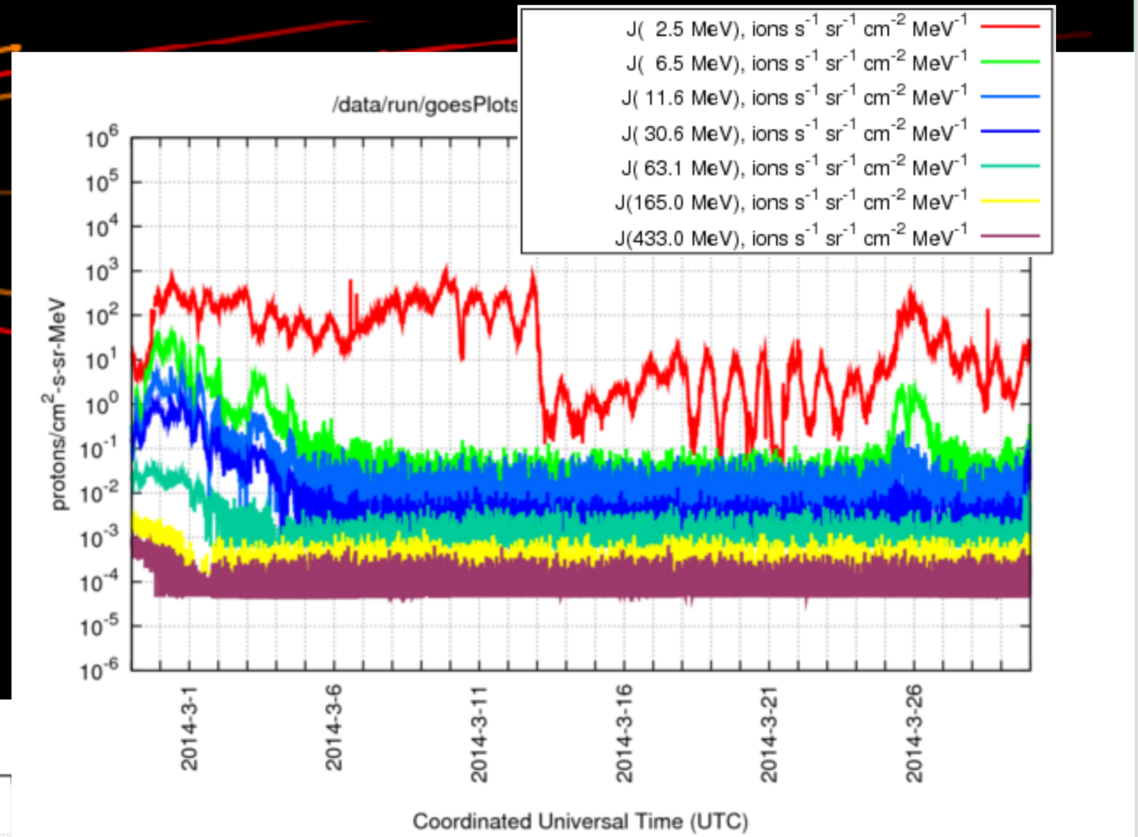
- *Approaching 1-yr Free Space Dose Limits at Mars*
- *See more at http://prediccs.sr.unh.edu/*



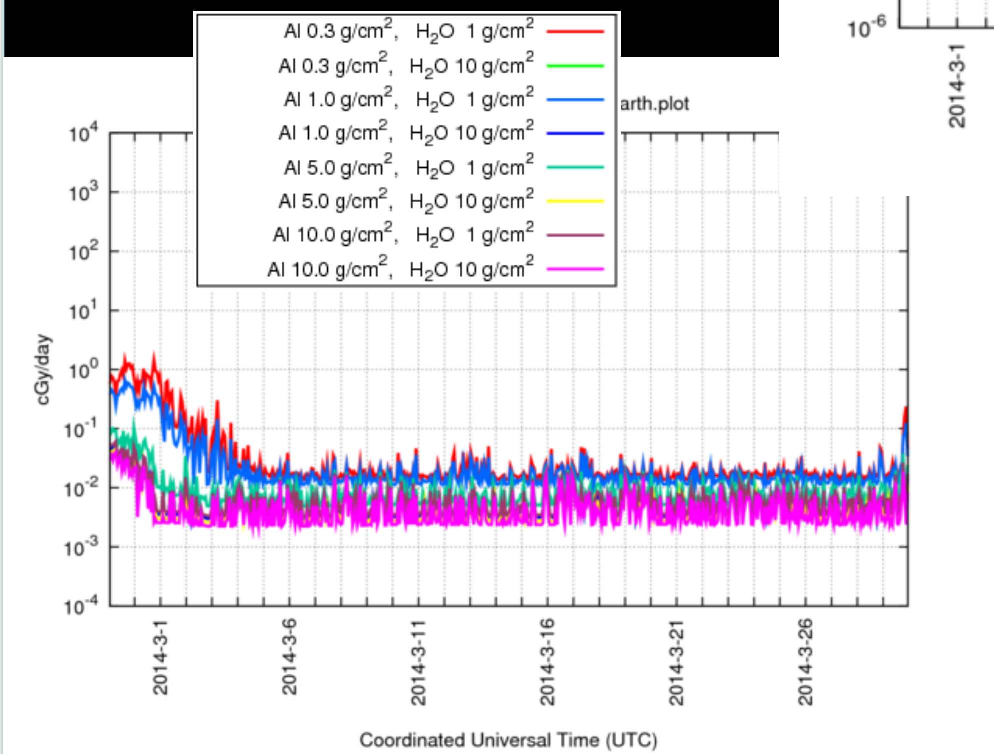


- *Hourly updates (Earth, Moon, Mars) give time-critical updates on space radiation at Earth, Moon & Mars*
- *Shown Here recent 7/12/2012 and 7/15/2012 events at Moon and Mars*



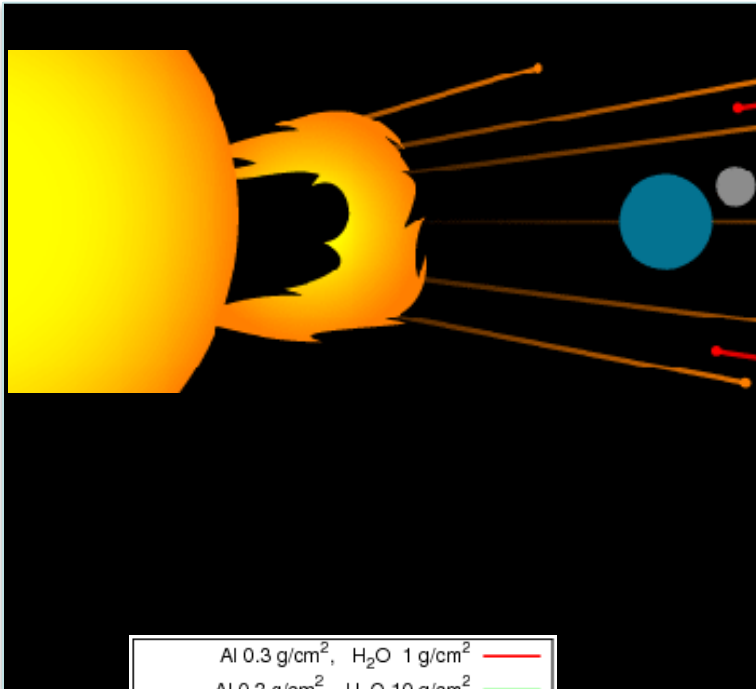


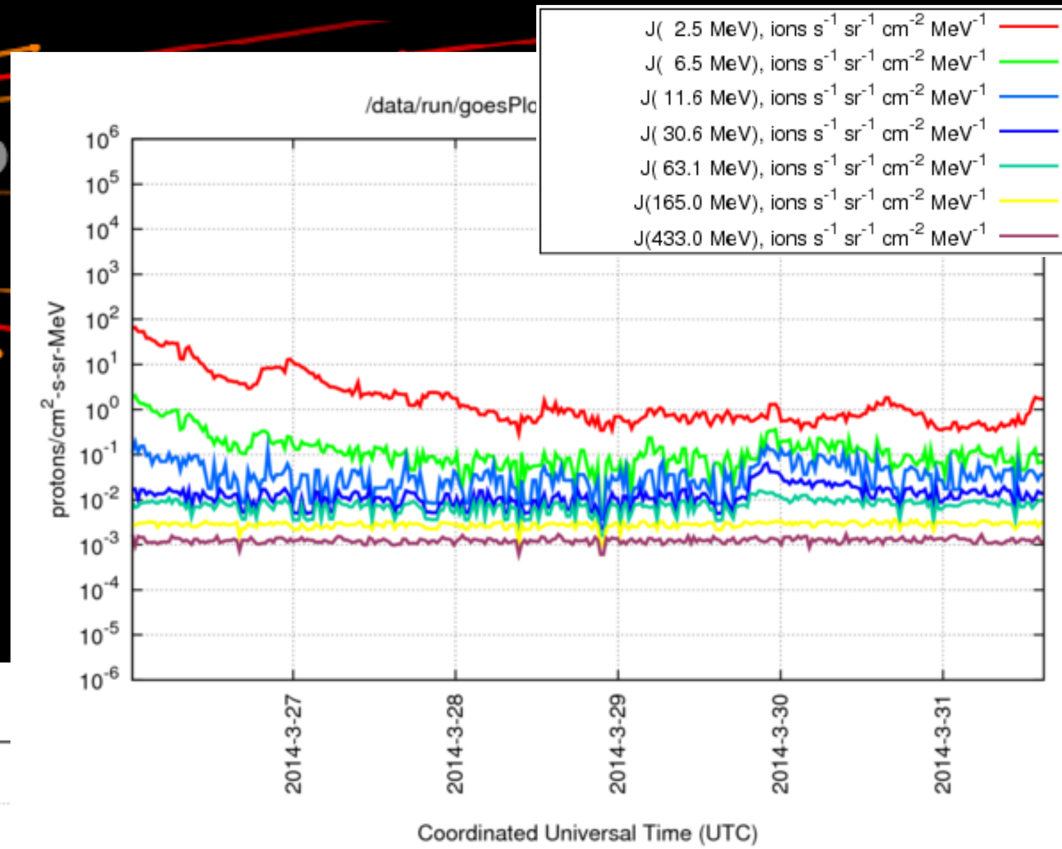
/data/run/goesPlots
J(2.5 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(6.5 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(11.6 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(30.6 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(63.1 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(165.0 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
J(433.0 MeV), ions s^-1 sr^-1 cm^-2 MeV^-1
protons/cm^2-s-sr-MeV
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
2014-3-1
2014-3-6
2014-3-11
2014-3-16
2014-3-21
2014-3-26
Coordinated Universal Time (UTC)



