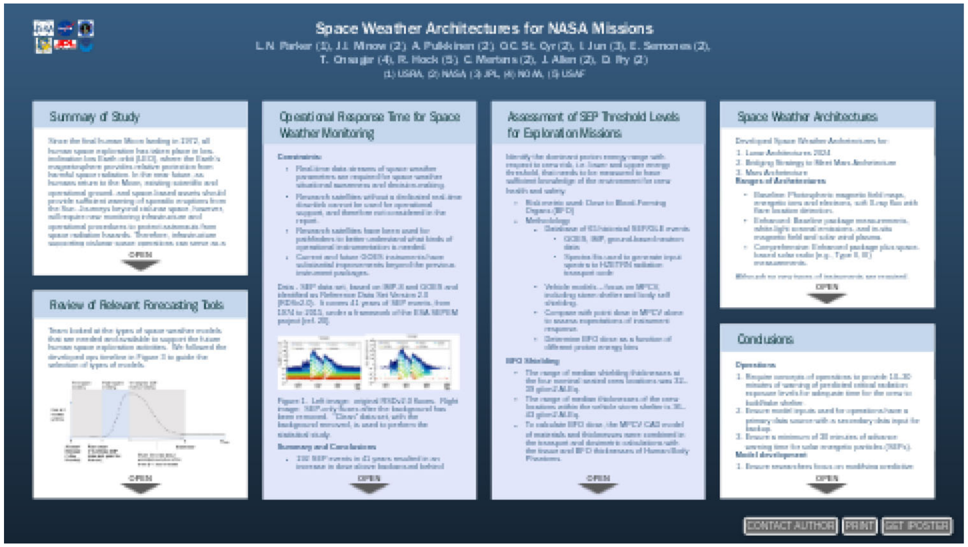
Space Weather Architectures for NASA Missions



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L.N. Parker (1), J.I. Minow (2), A. Pulkkinen (2), O.C. St. Cyr (2), I. Jun (3), E. Semones (2),
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(1) USRA, (2) NASA, (3) JPL, (4) NOAA, (5) USAF

Summary of Study

Review of Relevant Forecasting Tools

Operational Response Time for Space Weather Monitoring

Assessment of SEP Threshold Levels for Exploration Missions

Space Weather Architectures

Conclusions

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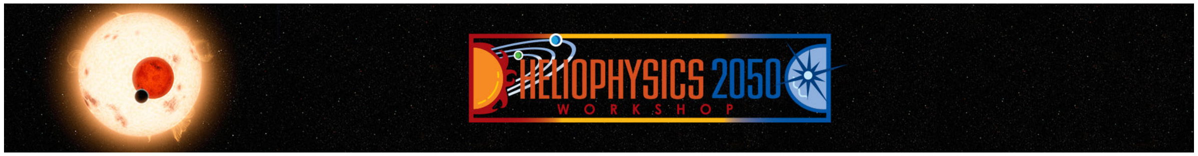

SUMMARY OF STUDY

Since the final human Moon landing in 1972, all human space exploration has taken place in low-inclination low Earth orbit (LEO), where the Earth's magnetosphere provides relative protection from harmful space radiation. In the near future, as humans return to the Moon, existing scientific and operational ground- and space-based assets should provide sufficient warning of sporadic eruptions from the Sun. Journeys beyond cislunar space, however, will require new monitoring infrastructure and operational procedures to protect astronauts from space radiation hazards. Therefore, infrastructure supporting cislunar space operations can serve as a testbed for these future needs.

A NASA Engineering and Safety Center (NESC) assessment team evaluated the required minimum latency for data streams and forecasts that will directly affect mission operations using the European Space Agency's Solar Energetic Particle (SEP) Environment Modeling RSDv2.0 41-year database of SEP events. The database contained 192 SEP events that resulted in a dose increase above background levels. Of those, 10% were "multiple events," or events that occurred in quick succession. The analysis provides probabilistic values for time to peak flux and dose rate for the duration of each event. This NESC assessment also evaluated the SEP threshold levels for exploration missions to determine the relevant energy range of required proton measurements. Accurate modeling and prediction of SEPs is a major challenge, and the performance of available models leaves room for improvement. However, promising paths for predictive SEP modeling have been identified and are actively being explored by the space weather community.

