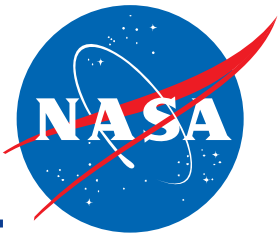


The Lunar Radiation Environment

Kaitlyn L. Ryder and Michael J. Campola

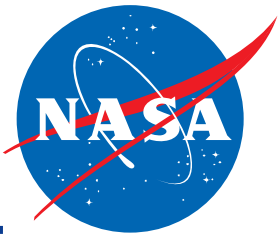
NASA GSFC, Code 561

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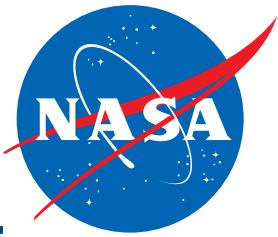
Special thanks to Andrew Tonigan and Joseph Minow for their expertise.

Acronyms



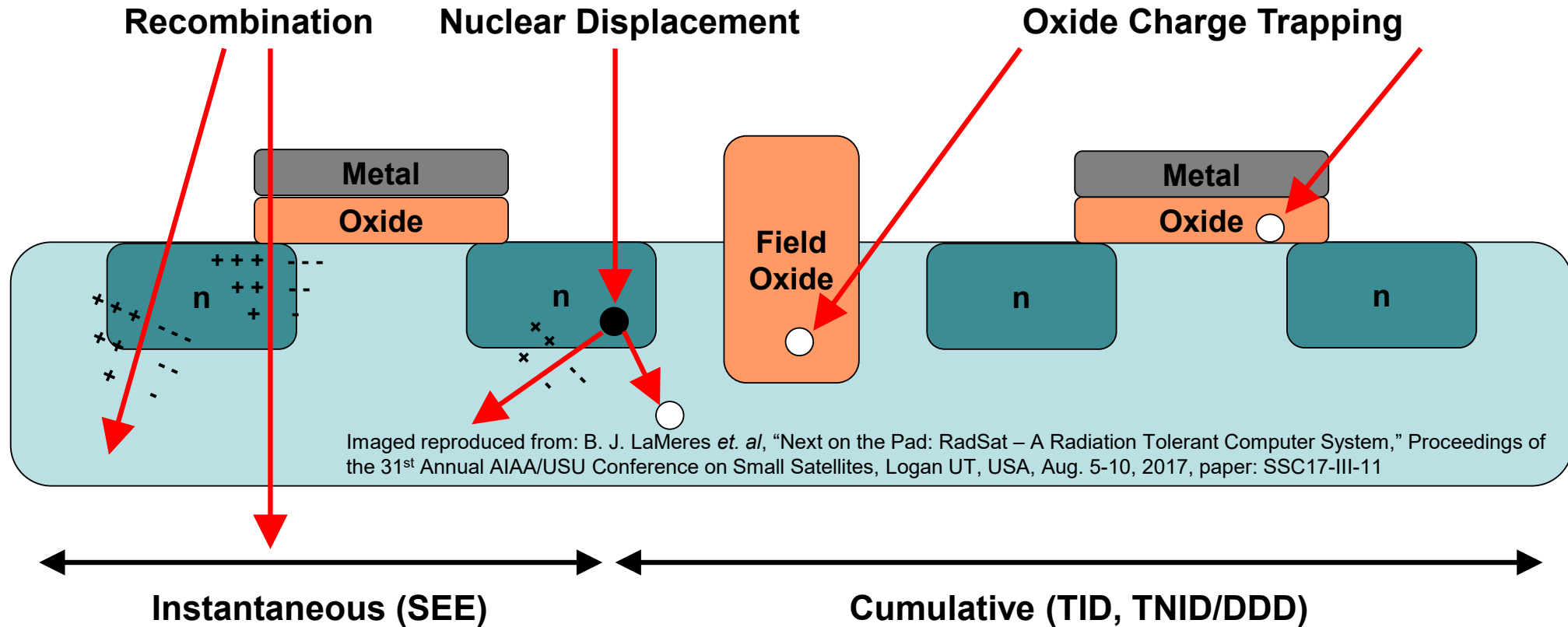
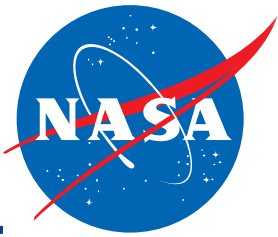
CCD	Charge Coupled Device	RTG	Radioisotope Thermoelectric Generator
CH-1	Chandrayaan-1	SEB	Single Event Burnout
DDD	Displacement Damage Dose	SEE	Single Event Effect
ESA	European Space Agency	SEFI	Single Event Functional Interrupt
EVA	Extravehicular Activity	SEGR	Single Event Gate Rupture
GCR	Galactic Cosmic Ray	SEL	Single Event Latchup
GEO	Geosynchronous Orbit	SET	Single Event Transient
GRAIL	Gravity Recovery and Interior Laboratory	SEU	Single Event Upset
LEO	Low Earth Orbit	SMART-1	Small Missions for Research in Technology 1
LRO	Lunar Reconnaissance Orbiter	SPE	Solar Particle Event
MEO	Middle Earth Orbit	TID	Total Ionizing Dose
RHU	Radiation Heater Unit	TNID	Total Nonionizing Dose