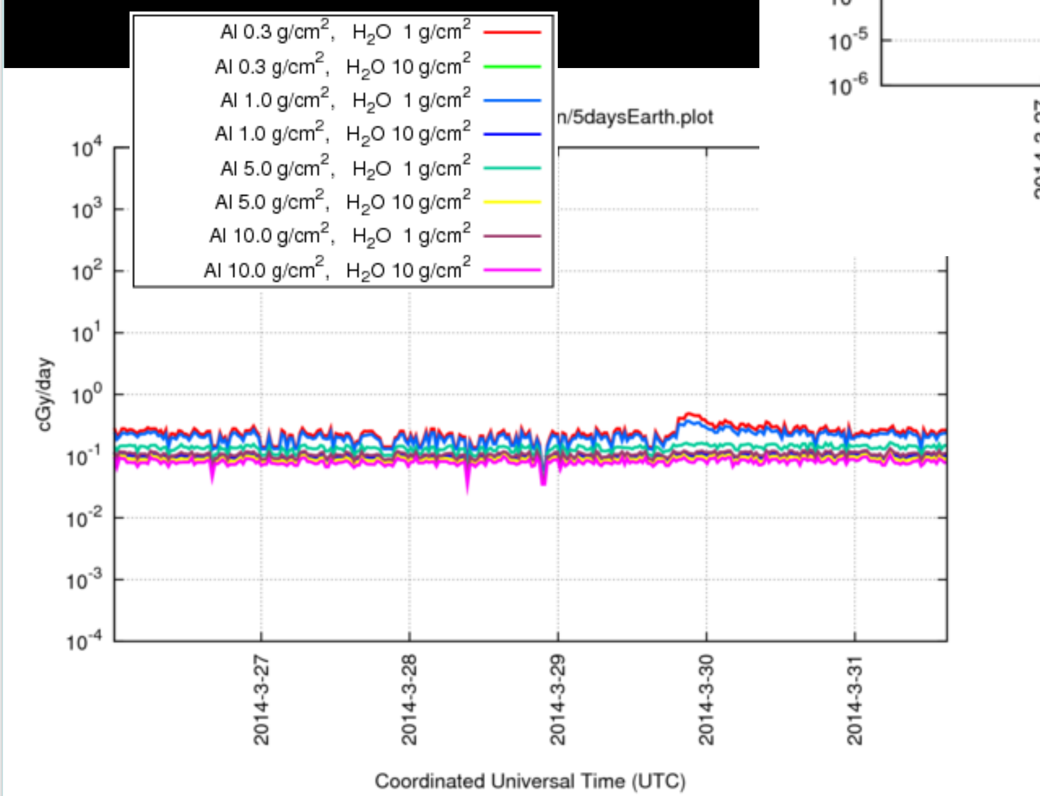
arth.plot
Al 0.3 g/cm^2, H2O 1 g/cm^2
Al 0.3 g/cm^2, H2O 10 g/cm^2
Al 1.0 g/cm^2, H2O 1 g/cm^2
Al 1.0 g/cm^2, H2O 10 g/cm^2
Al 5.0 g/cm^2, H2O 1 g/cm^2
Al 5.0 g/cm^2, H2O 10 g/cm^2
Al 10.0 g/cm^2, H2O 1 g/cm^2
Al 10.0 g/cm^2, H2O 10 g/cm^2
cGy/day
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
2014-3-1
2014-3-6
2014-3-11
2014-3-16
2014-3-21
2014-3-26
Coordinated Universal Time (UTC)

- Past 30 days



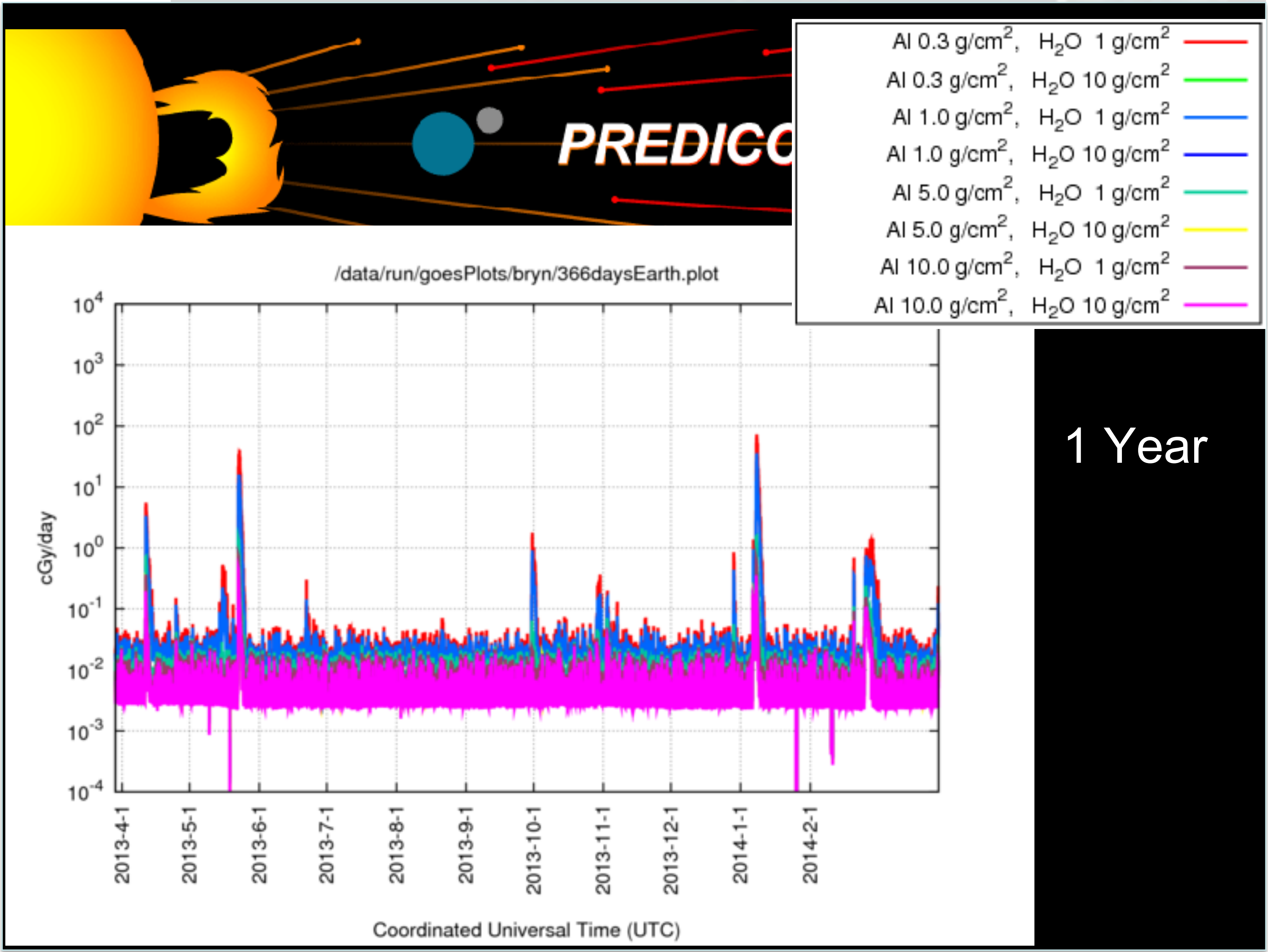


J(2.5 MeV), ions s-1 sr-1 cm-2 MeV-1
J(6.5 MeV), ions s-1 sr-1 cm-2 MeV-1
J(11.6 MeV), ions s-1 sr-1 cm-2 MeV-1
J(30.6 MeV), ions s-1 sr-1 cm-2 MeV-1
J(63.1 MeV), ions s-1 sr-1 cm-2 MeV-1
J(165.0 MeV), ions s-1 sr-1 cm-2 MeV-1
J(433.0 MeV), ions s-1 sr-1 cm-2 MeV-1
/data/run/goesPlo
protons/cm2-s-sr-MeV
2014-3-27
2014-3-28
2014-3-29
2014-3-30
2014-3-31
Coordinated Universal Time (UTC)



Al 0.3 g/cm2, H2O 1 g/cm2
Al 0.3 g/cm2, H2O 10 g/cm2
Al 1.0 g/cm2, H2O 1 g/cm2
Al 1.0 g/cm2, H2O 10 g/cm2
Al 5.0 g/cm2, H2O 1 g/cm2
Al 5.0 g/cm2, H2O 10 g/cm2
Al 10.0 g/cm2, H2O 1 g/cm2
Al 10.0 g/cm2, H2O 10 g/cm2
n/5daysEarth.plot
cGy/day
2014-3-27
2014-3-28
2014-3-29
2014-3-30
2014-3-31
Coordinated Universal Time (UTC)

- Now!