Operational time line requirements were developed to ensure general mission planning and situational awareness for lunar and Mars missions. Various architectures were developed for lunar and Mars missions, providing different cost categories in the form of instrument packages of increasing ability (i.e., baseline, enhanced, and comprehensive). Finally, the assessment provides a research and development strategy to bridge the time from successful lunar missions to Mars missions. We will provide an overview of the analysis and recommendations for future NASA space weather architectures.

1. Review of Previous Material
2. Assessment of Operational Response Time for Space Weather Monitoring
3. Review of Relevant Forecasting Tools
4. Assessment of SEP Threshold Levels for Exploration Missions
5. Development of Space Weather Architecture.

The study does not discuss costs, which are deeply dependent upon instrumentation priorities and requirements and on emerging technologies.

REVIEW OF RELEVANT FORECASTING TOOLS

Team looked at the types of space weather models that are needed and available to support the future human space exploration activities. We followed the developed ops timeline in Figure 3 to guide the selection of types of models.

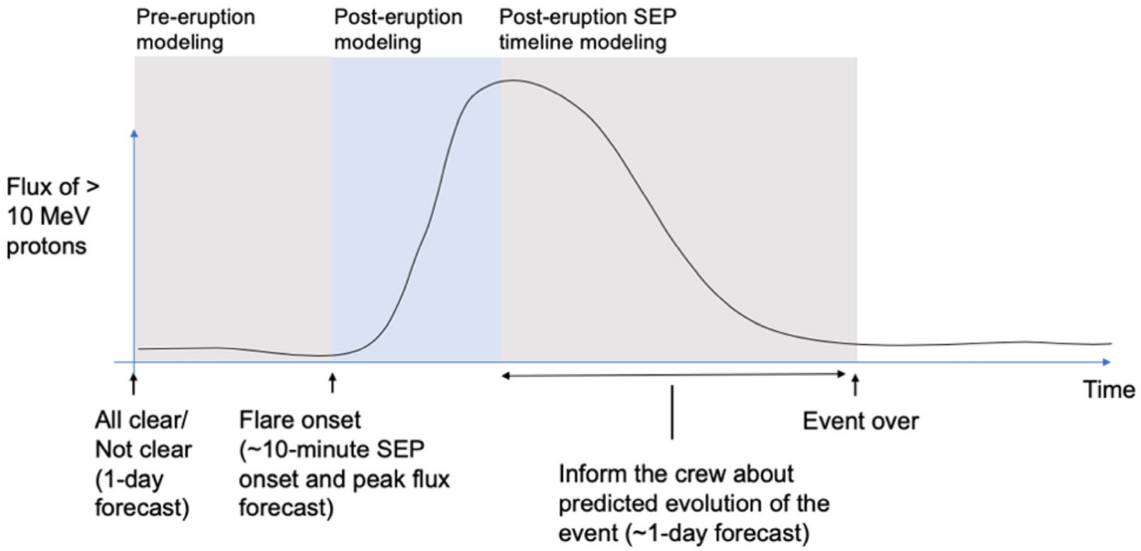

Figure 3. Operations timeline

Summary

Developed a comprehensive catalog of prioritized space environment models with observational requirements that could be used for space weather nowcasting and forecasting

- Probabilistic pre-eruption flare/SEP/CME prediction modeling
- Empirical post-eruption modeling
- Post-eruption time profile models
- Solar wind and CME transport models
- Space environment effects models

OPERATIONAL RESPONSE TIME FOR SPACE WEATHER MONITORING

Constraints:

- Real-time data streams of space weather parameters are required for space weather situational awareness and decision-making.
- Research satellites without a dedicated real-time downlink cannot be used for operational support, and therefore not considered in the report.
- Research satellites have been used for pathfinders to better understand what kinds of operational instrumentation is needed.
- Current and future GOES instruments have substantial improvements beyond the previous instrument packages.

Data - SEP data set, based on IMP-8 and GOES and identified as Reference Data Set Version 2.0 (RDSv2.0). It covers 41 years of SEP events, from 1974 to 2015, under a framework of the ESA SEPEM project [ref. 20].

