2019 Space Weather Enterprise Forum

Space Weather Issues for Human Spaceflight
June 26, 2019

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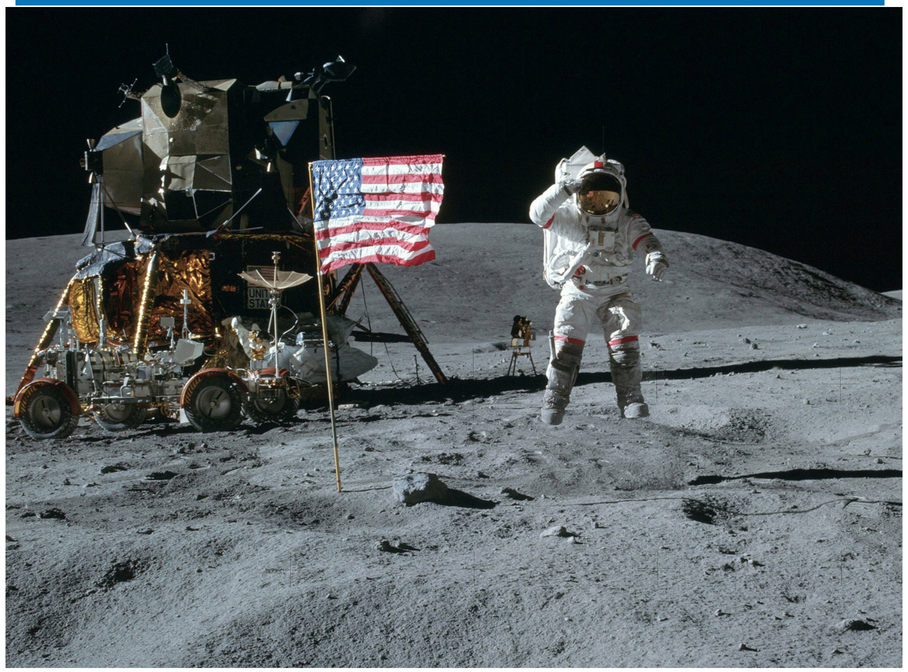
APOLLO ERA



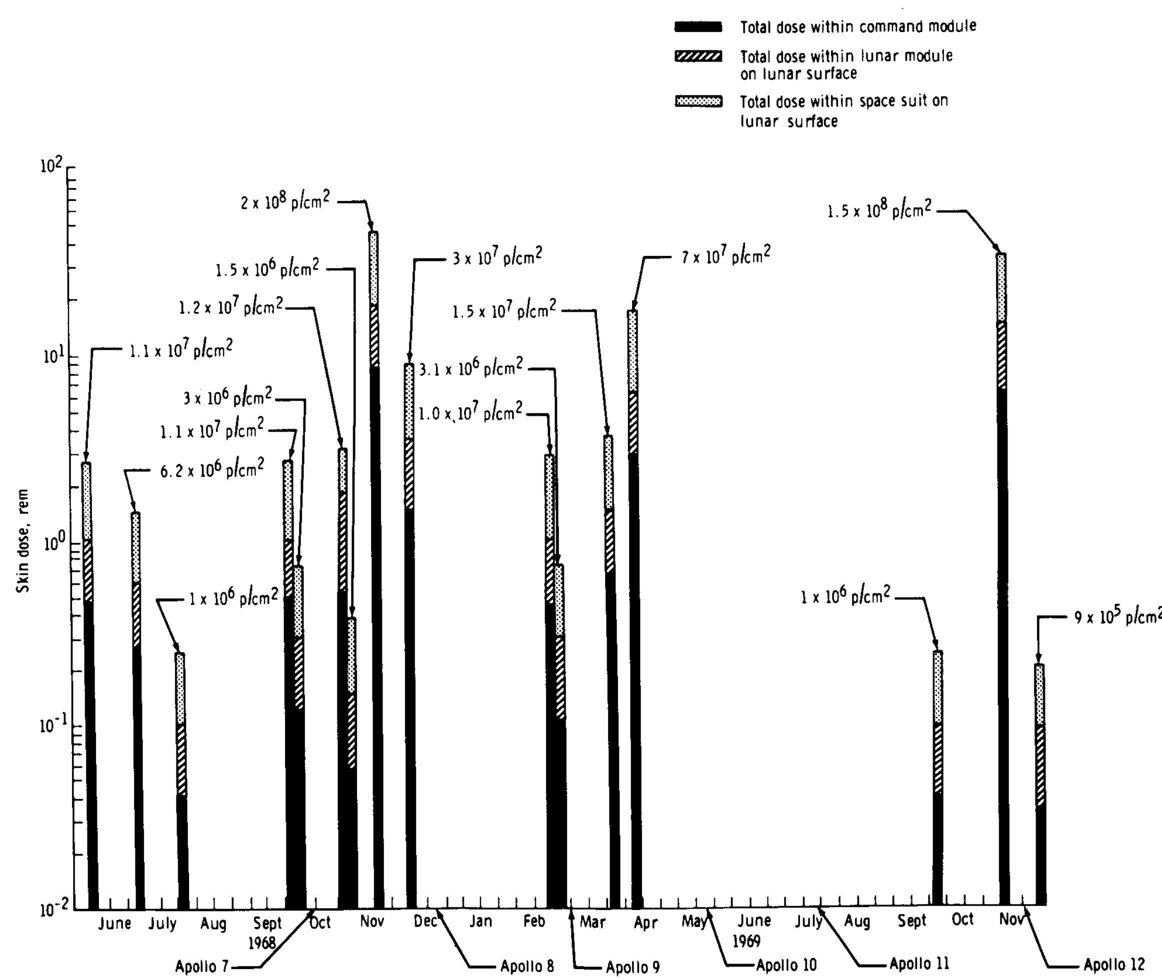


Figure 1. - Radiation-dose estimates for particle events between June 1968 and December 1969.