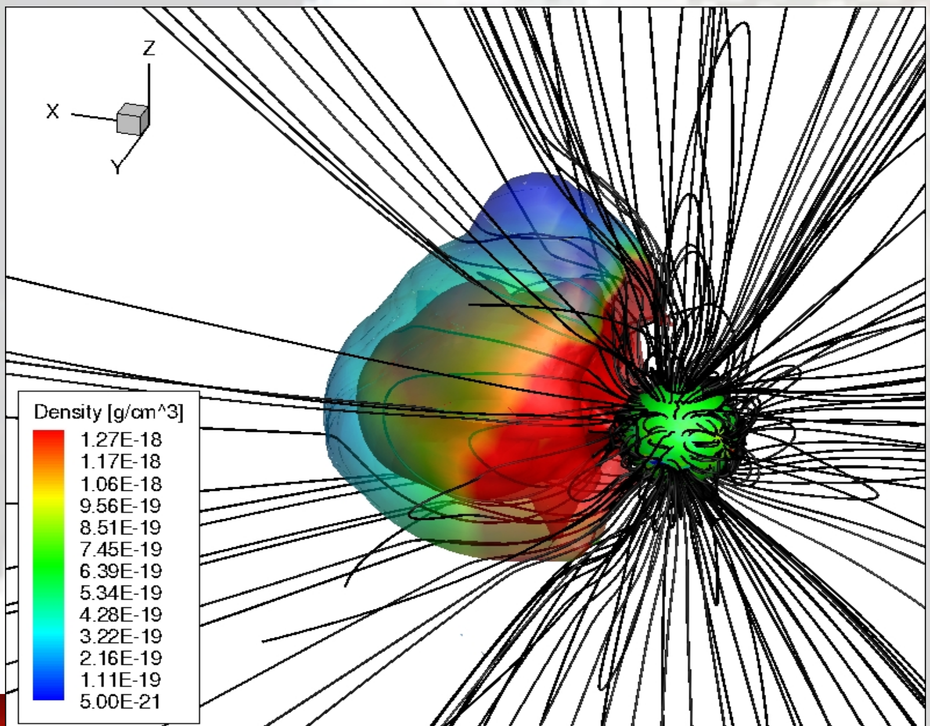

PREDICC
Al 0.3 g/cm², H₂O 1 g/cm²
Al 0.3 g/cm², H₂O 10 g/cm²
Al 1.0 g/cm², H₂O 1 g/cm²
Al 1.0 g/cm², H₂O 10 g/cm²
Al 5.0 g/cm², H₂O 1 g/cm²
Al 5.0 g/cm², H₂O 10 g/cm²
Al 10.0 g/cm², H₂O 1 g/cm²
Al 10.0 g/cm², H₂O 10 g/cm²
/data/run/goesPlots/bryn/366daysEarth.plot
cGy/day
Coordinated Universal Time (UTC)
2013-4-1
2013-5-1
2013-6-1
2013-7-1
2013-8-1
2013-9-1
2013-10-1
2013-11-1
2013-12-1
2014-1-1
2014-2-1

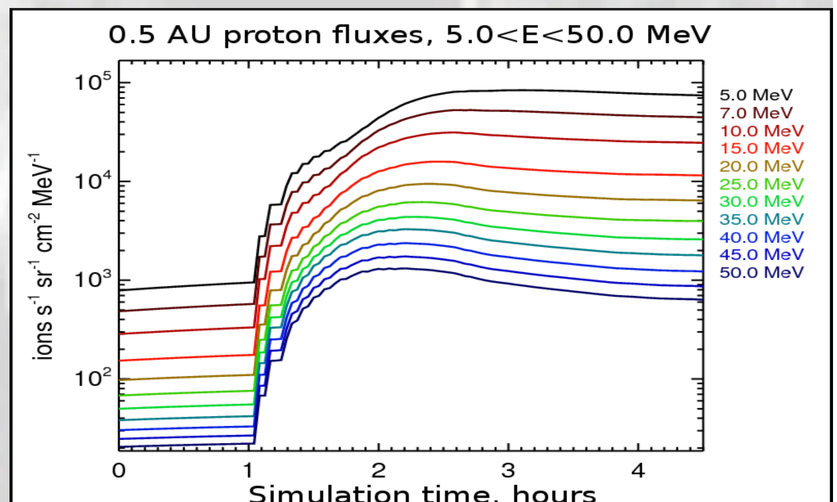
1 Year

EMMREM-MHD Coupling – Shock Acceleration from Seed Populations

Kozarev et al., ApJ 2013

Jack Eddy Fellow
SAO/CfA

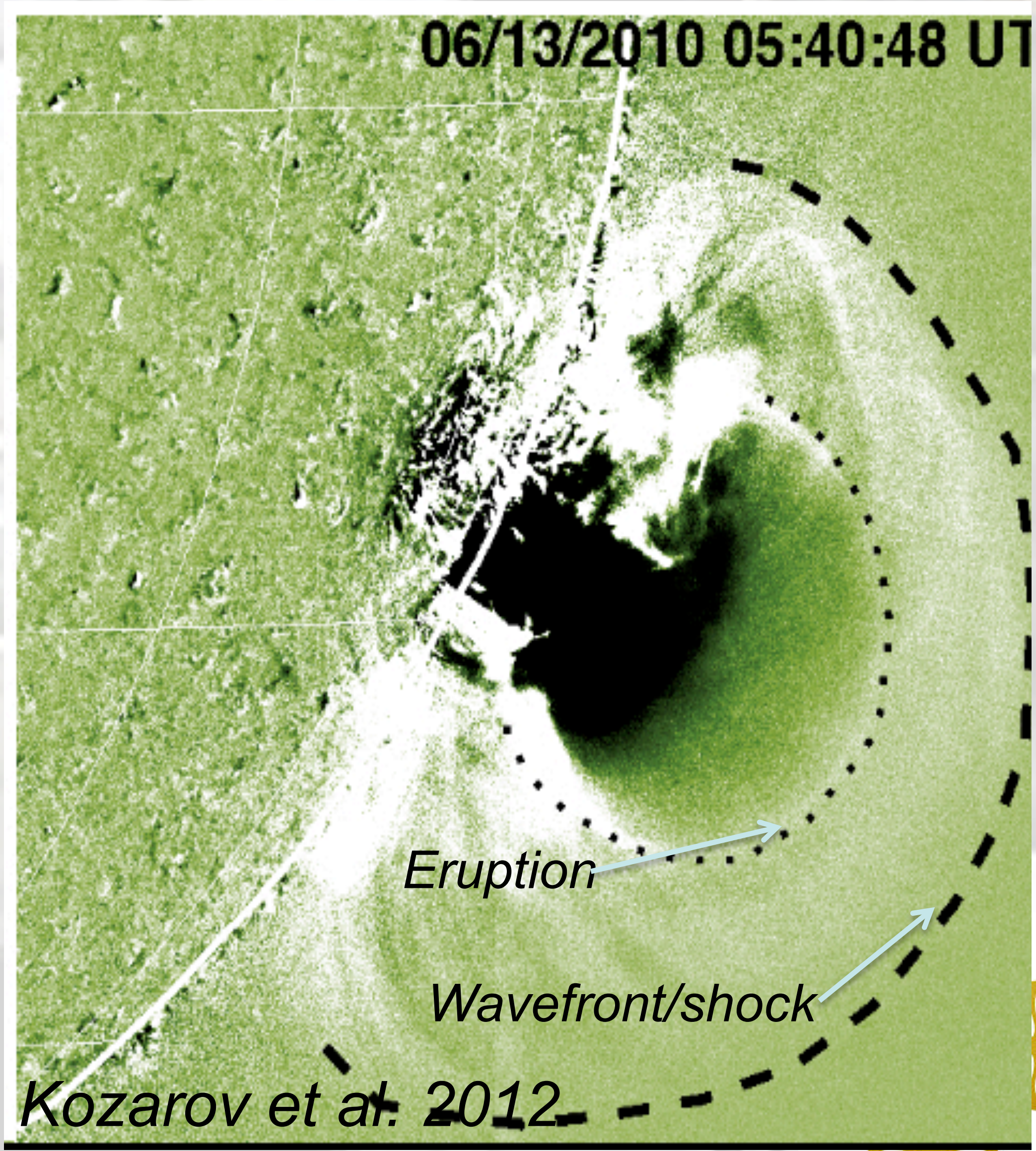


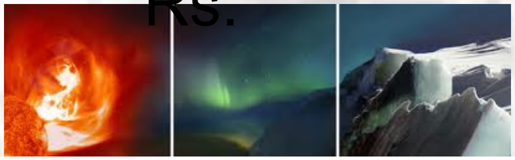


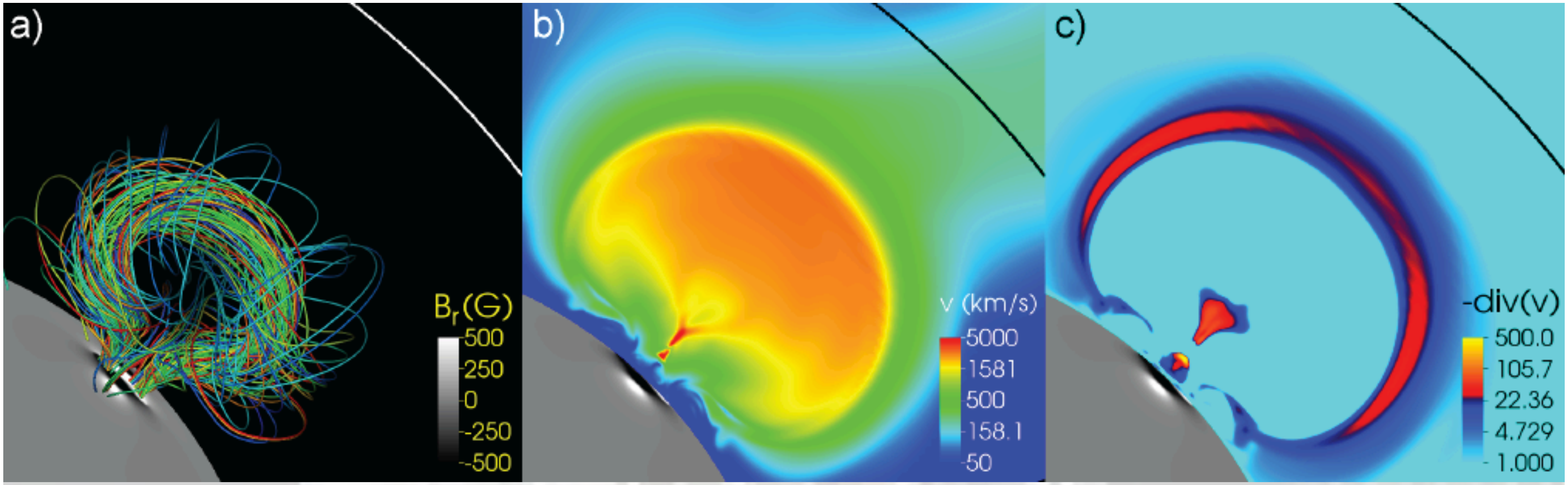
Remote Observations Showing Events from the Low Corona

Formation of acceleration regions (from shocks and compressions) in the low corona critical missing piece in understanding sudden SEP onsets.

- AIA/211 image shows a stage of the 2010 June 13 coronal wave with
- The shock was formed at ~1.2 Rs and observed here at 1.4 Rs.