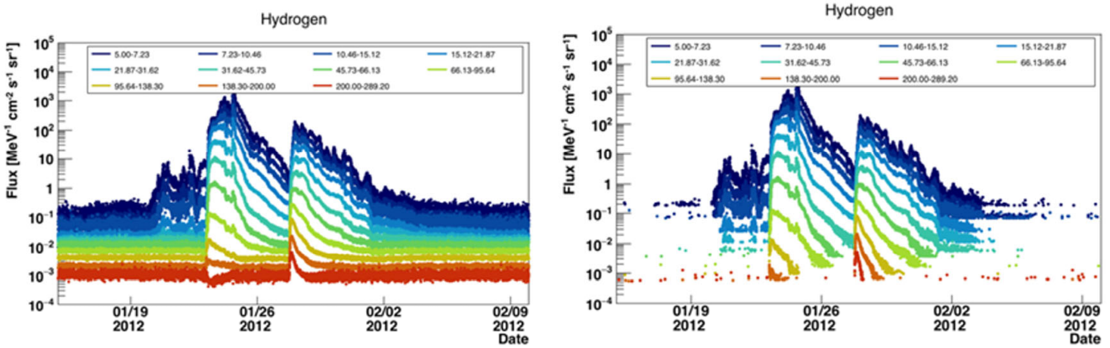

Figure 1. Left image: original RSDv2.0 fluxes. Right image: SEP-only fluxes after the background has been removed. “Clean” data set, with the background removed, is used to perform the statistical study.

Summary and Conclusions

- 192 SEP events in 41 years resulted in an increase in dose above background behind shielding (10 g/cm2 Aluminum sphere)
- 19 (10%) of those were actually multiple SEP events in quick succession, leading to elevated fluxes for up to 13 days
- If an SEP event begins, probabilistic values for duration, time to peak flux and dose rate, time to 10%, 50%, and 90% dose can be inferred from this study (see table of Cumulative Distribution Statistics for an example)

- Mitigation actions will be most effective if they occur within the first 2 hours of an SEP event, which will likely reduce at least 50% of the SEP dose
- If the timing and value of the peak flux can be predicted, it is possible to estimate:
    - The total dose
    - Determine whether 10%, 50%, or 90% dose has likely been reached

ASSESSMENT OF SEP THRESHOLD LEVELS FOR EXPLORATION MISSIONS

Identify the dominant proton energy range with respect to crew risk, i.e. lower and upper energy threshold, that needs to be measured to have sufficient knowledge of the environment for crew health and safety.

- Risk metric used: Dose to Blood-Forming Organs (BFO)
- Methodology
  - Database of 65 historical SEP/GLE events
    - GOES, IMP, ground-based neutron data
    - Spectra fits used to generate input spectra to HZETRN radiation transport code
  - Vehicle models – focus on MPCV, including storm shelter and body self shielding.
  - Compare with point dose in MPCV alone to assess expectations of instrument response.
  - Determine BFO dose as a function of different proton energy bins

BFO Shielding

- The range of median shielding thicknesses at the four nominal seated crew locations was 32–39 g/cm2 Al-Eq.
- The range of median thicknesses of the crew locations within the vehicle storm shelter is 36–43 g/cm2 Al-Eq.
- To calculate BFO dose, the MPCV CAD model of materials and thicknesses were combined in the transport and dosimetric calculations with the tissue and BFO thicknesses of Human Body Phantoms.

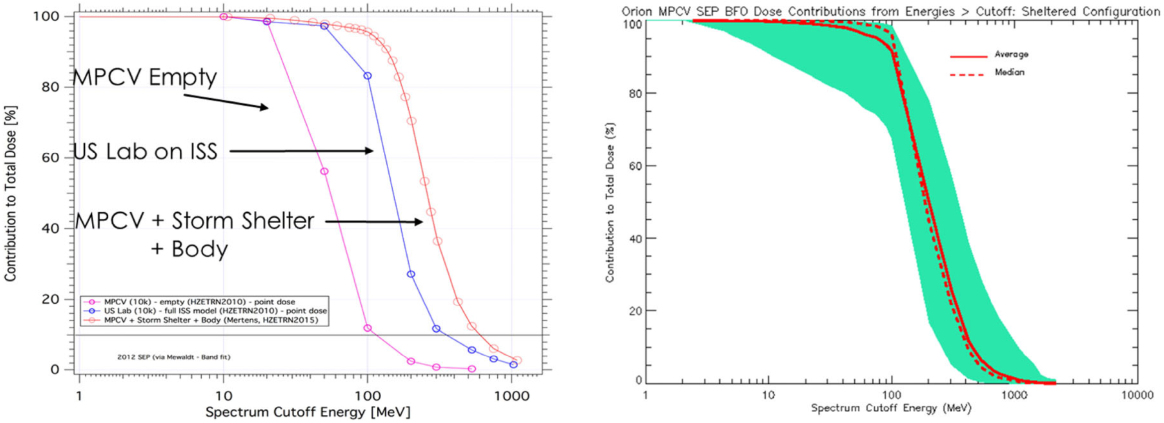

Figure 2. Contributions to total dose. Left - contribution to total dose for MPCV empty, US Lab on ISS, MPCV with storm shelter and body. Right - average and mediam total dose within the SEP/GLE database used.

