2019 Space Weather Enterprise Forum

Space Weather Issues for Human Spaceflight
June 26, 2019

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APOLLO ERA

TABLE II. - SOLAR-FLARE RULES FOR APOLLO MISSIONS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mission phase</th>
<th>Rule</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major solar flare has been</td>
<td>All</td>
<td>Continue mission.</td>
<td>Report: particles have not been confirmed. 90% mission impact is indicated.</td>
</tr>
<tr>
<td>predicted.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major solar flare has occurred.</td>
<td>All</td>
<td>Continue mission.</td>
<td></td>
</tr>
<tr>
<td>Unconfirmed particle event has</td>
<td>Prelaunch</td>
<td>Hold until data analysis indicates that the MOD will not be exceeded.</td>
<td></td>
</tr>
<tr>
<td>occurred.</td>
<td>Earth parking</td>
<td>Continue mission.</td>
<td>Translunar injection is go-go only if firm indication before go-go indicates more than the MOD.</td>
</tr>
<tr>
<td>Confirmed particle event</td>
<td>All other</td>
<td>Continue mission.</td>
<td></td>
</tr>
<tr>
<td>and SPAN or real-time analyses</td>
<td>phases</td>
<td>Consideration will be given to early (or extended) traversals and trajectories. Transfer to the lunar module.</td>
<td></td>
</tr>
<tr>
<td>indicate the MOD will be exceeded during the mission.</td>
<td>Translunar coast</td>
<td>Continue mission.</td>
<td></td>
</tr>
<tr>
<td>Confirmed particle event</td>
<td>All other</td>
<td>Continue mission.</td>
<td>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.</td>
</tr>
<tr>
<td>and spacecraft telemetry or</td>
<td>phases</td>
<td>Consideration should be given to entering in next best preferred target if the total dose can be reduced significantly without increasing total risk to the crew.</td>
<td></td>
</tr>
<tr>
<td>personal radiation dosimeter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>read-out projections indicate the MOD will be exceeded during the mission.</td>
<td>Lunar orbit</td>
<td>Continue mission.</td>
<td>Hatch-down attitude may be used to reduce the total dose.</td>
</tr>
<tr>
<td>Confirmed particle event</td>
<td></td>
<td>Consider extending lunar orbit stay time if the total dose to the crew would be reduced significantly by lunar shielding.</td>
<td></td>
</tr>
<tr>
<td>and spacecraft telemetry or</td>
<td>Lunar stay</td>
<td>Consider reducing the lunar stay time or extravehicular activities to the crew can be reduced significantly without increasing the total risk to the crew.</td>
<td></td>
</tr>
<tr>
<td>personal radiation dosimeter</td>
<td>All other</td>
<td>Continue mission.</td>
<td></td>
</tr>
<tr>
<td>read-out projections indicate the MOD will be exceeded during the mission.</td>
<td>phases</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

SPAC 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
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 translunar portion of the flight, in a fixed configuration with the lunar module docked to the command module.

The half-angle $\xi$ of the tangent cone at each point along the track, $V_0$, the launch speed, and $V_f$, the final speed at the point of interest, are related by

$$\frac{V_f}{V_0} = \frac{1}{\cos \xi}$$

(3)

and that the associated range is found at the intersection 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.

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


(4) MOGRO-CAMPERÓ A. and SIMPSON J., L5-1-9.
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*
• 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.
• 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

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

Flux and fluence units are [MeV⁻¹ cm⁻² s⁻¹ sr⁻¹] and [cm⁻²]. Dose calculated for 10 g/cm² Al sphere.

**Uncertainty in timing is approx. ±30 min.**

• 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.
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? Need reliable forecasts of SEP event peak flux and temporal evolution

How long will it last?

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)
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

- Exploration Concept of Operations: Guideline Development
- Real-Time Satellite Data / NOAA Forecast Report
- Flight Rule Development
- SRAG Real-Time Acute Dose Projections
- Flight Rule Reference Real-Time
- ISEP Environment Predictions
- Contingency Actions
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

Download Data
Mockup: Proton Peak Flux Scoreboard

Question: How intense will the event be?
‘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
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