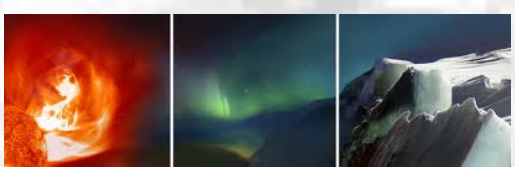






Titov et al., 2013

- Insert modified version of the flux rope model by Titov & Demoulin (1999) above the central polarity inversion line of AR.
  - AR + Flux Rope total unsigned flux of 7.5 x 10^{22} Mx
  - Max radial-field strength of 1070 G at the photospheric level



EMMREM

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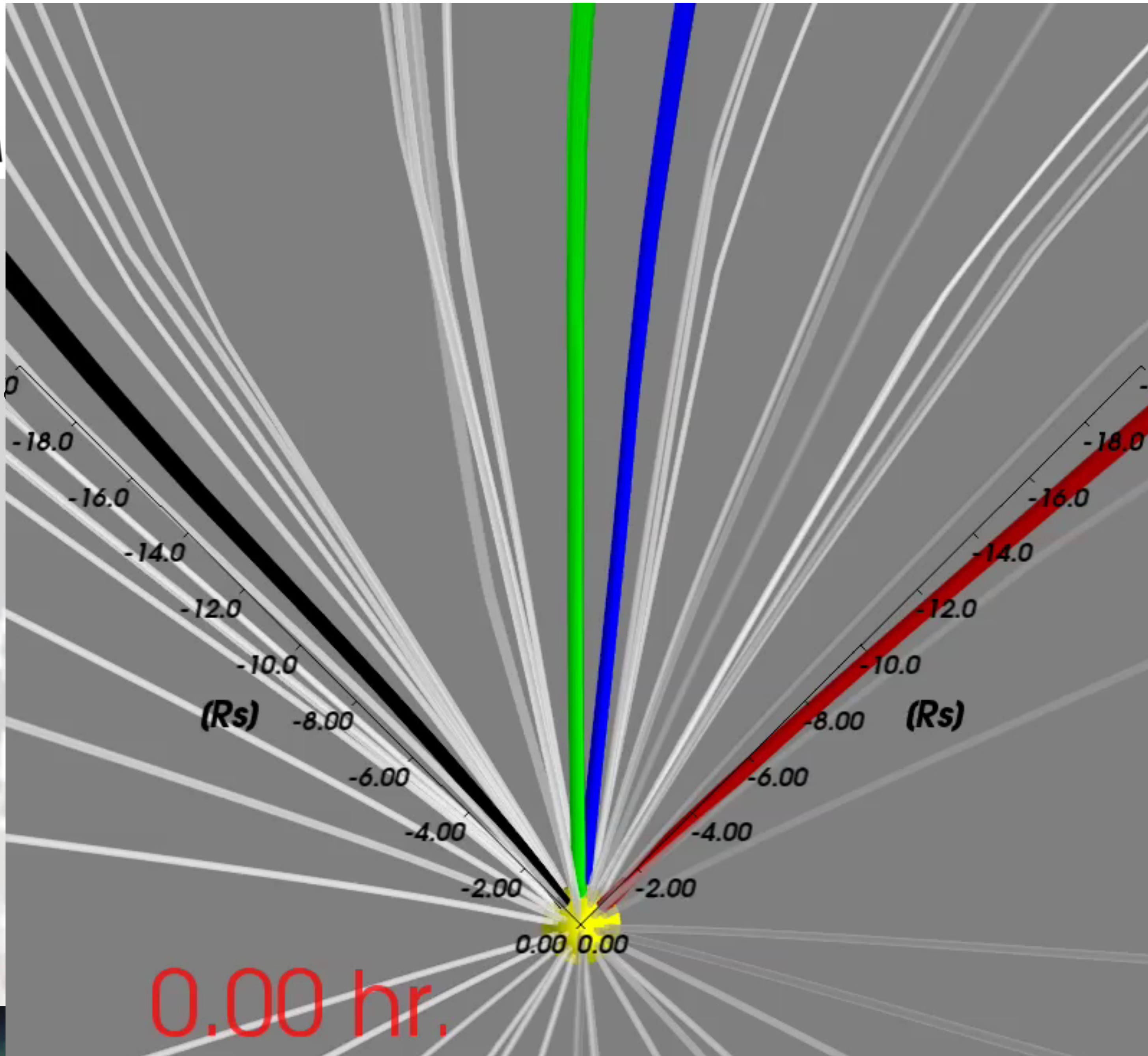
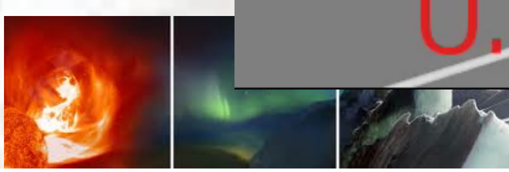
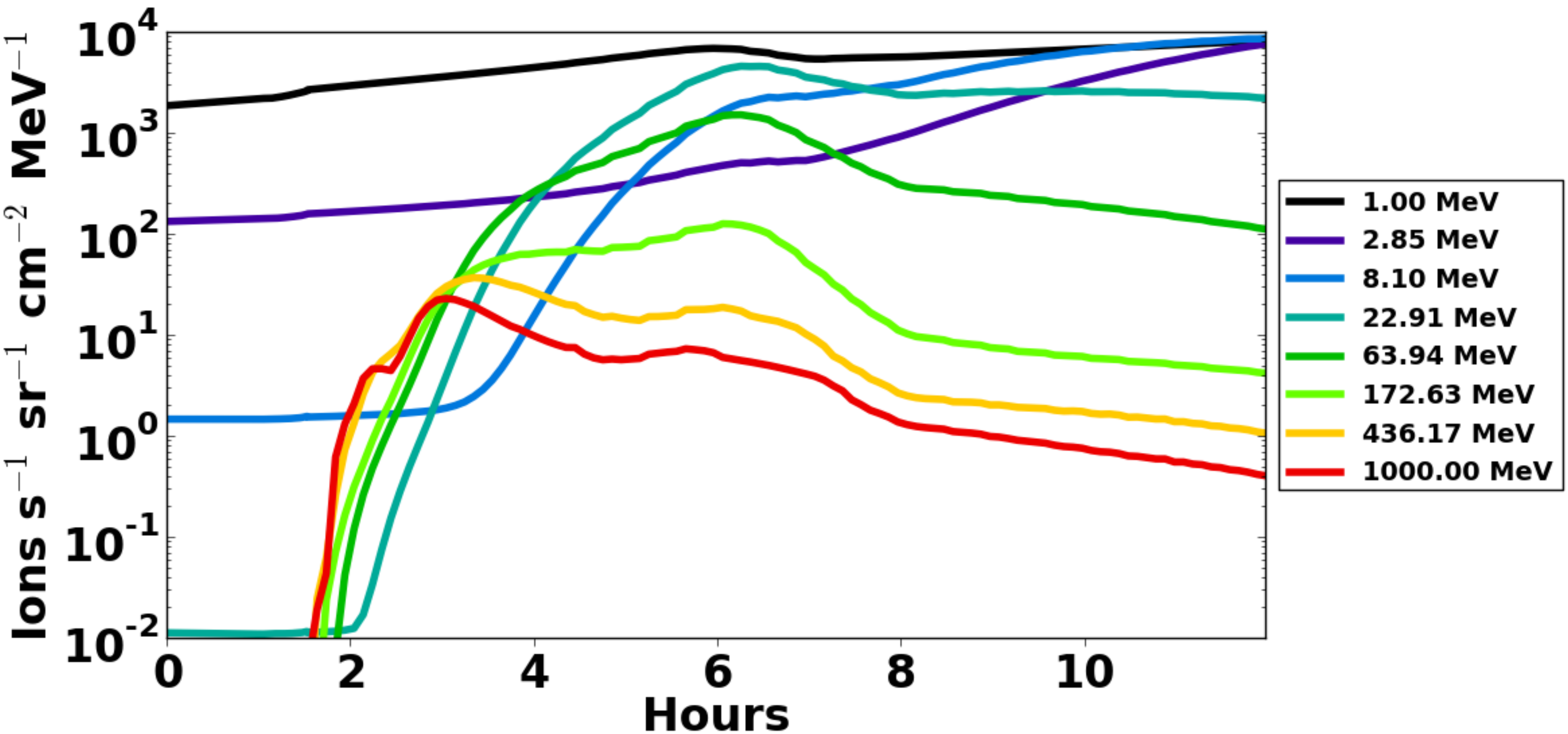
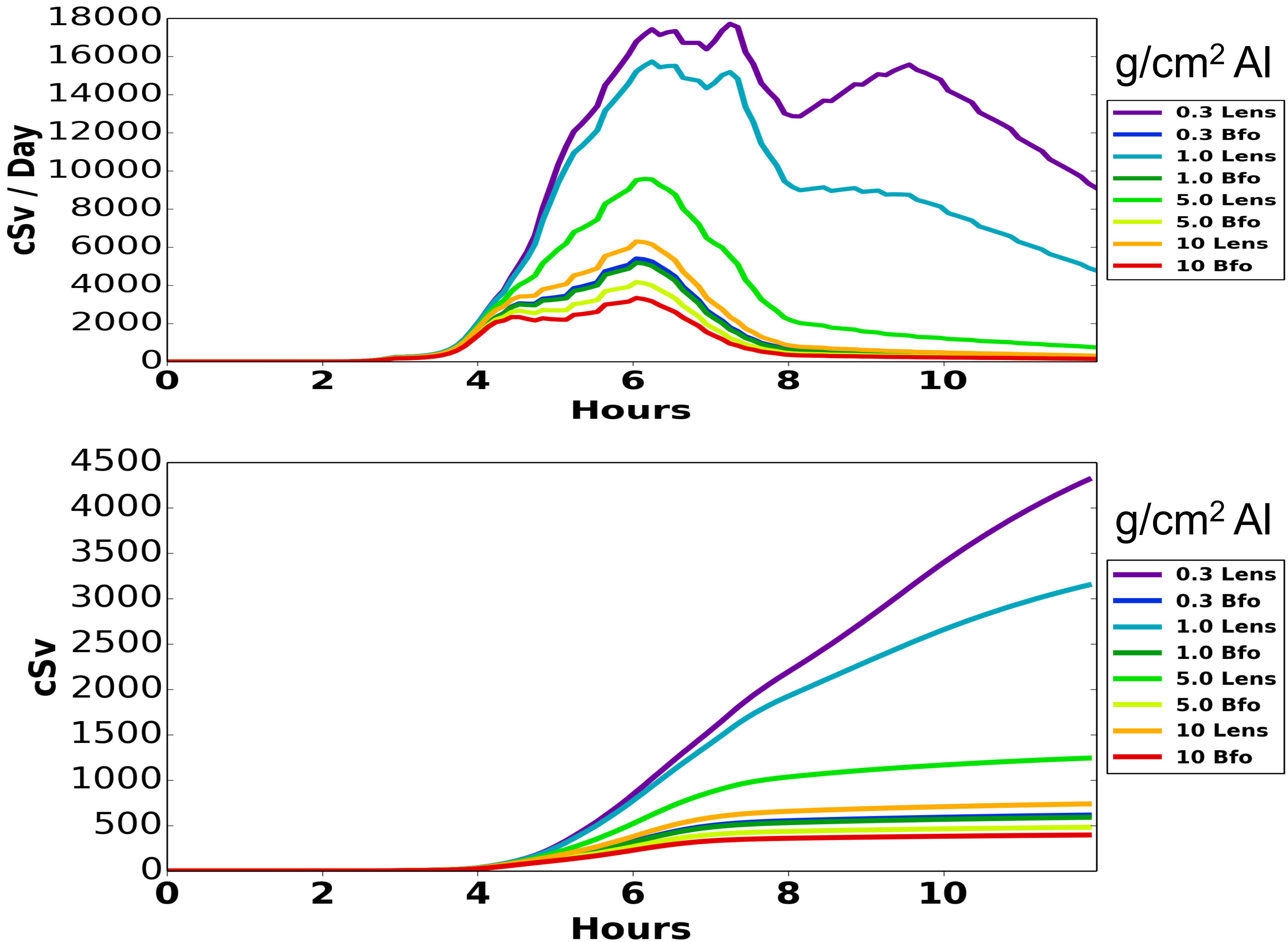