TABLE II. - SOLAR-FLARE RULES FOR APOLLO MISSIONS

Condition	Mission phase	Rule	Comments
Major solar flare has been predicted.	All	Continue mission.	
Major solar flare has occurred.			
Unconfirmed particle event has occurred.	All	Continue mission.	Report: particles have not been confirmed. No mission impact is indicated.
Confirmed particle event and SPAN or real-time analyses indicate the MOD will be exceeded during the mission.	Prelaunch	Hold until data analysis indicates that the MOD will not be exceeded.	
	Earth parking	Continue mission. If data analysis indicates that the MOD will be exceeded by a significant amount before mission completion, translunar injection is no-go.	Translunar injection is no-go only if firm computation before go/no-go indicates more than the MOD.
	All other phases	Continue mission. Consideration will be given to early (or extended) transearth injection and inhibiting crew transfer to the lunar module.	
Confirmed particle event and spacecraft telemetry or personal radiation dosimeter read-out projections indicate the MOD will be exceeded during the mission.	Translunar coast	Continue mission. Consideration should be given to entering in next best preferred target point if the total dose can be reduced significantly without increasing total risk to the crew.	Crew should begin personal dosimeter and radiation survey meter read-outs. A projection of greater than the MOD is not required for crew read-outs.
	Lunar orbit	Continue mission. Consider extending lunar orbit stay time if the total dose to the crew would be reduced significantly by lunar shielding.	Hatch-down attitude may be used to reduce the total dose. If a particle event is confirmed, the crew will transfer from the lunar module to the command and service module.
	Lunar stay	Consider reducing the lunar stay time or extravehicular activities if the total dose to the crew can be reduced significantly without increasing the total risk to the crew.	Comparison of command and service module and lunar surface personal radiation dosimeters is advised.
	All other phases	Continue mission.	

SPACE ENVIRONMENT MISSION RULES

- ACTION WILL BE BASED ON CONFIRMED EVENTS BY MORE THAN ONE DATA SOURCE
- MAXIMUM OPERATIONAL DOSE LIMITS
  - SKIN 400 REM
  - DEPTH 50 REM (5 cm)
- NATURAL RADIATION
- ARTIFICIAL RADIATION

APOLLO 16, April 1972

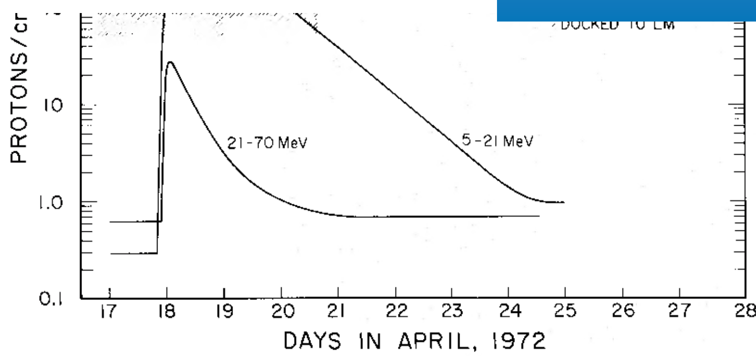


FIG. 1.—Flight history of the *Apollo 16* mission. The shaded bars indicated the periods during which the command module was in lunar orbit and when the lunar module was docked to the command module. The proton data from ATS-1 are adapted from Price *et al.* (1972).

If it is assumed that the fluxes of Fe and transiron nuclei had similar time histories during the mission, then the geometrical factors cancel in the fluence ratios reported in this paper. This assumption may be suspect because of the observations of Krimigis and Armstrong (1973) that the α/M and Fe/O ratios varied with time during a different flare. Their observations do show that the onset and end of the event occurred at nearly the same time in all of their charge channels. Figure 1 shows that the spacecraft was, in the trans-lunar portion of the flight, in a fixed configuration with the lunar module docked to the command module

half-angle ξ of the tangent cone at each point along the track. It can be shown that

$$V_t/V_g = \text{cosec}\,(\xi) \qquad (3)$$

and that the associated range is found at the inter-section of a normal to the surface and the particle trajectory. Except for extremely large tracks, this type of measurement must be done using replicas in a scanning electron microscope (SEM) which can view the replicated tracks at an angle nearly normal to the trajectory.

APOLLO 16 COSMIC RAY

Hart, H. R., Jr. et al.

(3) PRICE P.B., HUTCHEON I., COWSIK
Phys. Rev. Lett. 26, 916-919.
(4) MOGRO-CAMPERO A. and SIMPSON J.
L5-L9.

Space Weather Concerns for Human Spaceflight – A Quick Summary

- **X-Ray Flare**
  - **No Impact**
  - **Can be associated with SPE/ESPE**
- **Geomagnetic Storm**
  - **Impact *only* if there is an increase in solar energetic particles (SEP)**
  - **Can 'compress' Earth's geomagnetic field/ protection**
- **Solar Particle Event (SPE)**
  - **Definition: >10MeV proton flux >10pfu (GOES)**
  - **Minimal impact unless crew is EVA**
  - **Low energy particles do not penetrate vehicle**
- **Energetic Solar Particle Event (ESPE)**
  - **Definition: >100MeV proton flux >1pfu (GOES)**
  - **Concern – SRAG monitors closely and makes recommendations to Flight Control Team (FCT)**
  - **Crew may be asked to avoid lower-shielded areas or shelter in highly-shielded areas of vehicle**