Summary of Results

- Protons with energies <= 1 GeV need to be incorporated to include more variance among ensemble of relatively hard spectra.
- Generally, only protons of energy >30 MeV can penetrate the pressure vessel.
- Flux increases at these lower energies have served as a signature of adverse space weather conditions
- Real-time information on proton flux at energies as low as 10 MeV are valuable for EVA operations.

SPACE WEATHER ARCHITECTURES

Developed Space Weather Archetectures for:

1. Lunar Architectures 2024
2. Bridging Strategy to Meet Mars Archetecture
3. Mars Archetecture

Ranges of Archetectures

- Baseline: Photospheric magnetic field maps, energetic ions and electrons, soft X-ray flux with flare location detection.
- Enhanced: Baseline package measurements, white-light coronal emissions, and in-situ magnetic field and solar wind plasma.
- Comprehensive: Enhanced package plus space-based solar radio (e.g., Type II, III) measurements.

Although no new types of instruments are required, continued work in maturing predictive SEP modeling and prediction will be essential.

Table 1. Summary of developed architectures.

HEO Mission Target	Classification	Description
Moon	Lunar 2024	No additional hardware required over the existing NOAA and USAF assets. However, lunar platform should be used as a proving ground for future Mars missions (see Bridging Missions)
Bridging Missions	ISS Platform	Proving ground for the Lunar/Mars mission. Instrument priorities: magnetograph, coronagraph
	Gateway Phase I	Energetic charged particle sensors
	Gateway Phase II	Develop a Mars vehicle instrument package using lessons learned from the ISS proving ground and Phase I
	Mars	Instrumentation flying as a hosted payload on robotic Mars science missions
Mars	Baseline	Sustained Sun-Earth line assets. Crewed vehicle flying with Mars baseline instrumentation
	Enhanced	Sustained Sun-Earth line instrumentation. Crewed vehicle flying with Mars enhanced instrumentation.
	Comprehensive	3 spacecraft 120° apart @1AU; all spacecraft have the same remote sensing and in situ instrumentation

Due to the orbit of Mars, instrumentation along the Sun-Earth line will not be sufficient. At times, the crew will be susceptible to SEP events originating from the far side of the Sun. Available instrumentation (e.g., located with the crew or in a Mars orbit) and existing models are capable of providing space weather forecasting at the current state of the art. Given optimal outbound and inbound travel paths, monitoring assets at the Sun-Earth L1, L4 and L5 may provide sufficient additional warning. The Sun-Mars Libration points represent additional locations for environmental architects to consider in the future. A platform at Sun-Mars L1 would provide upstream monitoring for activities on and near the planet and, combined with Sun-Earth Libration monitors, may be sufficient to provide adequate protection. Such an idealized concept is shown in Figure 11-2-1. The time frame for Mars missions is far enough in the future that it is reasonable to expect significant advances in space weather instrumentation and modeling. As a result, lower-ARL models listed in Appendix A have the potential to support Mars missions.