-18.0
-16.0
-14.0
-12.0
-10.0
(Rs)
-8.00
-6.00
-4.00
-2.00
0.00
0.00
-2.00
-4.00
-6.00
-8.00
(Rs)
-10.0
-12.0
-14.0
-16.0
-18.0
0.00 hr.



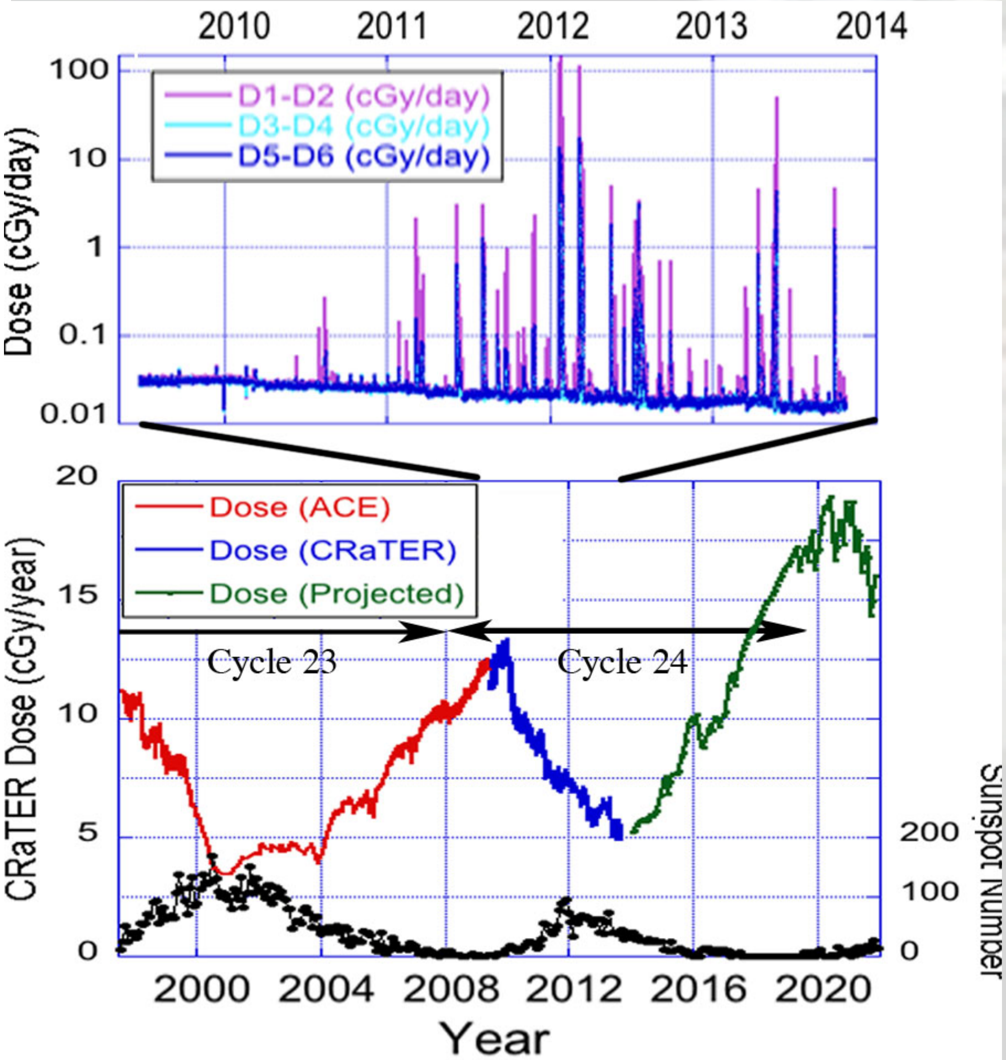
Earth Observer

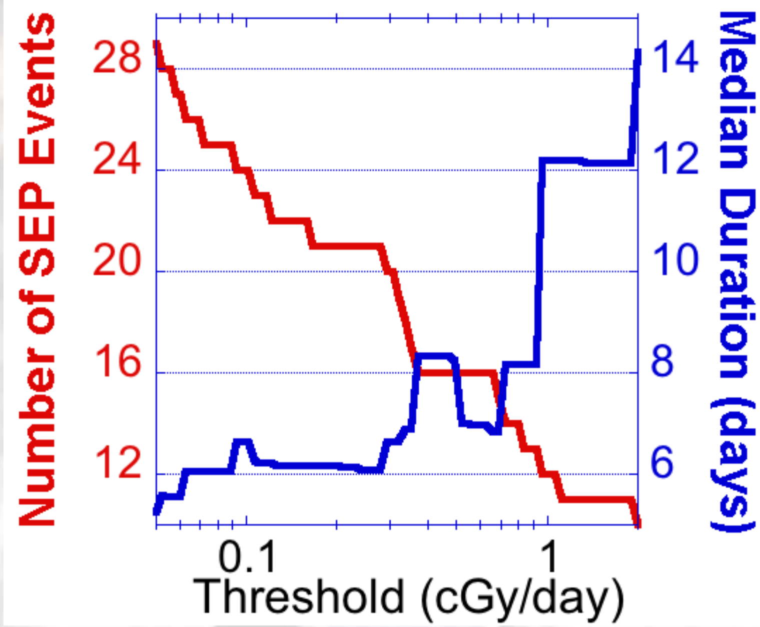


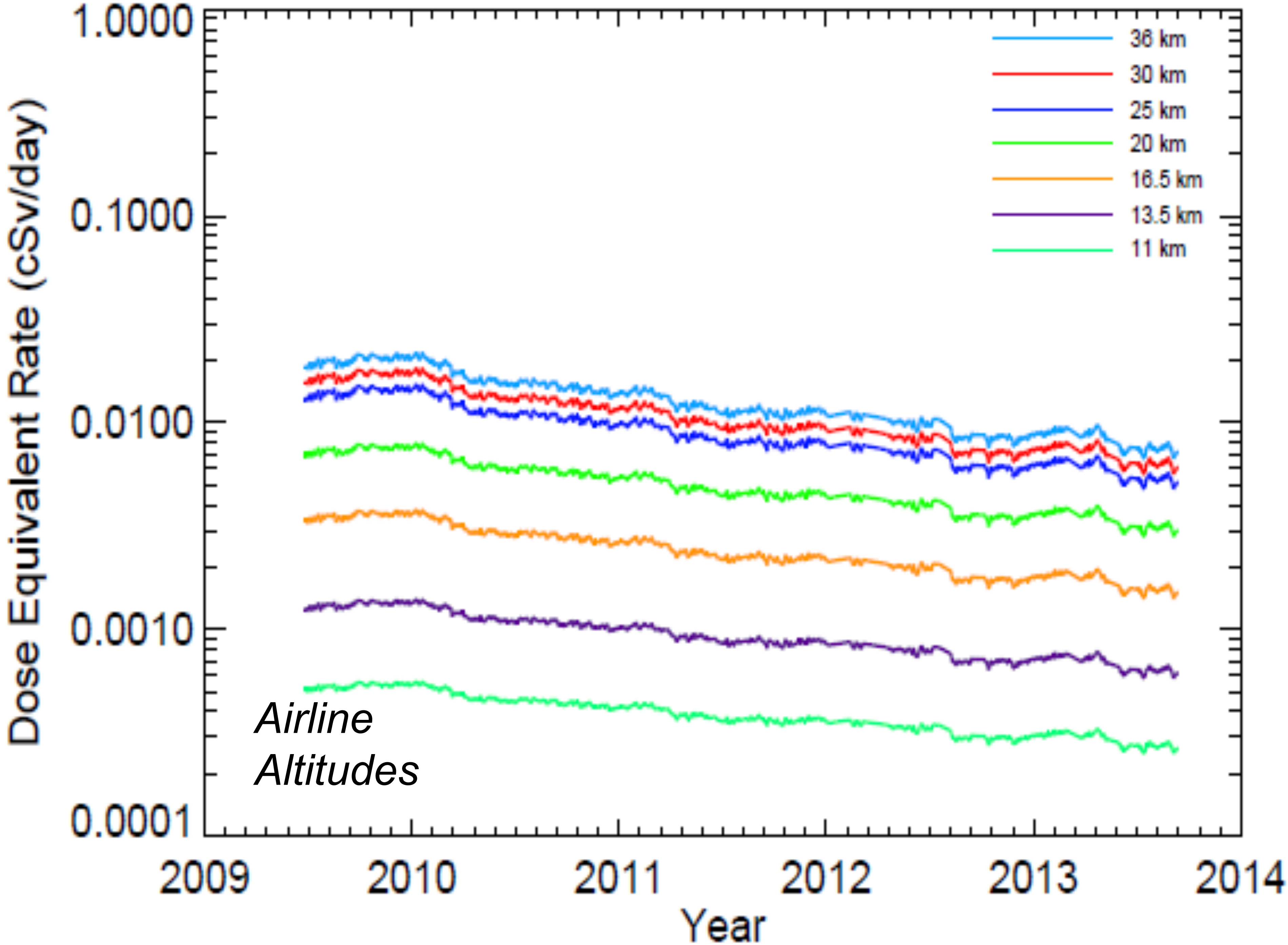


cSv / Day
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
2
4
6
8
10
Hours
g/cm2 Al
0.3 Lens
0.3 Bfo
1.0 Lens
1.0 Bfo
5.0 Lens
5.0 Bfo
10 Lens
10 Bfo
cSv
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
Hours
g/cm2 Al
0.3 Lens
0.3 Bfo
1.0 Lens
1.0 Bfo
5.0 Lens
5.0 Bfo
10 Lens
10 Bfo