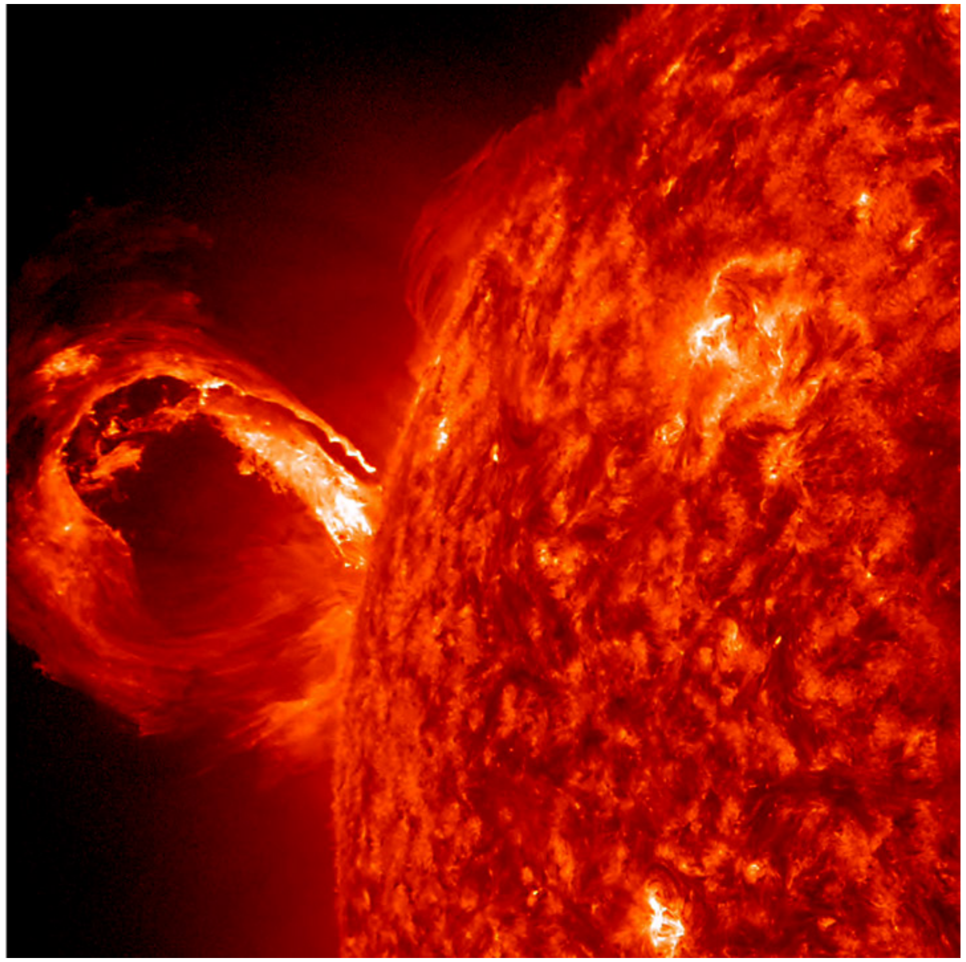
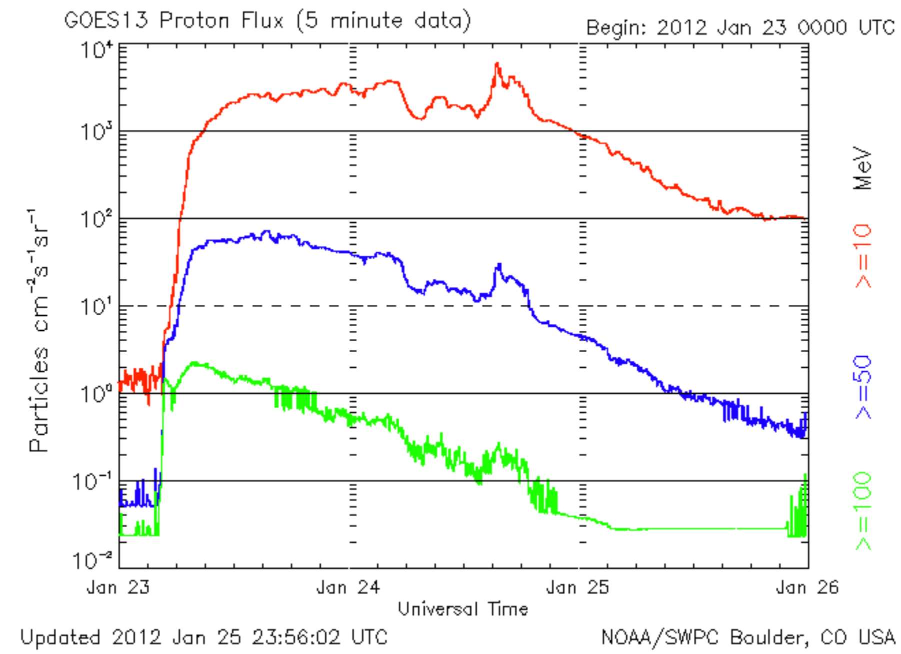
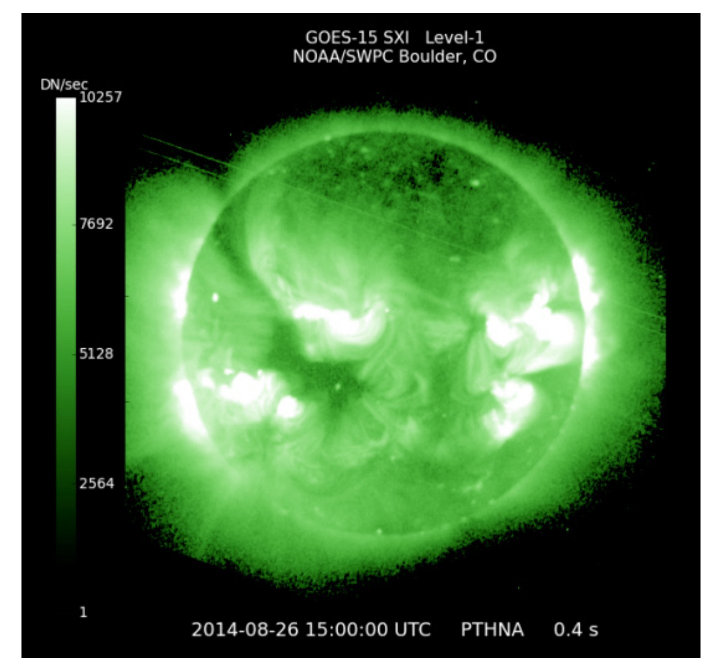


Image of Coronal Mass Ejection (CME) taken by NASA's Solar Dynamics Observatory (SDO) on May 1, 2013.
From: https://sdo.gsfc.nasa.gov

Current State: ISS SEP Operations

- All SEP forecasting/nowcasting is based on direct SRAG-SWPC interface
- SRAG flight controller monitors console during space weather contingency operations such as Solar Energetic Particle (SEP) events
  - Alert/Warning messages to management and flight control team
  - Ensure ISS radiation monitoring system availability
- If SEP dose projection is determined to be negligible, then no action will be taken
- If energetic particle event has increased above threshold or radiation detector alarm activation is confirmed, inform crew to remain in higher shielded areas during intervals of high risk orbital alignments.
- ISS higher shielded locations used to protect crew
  - Service module aft of treadmill (panel 339), Node 2 crew quarters, and U.S. Lab
- This response evolves over several hours with international coordination. Beyond low earth orbit missions will require this process to be much faster. SEPs can reach peak flux levels in < 5 hours.