Outline



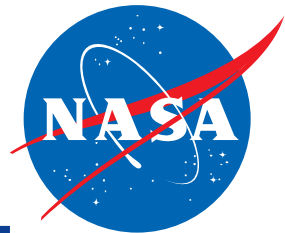
- Overview of Radiation Effects
- Observed Effects from Radiation
- Space Radiation Environment
- Lunar Radiation Environments
 - Transfer Orbit
 - Lunar Orbit
 - Lunar Surface
- Radiation Environment Modeling Tools
- Spacecraft Charging
- Nuclear Power Solutions
- Resources
- Summary

Overview of Radiation Effects



- Single Event Effects (SEE): instantaneous effect caused by a single ionizing particle
- Total Ionizing Dose (TID): cumulative degradation due to accumulation of trapped charge
- Total Non-Ionizing Dose (TNID)/Displacement Damage Dose (DDD): cumulative degradation due to accumulation of lattice defects

Commonly Observed Effects from Radiation



TID

- Increased leakage current, power consumption
- Threshold voltage shifts
- Stuck bits in memory cells
- Changes in timing
- Decreased functionality

TNID/DDD

- Decreased efficiency in optical devices
- Increased dark current in CCDs
- Degradation of CCD charge transfer efficiency
- Degradation of solar cells, optocouplers, linear bipolar devices

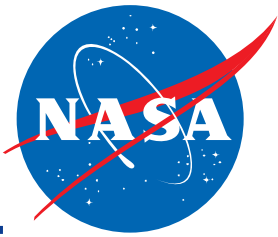
SEE

- Voltage/current spikes (SET)
- Bit-flips (SEU)
- Instantaneous high current states (SEL)
- Program crashes (SEFI)
- Catastrophic device failure in power devices (SEB, SEGR)

Charging

- Electrostatic discharge
- Arching
- Enhanced surface contamination
- Local dielectric breakdown

Space Radiation Environment



- **Trapped Particle Environment**
 - Van Allen Belts
 - Proton and electron rich environment
 - TID, DDD
- **Solar Wind**
 - Protons, electrons, and heavy ions
 - Solar particle events
 - SEE, TID, DDD
- **Galactic Cosmic Rays (GCRs)**
 - Protons and heavy ions
 - SEEs
- **Plasma environment**
 - Spacecraft Charging