Most Peculiar Cycle of Space Age





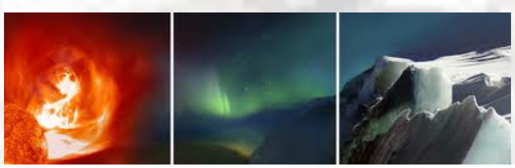


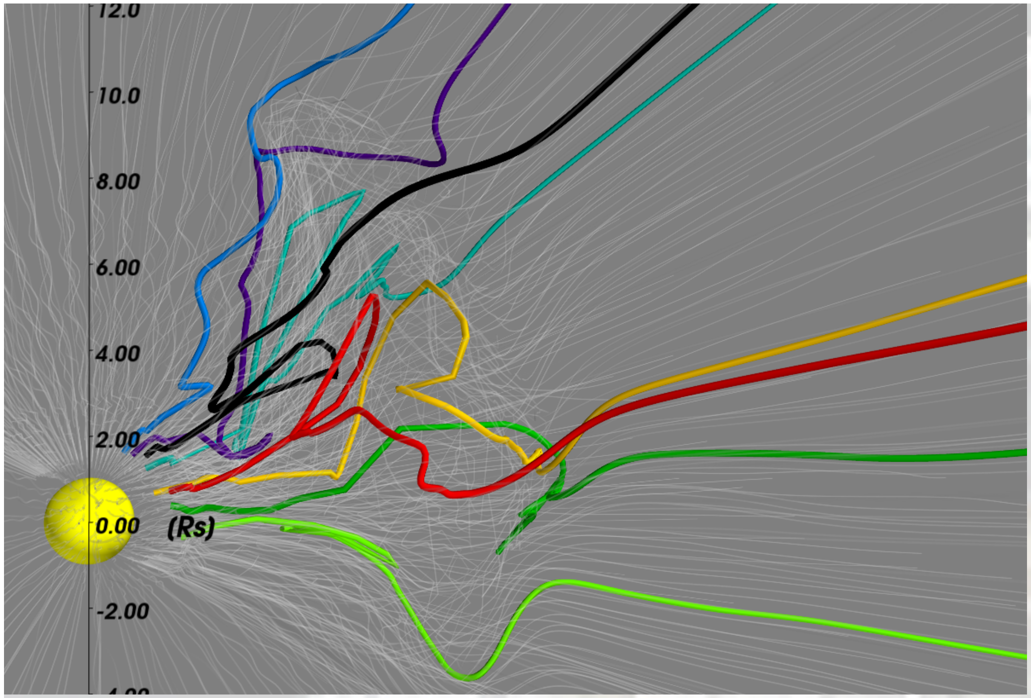
1.0000
0.1000
0.0100
0.0010
0.0001
Dose Equivalent Rate (cSv/day)
2009
2010
2011
2012
2013
2014
Year
36 km
30 km
25 km
20 km
16.5 km
13.5 km
11 km
Airline
Altitudes

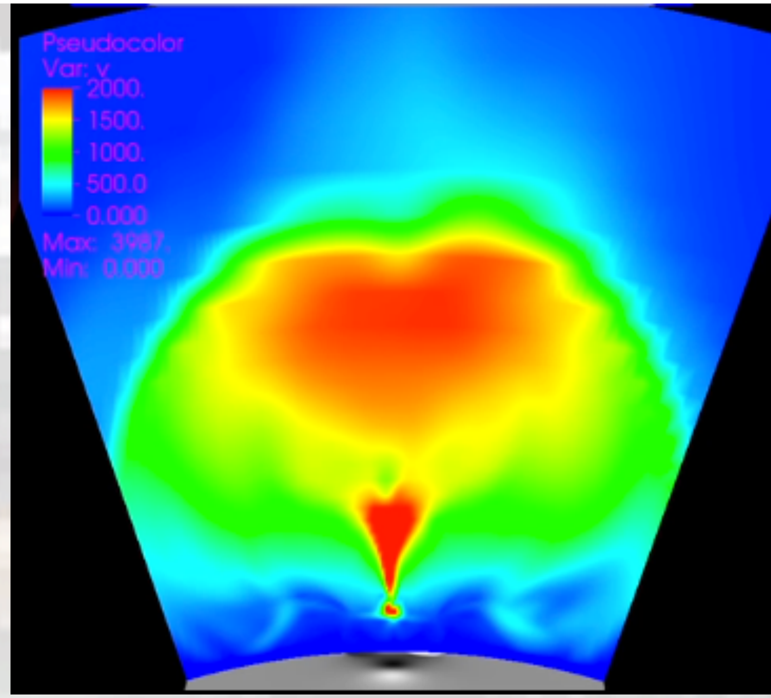
Web Interface for the Energetic Particle Radiation Environment Module (EPREM)

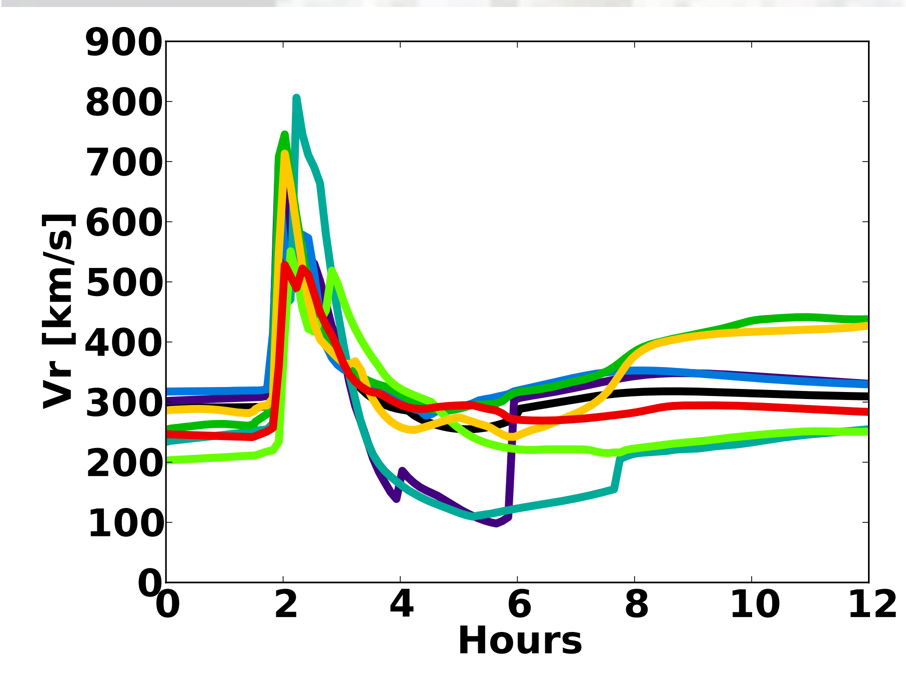
Matthew Gorby
Information Technologist III
UNH – Space Science Center

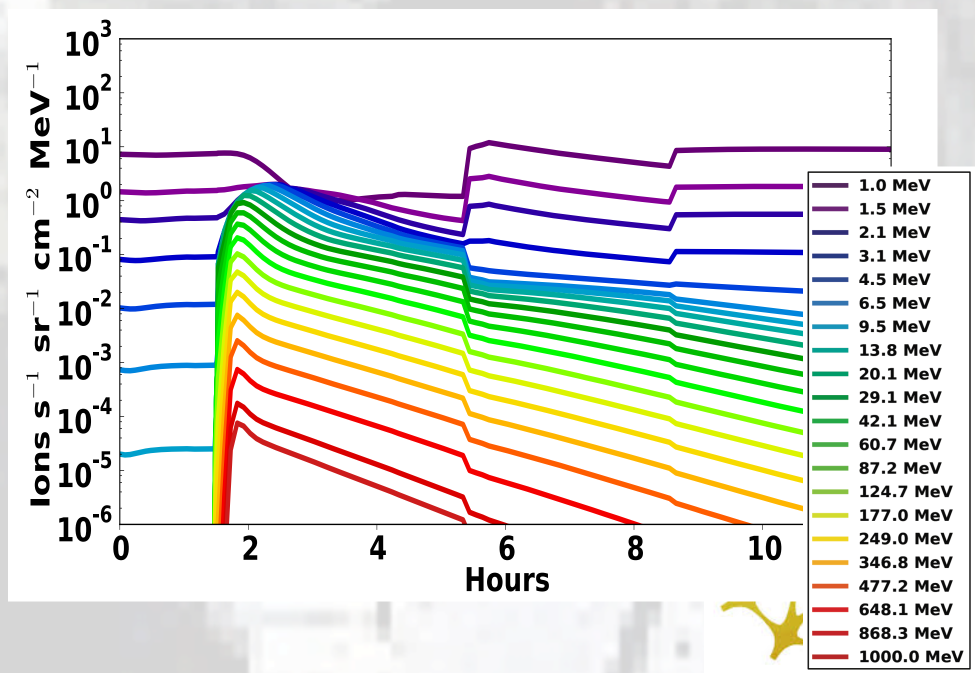
17 October 2013




12.0
10.0
8.00
6.00
4.00
2.00
0.00
(Rs)
-2.00


Pseudocolor
Var: v
2000.
1500.
1000.
500.0
0.000
Max: 3987.
Min: 0.000

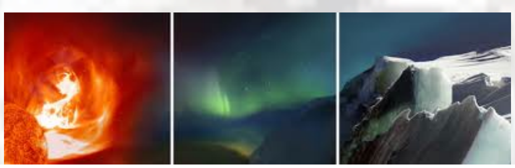

Vr [km/s]
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Hours


Ions s^{-1} sr^{-1} cm^{-2} MeV^{-1}
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
Hours
1.0 MeV
1.5 MeV
2.1 MeV
3.1 MeV
4.5 MeV
6.5 MeV
9.5 MeV
13.8 MeV
20.1 MeV
29.1 MeV
42.1 MeV
60.7 MeV
87.2 MeV
124.7 MeV
177.0 MeV
249.0 MeV
346.8 MeV
477.2 MeV
648.1 MeV
868.3 MeV
1000.0 MeV