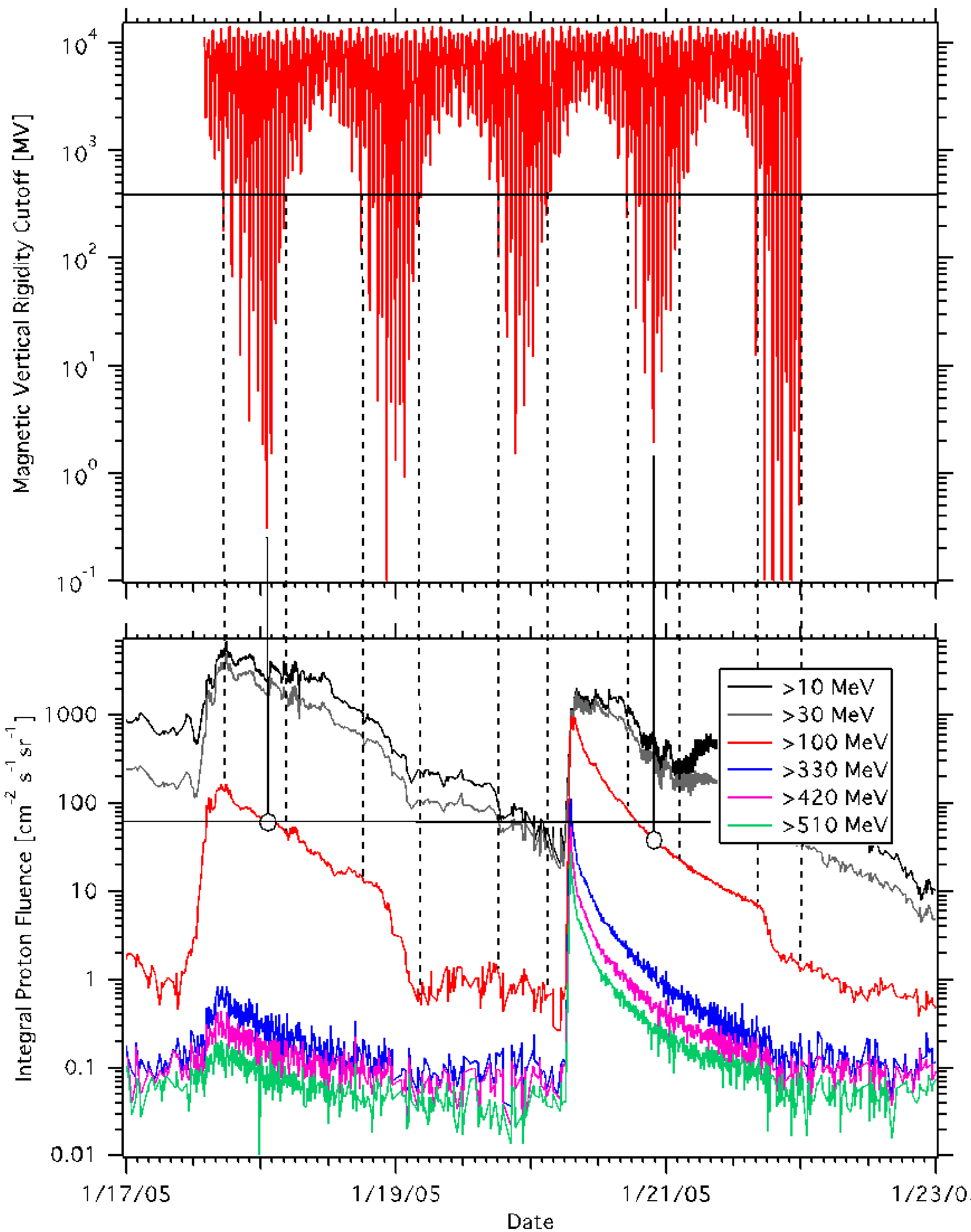


How Do Exploration and LEO (ISS/Shuttle) Missions Differ?

- The graphs to the right show impact to ISS – behind the geomagnetic field
- Top graph shows the magnetic vertical rigidity cutoff
  - The geomagnetic field is in essence a 'filter' of ionizing particles
  - Places where the cutoff is low (high latitudes) ionizing particles can stream into ISS altitudes
  - Cutoff modulates – ground track passes in and out of high latitudes.
- Exposures to ISS crew have not been extreme due to significant protection by the geomagnetic field during the most intense SEP time intervals
  - Operationally, impact modulated by phasing between SEP event and portion of ground track at upper latitudes – ~10 min twice per 90 min revolution for ~12h per day.

Missions beyond LEO where crew-vehicle system spends substantial time in 'free-space' the scenario is very different:

Human-vehicle will see full extent of storm!