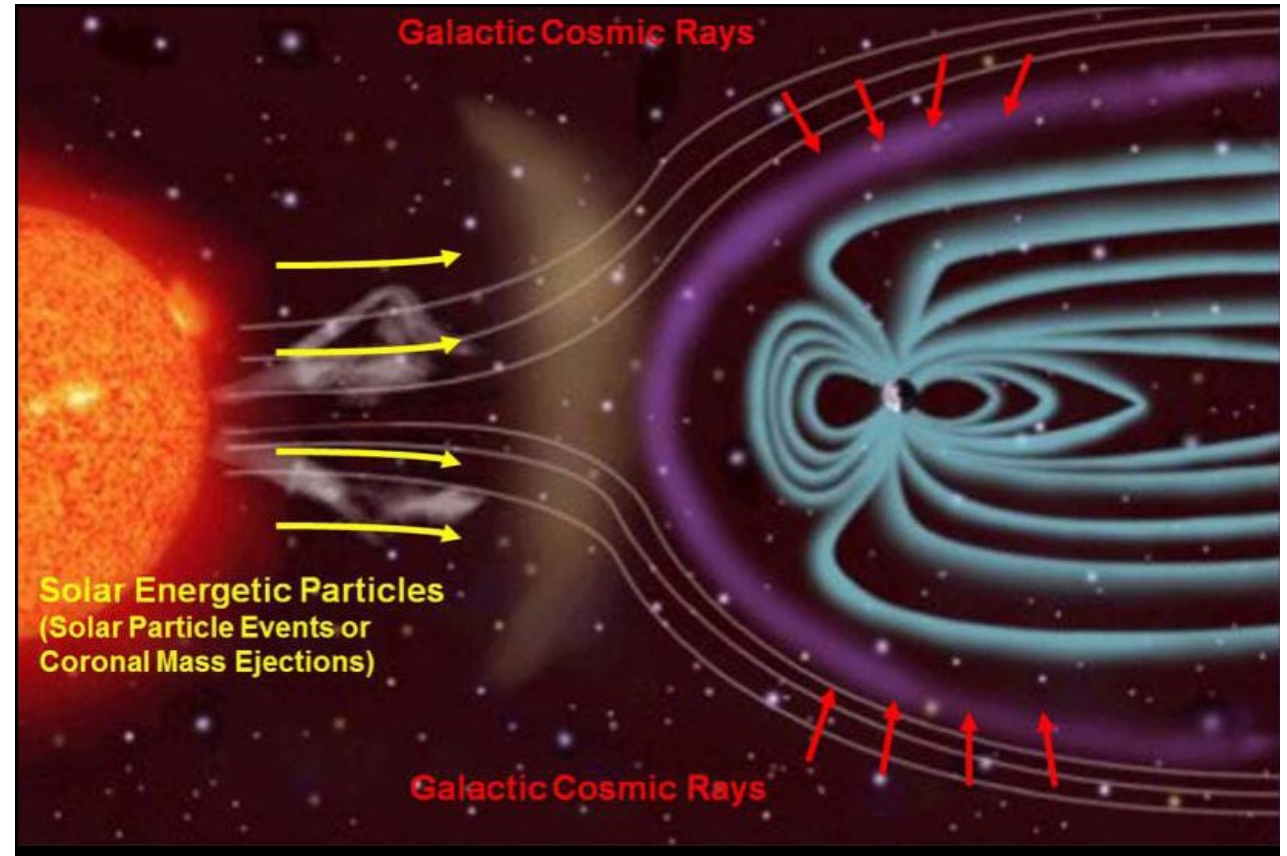


Image Credit: Sources of Ionizing Radiation in Interplanetary Space, JPL
Courtesy of NASA/JPL-Caltech
Available at: <https://www.jpl.nasa.gov/images/pia16938-sources-of-ionizing-radiation-in-interplanetary-space>