Core Needs

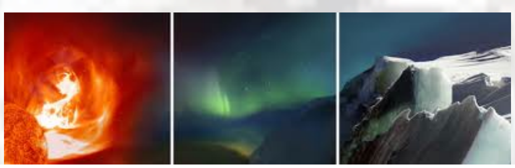
Web Interface:

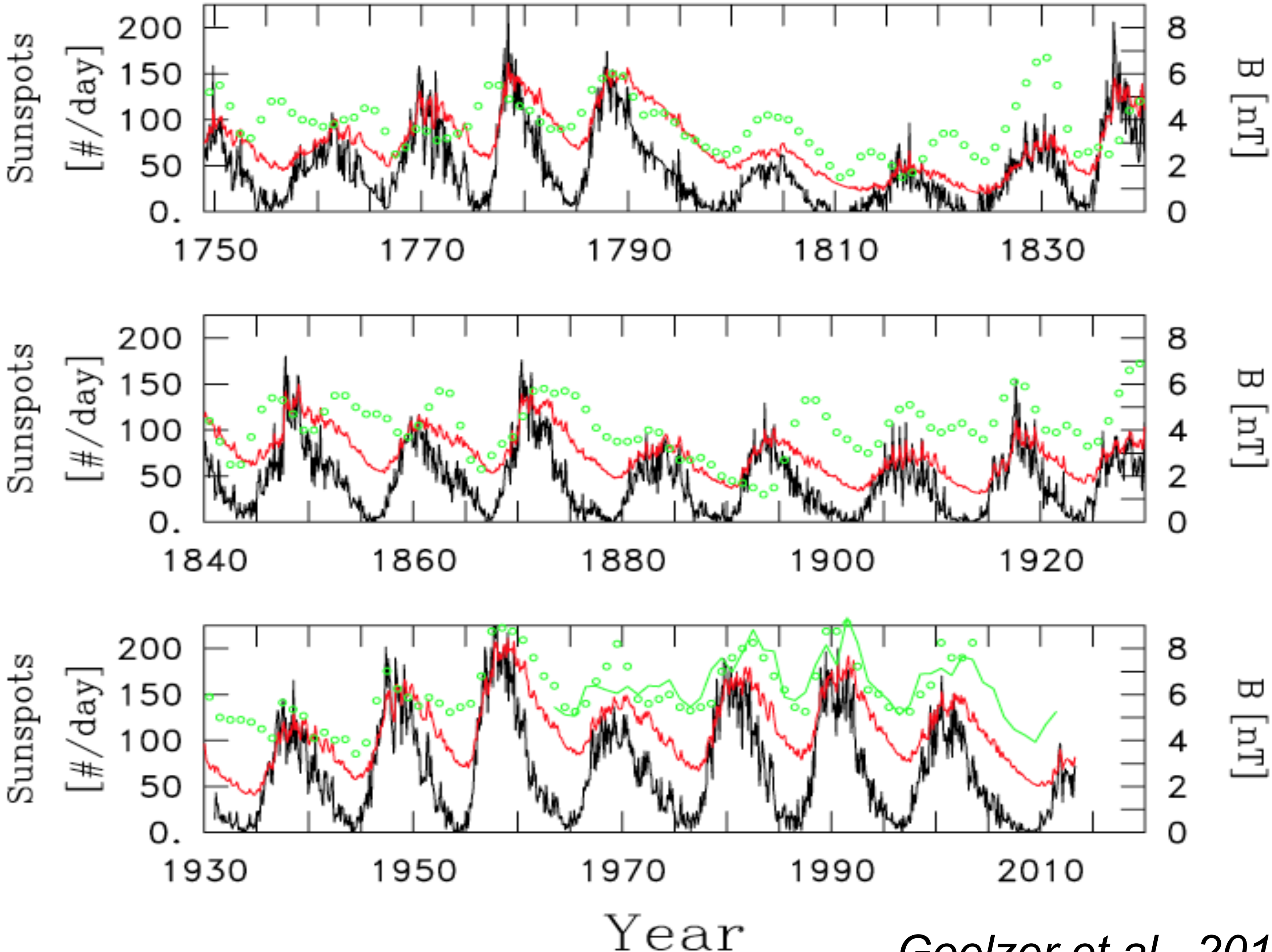
- Login / Request Access
- EULA
- Create Job
  - control simulation variables (limited set)
  - set queue parameters (nodes, procs / node, etc.)
- Check Status of Run
- Retrieve Output



Summary

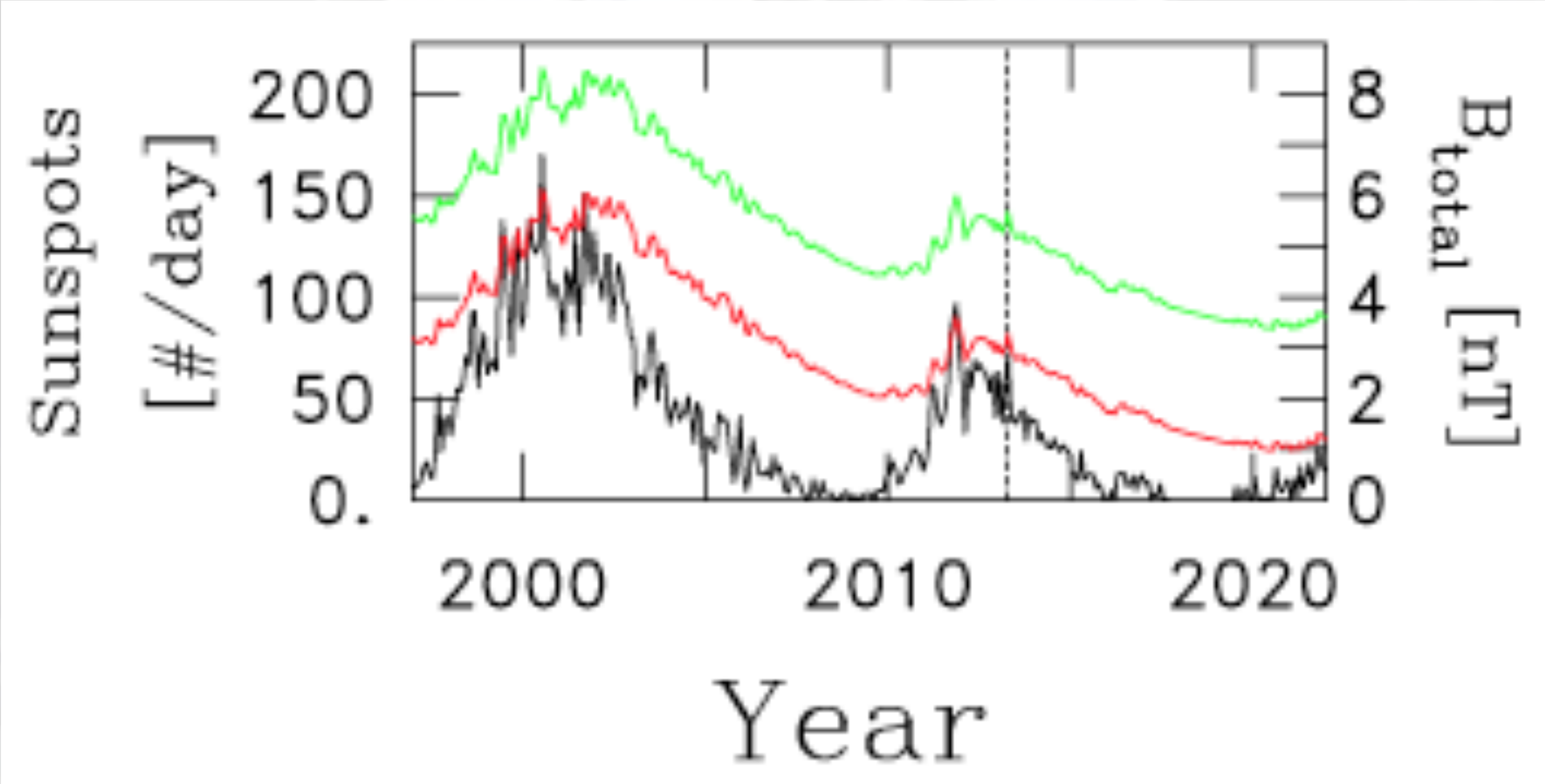
- Earth-Moon Mars Engineering Model Successes!
- PREDICCS Situational Awareness of Space Radiation
- Discovering the Genesis of SEPs from the solar corona
- The remarkable evolution of the Sun into new states not observed in the space age