Timing Results for 10 Large SEP Events in Dose

SEP Event Date	Onset Time	Duration (Days)	Peak Flux (66.13 – 95.64 MeV)	Fluence >66.13 MeV	Fluence >95.64 MeV	Peak Dose Rate (cGy/Hr)	Total Dose (cGy)	Time to Peak Flux (66.12 – 95.64 MeV) (Hr)	Time to Peak Dose Rate (Hr)	Time to 10% Dose (Hr)	Time to 50% Dose (Hr)	Time to 90% Dose (Hr)
1989/10/19	13:05:00	13.96	10.90	3.96e8	1.80e8	1.15	21.84	26.3	26.3	9.8	29.8	134.1
2000/07/14	10:35:00	5.67	10.70	2.79e8	8.66e7	1.19	13.24	5.8	2.6	1.8	7.3	23.8
2000/11/08	23:40:00	5.93	11.10	2.42e8	6.30e7	0.956	10.63	4.0	4.3	2.5	7.5	16.8
1989/09/29	11:50:00	10.45	3.72	1.64e8	7.38e7	0.580	9.17	8.0	8.1	3.6	11.6	28.8
2003/10/28	11:20:00	3.93	6.86	2.05e8	5.66e7	0.480	9.10	12.9	13.1	5.1	14.1	42.3
2001/11/04	16:45:00	5.10	9.83	1.61e8	3.84e7	0.672	6.49	33.6	33.7	4.9	29.2	36.2
2005/01/15	23:55:00	8.28	10.19	1.14e8	4.87e7	2.04	6.37	103.3	103.3	52.3	104.5	113.8
2012/03/07	02:00:00	5.58	1.76	8.19e7	2.62e7	0.187	4.06	13.4	13.4	11.2	25.2	47.2
2001/04/15	14:00:00	5.71	2.47	4.40e7	2.19e7	0.512	2.73	1.7	1.2	0.9	3.7	65.4
1989/08/12	15:25:00	12.92	1.52	5.40e7	1.71e7	0.104	2.36	13.1	85.8	11.8	86.3	119.3

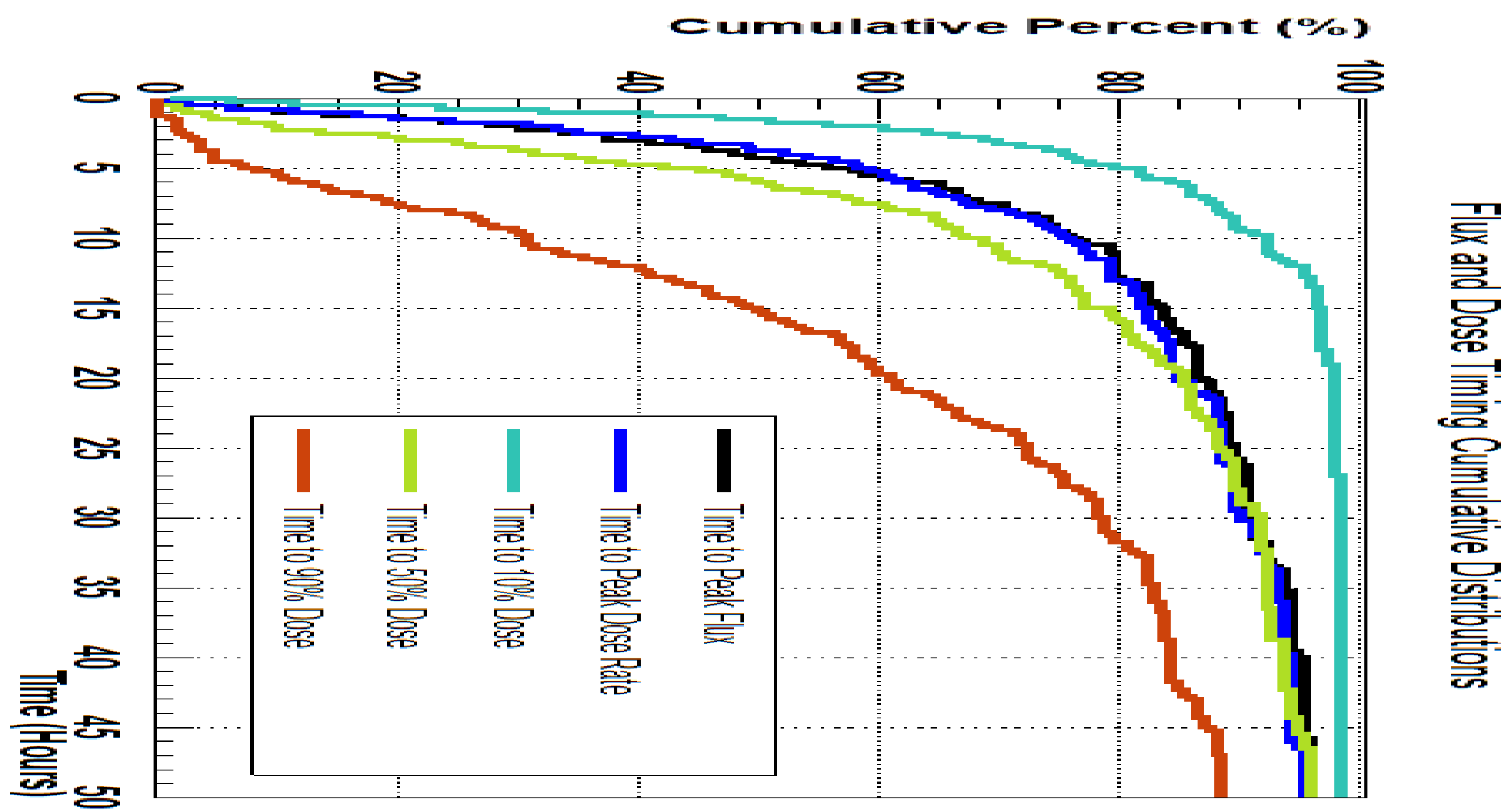
Flux and fluence units are [MeV^{-1} cm^{-2} s^{-1} sr^{-1}] and [cm^{-2}]. Dose calculated for 10 g/cm^2 Al sphere.

Uncertainty in timing is approx. ± 30 min.

1989/10/19, 2005/01/15, 2001/04/015, 1989/08/12 consist of multiple SEP events in quick succession.

Flux-Dose Timing Comparison: Cumulative Distributions

- Time to Peak Flux (**black**) and Time to Peak Dose Rate (**blue**) are very similar
- Events that reach peak flux after 20 hours, also reach 50% dose (**green**) at about the same time



Beyond Low-Earth Orbit Differences –Artemis (lunar surface and Gateway)

- Each SEP event will impact Artemis
  - Will need more detailed forecasting to discern which ones may be serious with advance warning
  - NASA will continue to utilize SPWC for core forecasting for Artemis, but additional operational tools will be utilized for fast response to mission control
- Big Three questions the Console Operator always fields during periods when large active regions are present on sun:
  - Will there be an event (SEP)?
  - How intense will it be?
  - How long will it last?