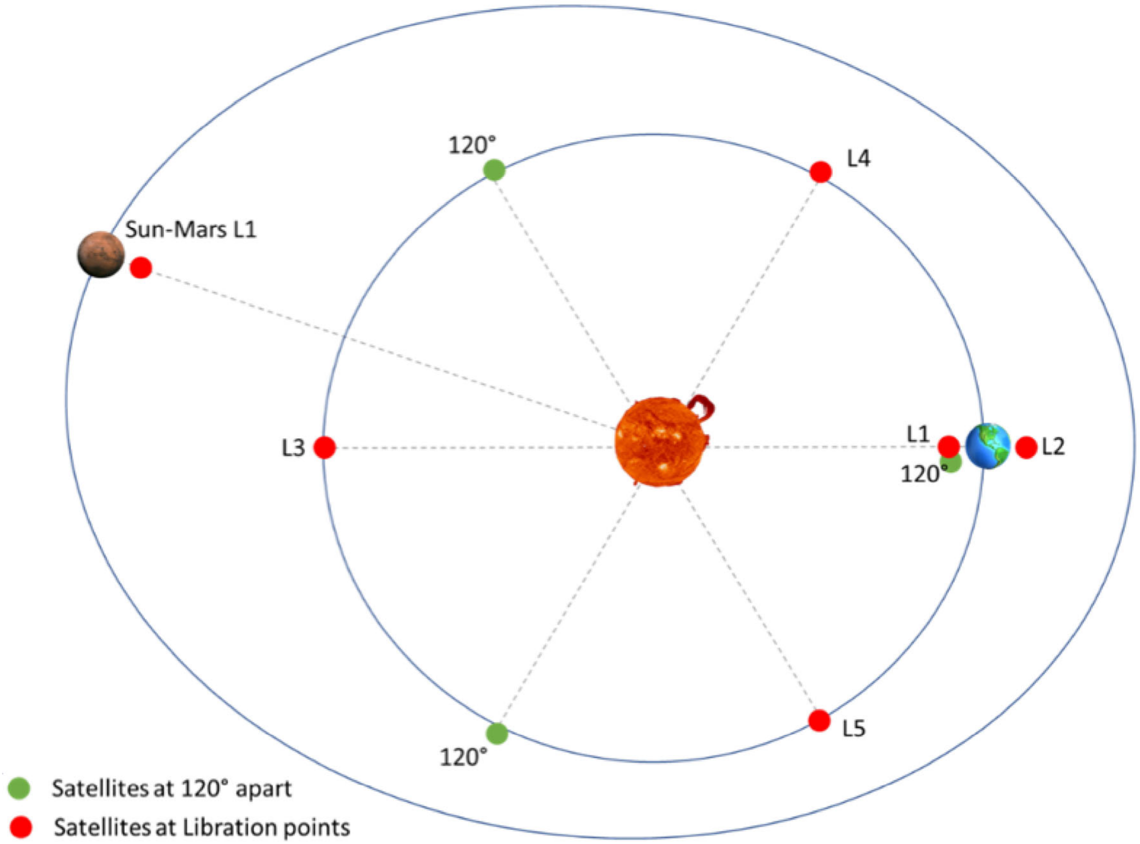

Figure 11.2-1

Figure 4. Visualization of potential satellite archetectures.

CONCLUSIONS

Operations

1. Require concepts of operations to provide 10–30 minutes of warning of predicted critical radiation exposure levels for adequate time for the crew to build/take shelter.
2. Ensure model inputs used for operations have a primary data source with a secondary data input for backup.
3. Ensure a minimum of 30 minutes of advance warning time for solar energetic particles (SEPs).

Model development

1. Ensure researchers focus on modifying predictive models to target the >100 MeV proton fluxes, in addition to >10 MeV.
2. Ensure researchers focus on adapting the pre-eruptive models to add a 6-hour window to the 24-hour window.
3. Ensure rigorous validation and prototyping efforts in a real-time environment for proving the operational utility of SEP prediction models.

Instrumentation

1. Determine if NSF's GONG magnetograms are adequate for space weather models.
2. Plans to replace NASA's SDO or GONG should be put in place to support space weather architecture beyond 2024.
3. Include space weather monitoring instrumentation on robotic Mars missions.
4. Position a charged particle sensor outside Gateway Phase I.
5. Investigate ground-based lower-corona coronagraph observations in SEP predictions.
6. Ensure future space weather architectures can accurately measure proton fluxes from 10 MeV to 1 GeV. F-2, F-10, O-7

General

1. In accordance with the National Space Weather Strategy and Action Plan, NASA should ensure sustained research and analysis (R&A) and R2O-O2R funding for space weather prediction capability development (including SEP).
2. Fund development to target miniaturization of instruments needed for Mars vehicles.
3. Provide guidance, including priorities and rationale, for satellite deployment at 1 AU for Mars exploration. Use the ISS and Gateway Programs as an instrument proving ground for Mars missions. Ensure appropriate space environment design standards and specifications are levied on commercial vendors.
4. Support European efforts to deploy a space weather monitoring satellite, including a coronagraph, at L5.

To request a copy of the report, please follow the instructions found on the NESC website:
https://www.nasa.gov/offices/nesc/knowledgeproducts/index.html