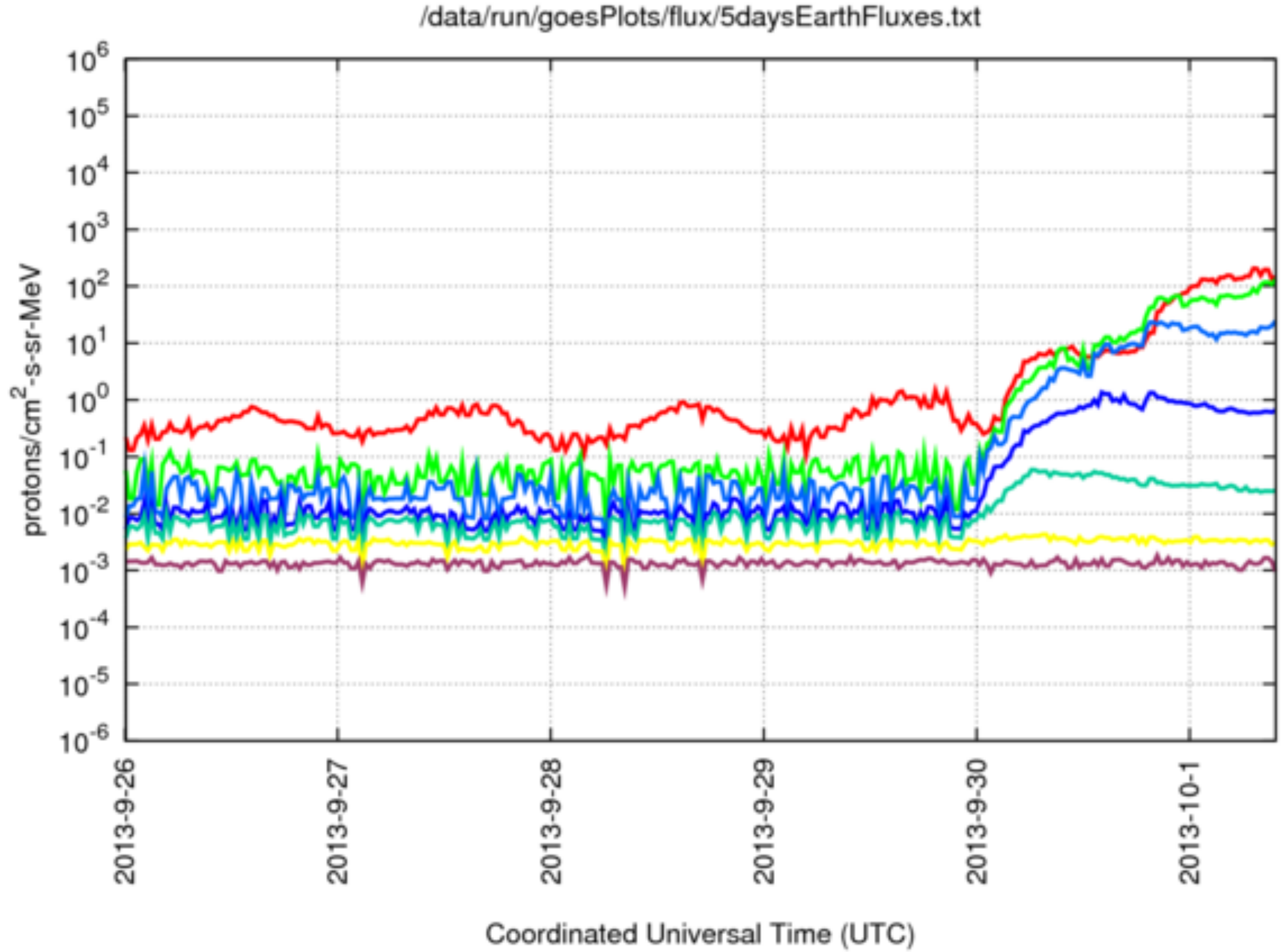
Goelzer et al., 2013

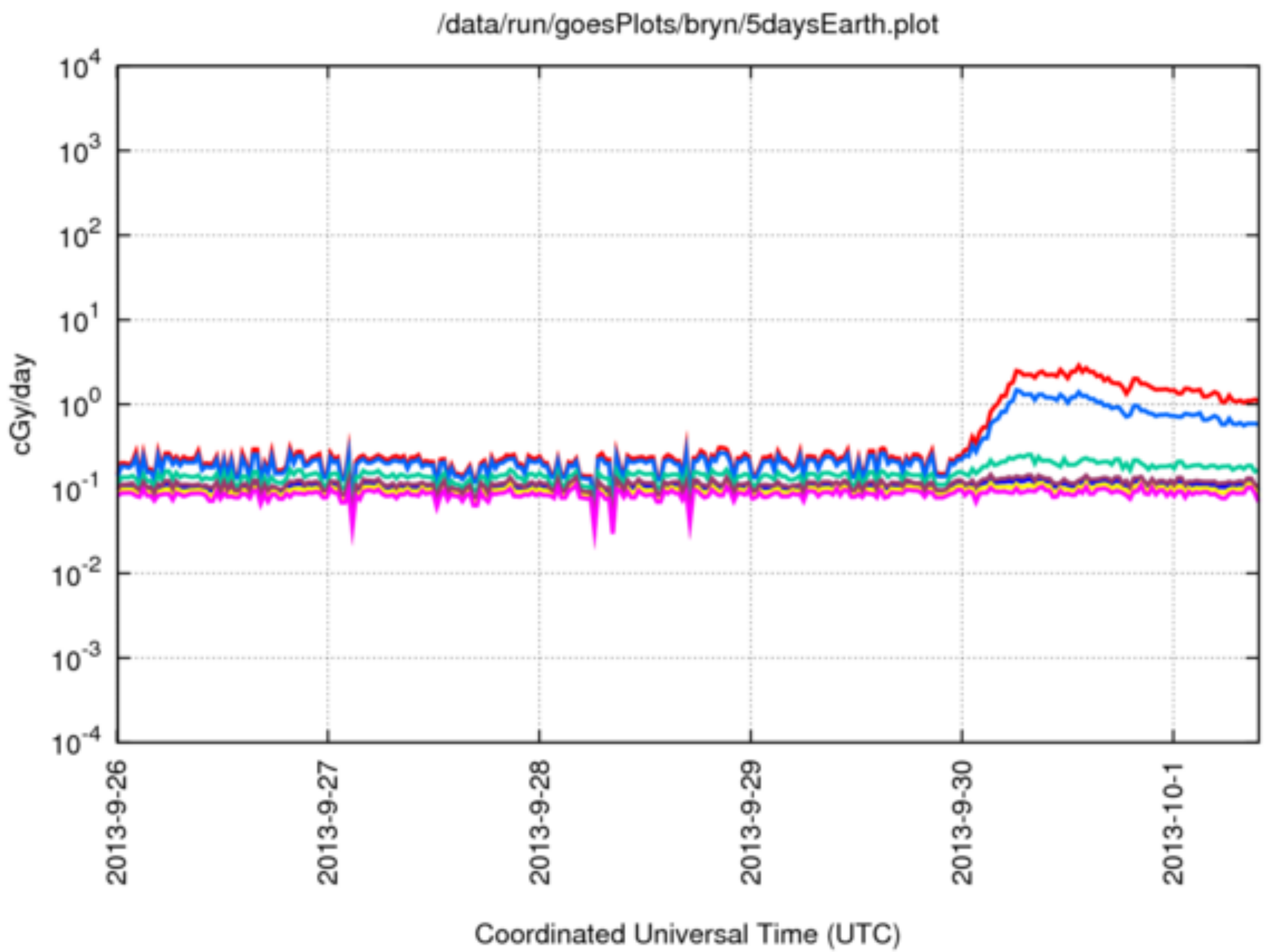
The remarkable evolving Sun



Will the next cycle also look like the Dalton minimum (1807-1840)?

Goelzer et al., 2013


/data/run/goesPlots/flux/5daysEarthFluxes.txt
protons/cm2-s-sr-MeV
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
2013-9-26
2013-9-27
2013-9-28
2013-9-29
2013-9-30
2013-10-1
Coordinated Universal Time (UTC)



/data/run/goesPlots/bryn/5daysEarth.plot
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
cGy/day
2013-9-26
2013-9-27
2013-9-28
2013-9-29
2013-9-30
2013-10-1
Coordinated Universal Time (UTC)

U. Tennessee – EMMREM Accomplishments

NNX07AC14G – L. Townsend

- Lead development of Scenario and Transport code modules
- Provided capability, in near-real-time, to calculate radiation doses and LET spectra for tissue and electronics behind spacecraft aluminum shields using "looping" BRYNTRN code
- Provided database of human organ radiation exposures for Al shielding thicknesses relevant to vehicle and habitat designs anywhere in free space or in Mars atmosphere for GCR and SEP spectra covering the entire solar cycle
- Calculations of doses, dose equivalents and effective dose for GCR and SEP protons at aircraft altitudes in Earth's atmosphere are completed. Heavy ion component calculations are in progress
- Publications (author/coauthor)
  - 10 journal articles
  - 4 invited paper presentations
  - 15 contributed paper presentations
- 3 graduate students supported

Transition to Prediction & Operations

- New ESMD/LRO Predictive Model

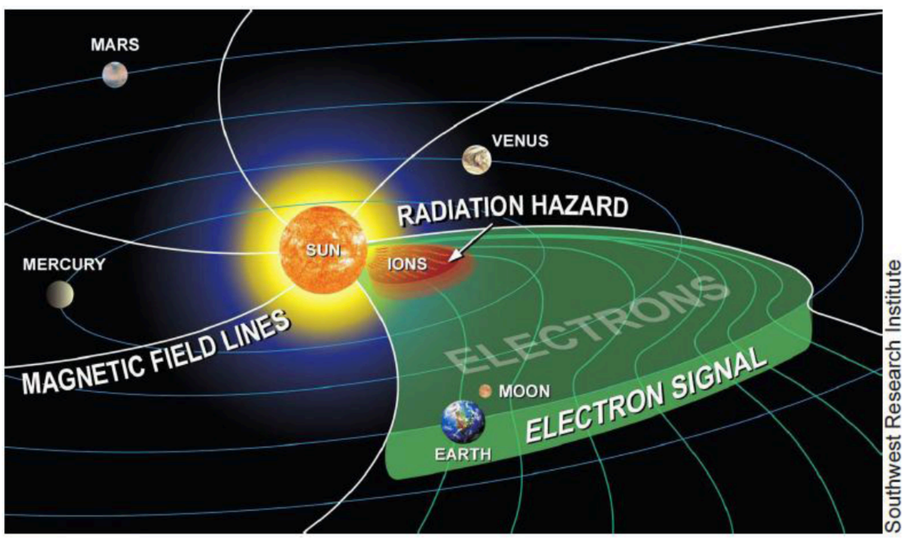
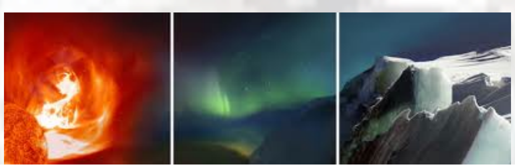


Figure from Posner et al. (2009) demonstrating how relativistic electrons racing ahead of SEP ions provide an early warning of the radiation hazard to follow up to one hour later.

Task Description	Value to ESMD
(1) SEP Prediction Development	Uses CRaTER observations and existing models to **improve advanced warning of solar proton events**
(2) Radiation Environment Forecasting	Develops analysis and modeling tool combined with CRaTER observations to **extend prediction of the radiation environment well beyond low Earth orbit**, not only at Moon but also throughout the inner heliosphere, including at Earth, Moon, Mars, Asteroids, and Comets

Next Steps for EMMREM

- Transition to Operations and Predictive Models
- Development of Comprehensive Risk Models
- Coupling between MHD & EPREM
- Continued development of PATH into a predictive model



Modeling Large SEP Events with PATH Code

- Zank et al., AGU, 2010