Need reliable <u>forecasts</u> of SEP <u>event peak flux and temporal evolution</u>

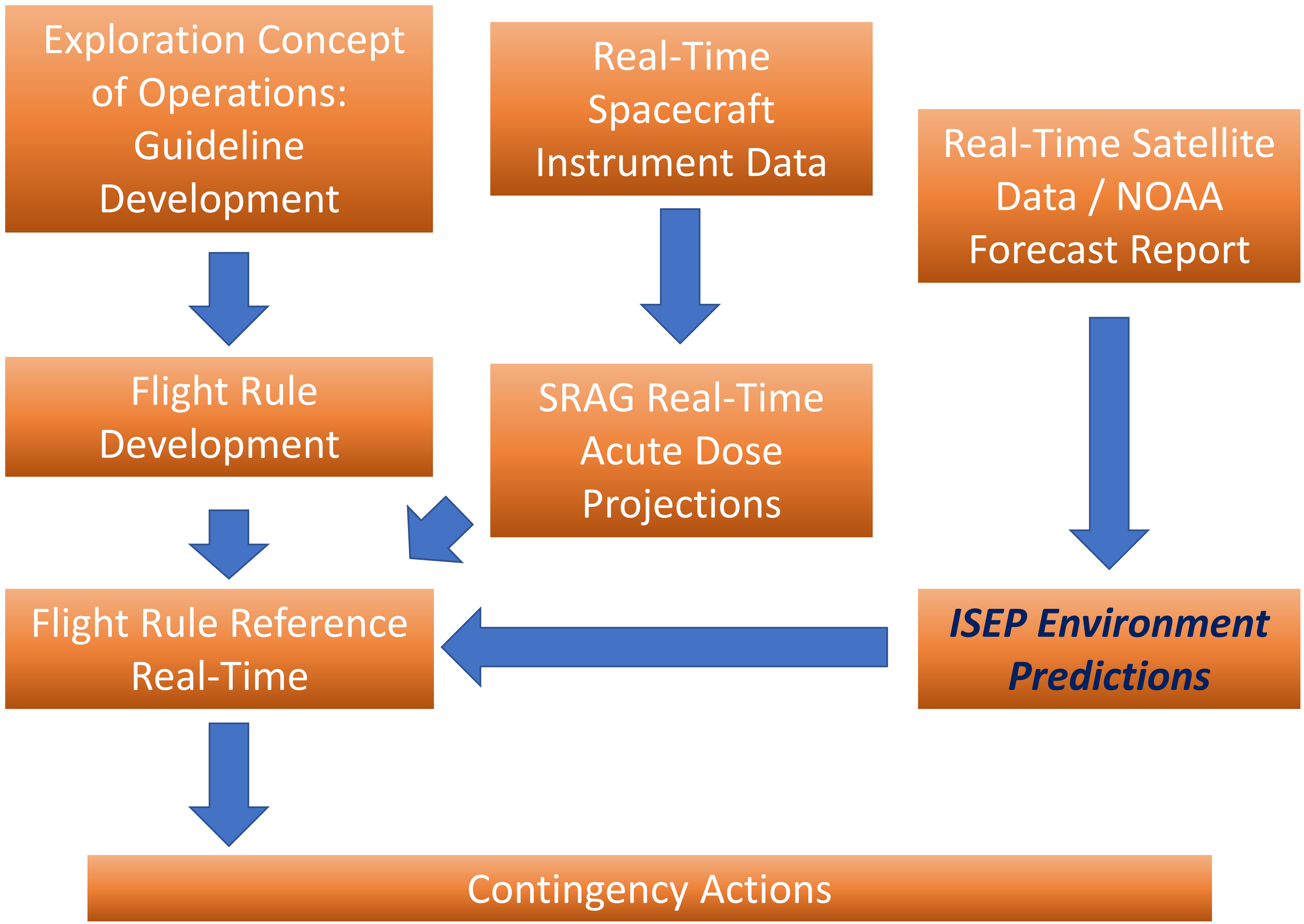
- To help answer these questions SRAG-CCMC have collaborated on a joint project to assemble suite of models in scoreboard framework that includes both US and ESA/EU component. We call it the Integrated Solar Energetic Proton Event Alert / Warning System (ISEP)

Research Model Investments to Operational Tools

- Focus on two paths
  - Statistical-based/Empirical models:
    - Models will be integrated to run as an ensemble output: Scoreboard approach
  - Physics-based models:
    - Higher complexity over statistical models
    - Less mature for forecasting
    - Build on past agency investment in forecasting temporal evolution.

- Leverage current capabilities
  - Multiple models previously developed under SMD-ESA-EU
  - Current SMD data streams
  - GSFC/CCMC and JSC/SRAG expertise and functionality to develop ensemble techniques and operational architectures

Operational Schema for Artemis Missions

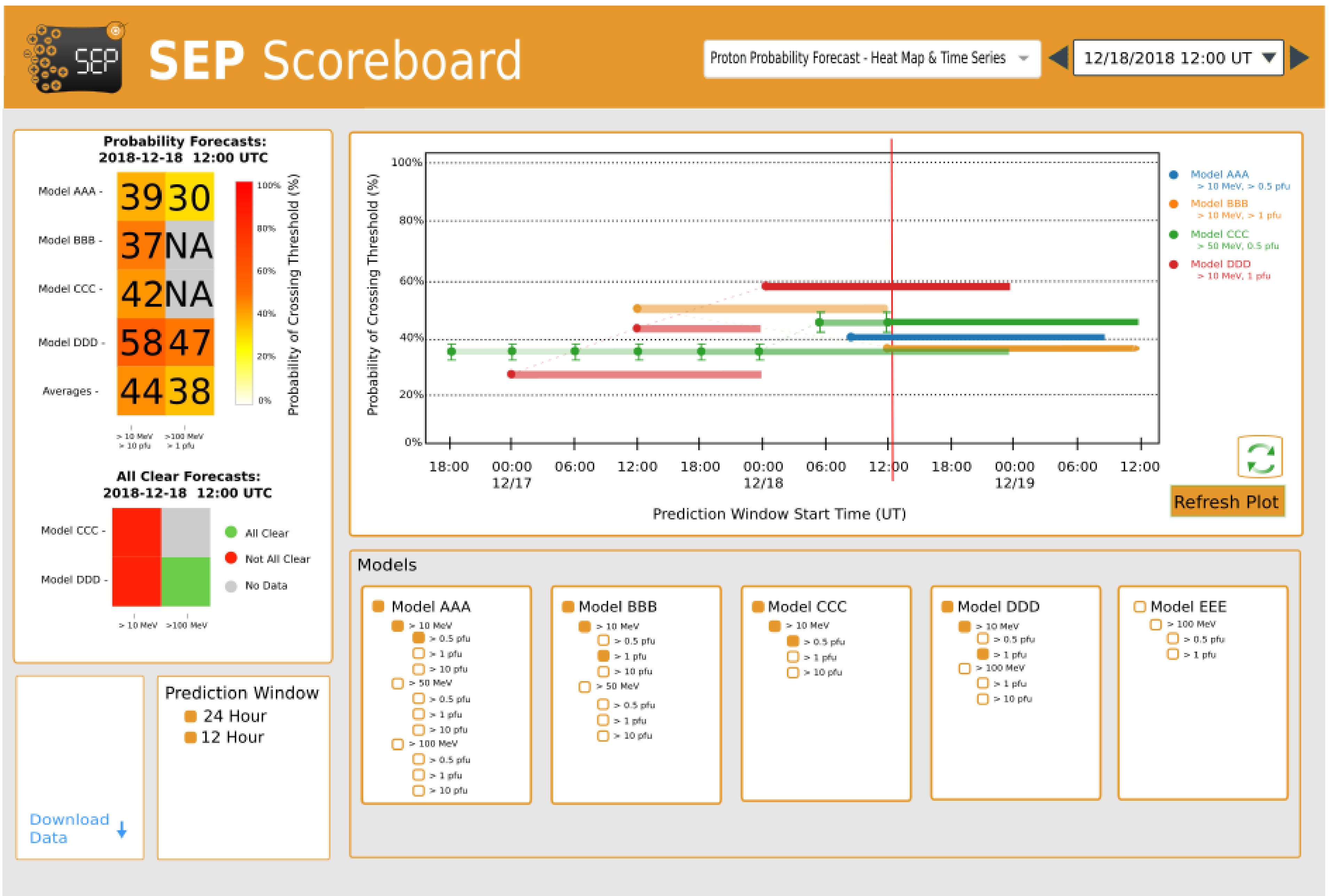


Mockup: Probability Scoreboard

Question: Will an event occur?

Overview of probabilities for SPE/ESPE

'All-Clear' Forecast – mission planning aid



Model output ensemble display

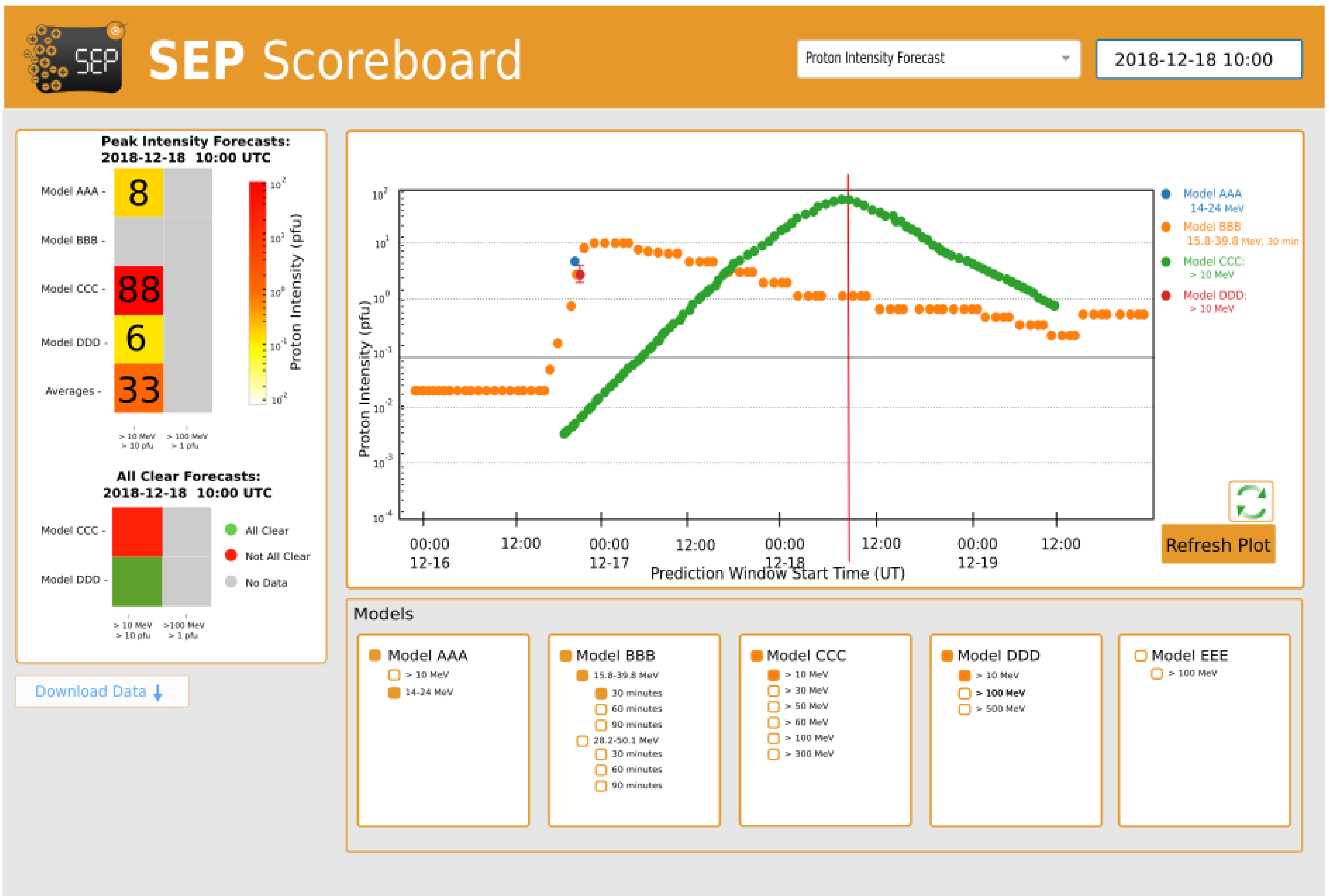
Model output selection

Mockup: Proton Peak Flux Scoreboard

Question: How intense will the event be?

Overview of intensity forecasts

‘All-Clear’ Forecast – mission planning aid



Model output ensemble display

Model output selection

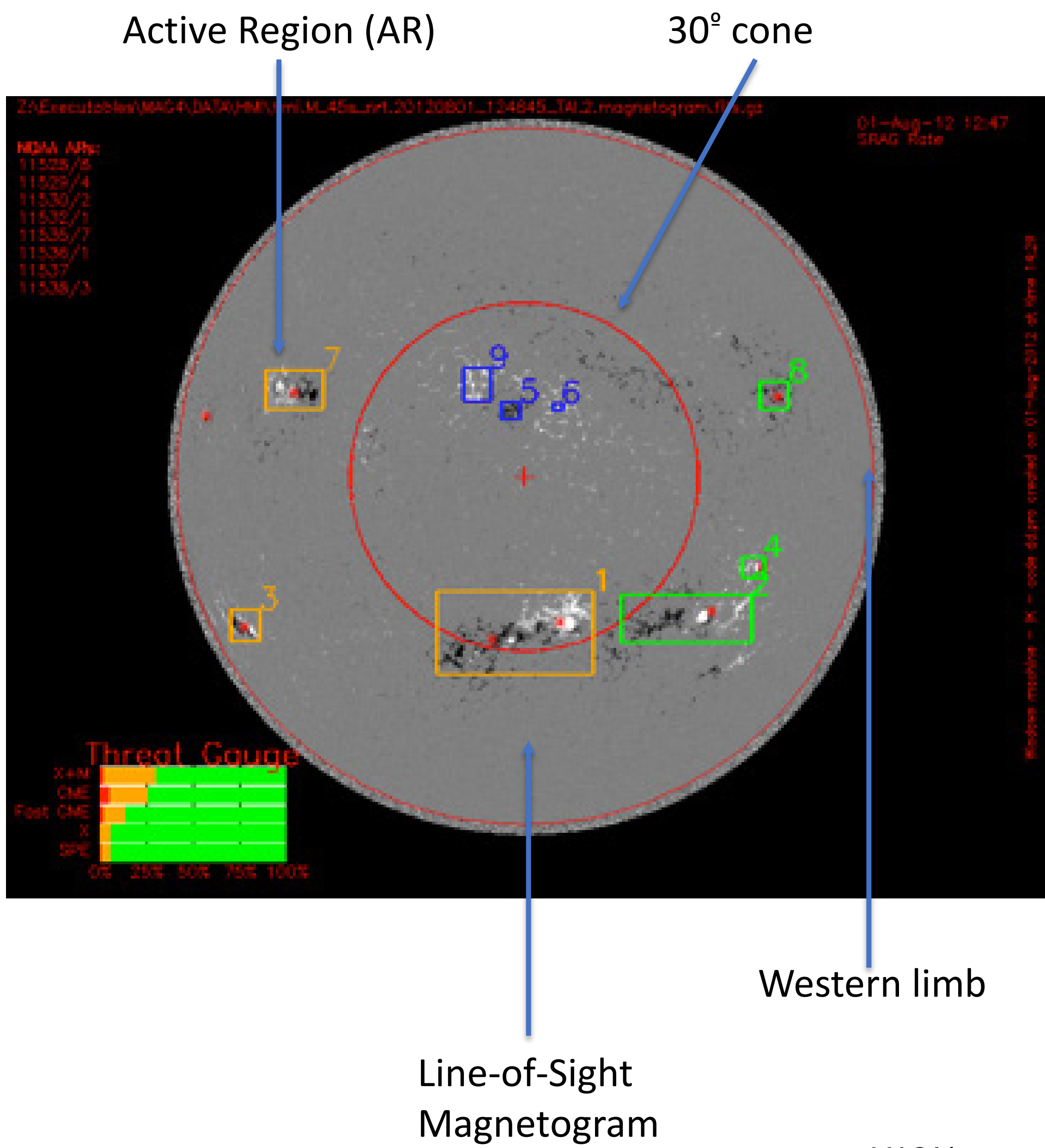
'All-Clear' With Vector Magnetograms

Model Developers

- MAG4: University of Alabama at Huntsville (D. Falconer)

Methodology

- MAG4 – Probabilistic forecast
  - Input: Solar magnetograms
  - Assesses strength and characteristics of region magnetic field
  - Output: M/X, X, CME, fast CME, SEP probabilities
- Current Line-of-Sight magnetograms limit forecast to regions that lie inside 30° cone.
  - With inclusion of SDO in SMD observational suite, increased vector magnetogram resolution could facilitate expansion to 60° cone.
  - Historically, some of the most intense events for Earth occurred when regions were on the western solar limb
- ISEP: MAG4 model improvements in FY18/FY19
  - Improve robustness and statistics
  - Examine use of SDO/HMI vs SOHO/MDI imagery



MAG4 image

Recommendations

- We need to communicate evolving forecast needs and requirements to forecasting centers (SWPC) and researchers to establish core forecasts beyond LEO
- Create international/national SEP forecasting collaborations between/within space agencies
  - Not only at modeler/scientific project level, but at space agency operations/implementation level: SRAG/CCMC
- Lay the groundwork for Artemis by developing forecast tools now that can be tested during ISS operations and short Artemis missions, before longer Artemis missions take place
- Build the foundation for human Mars missions by collaborating on space weather architectures that could be possibly flown on manned vehicles to provide input data for forecast models at locations away from Sun-Earth