Space Radiation Environment – Solar Cycle Effects

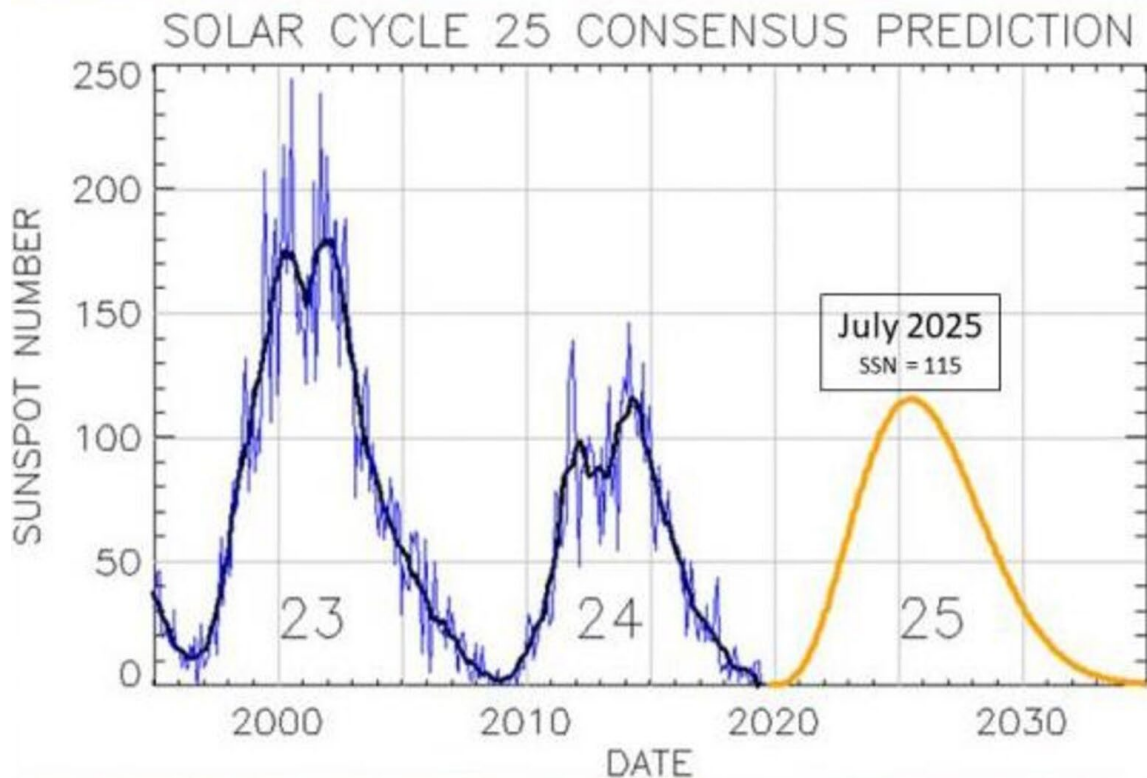
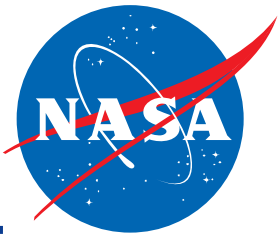
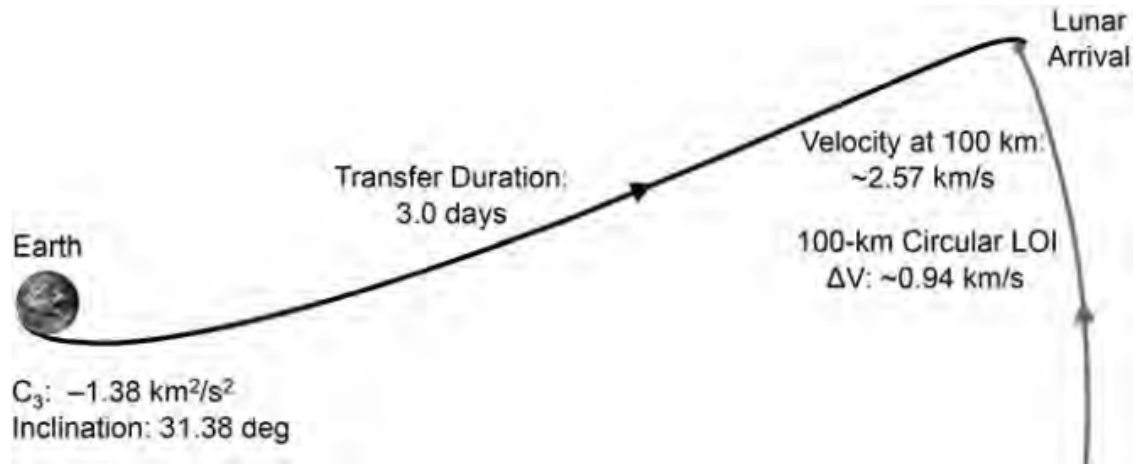


Image Credit: The European Space Agency, Solar Cycle 25 Prediction, NOAA
Available at:
https://www.esa.int/ESA_Multimedia/Images/2020/10/Solar_cycle_25_prediction_NOAA

- **Solar Maximum:**
 - Solar proton fluxes are higher
 - Solar electron fluxes are lower
 - Galactic cosmic ray fluxes are lower
 - Solar particle events are more frequent and of greater intensity
- **Solar Minimum:**
 - Solar proton fluxes are lower
 - Solar electron fluxes are higher
 - Galactic cosmic ray fluxes are higher
 - Solar particle events are less frequent and of less intensity

Lunar Radiation Environments – Transfer Orbits

- Effects amount of time in Van Allen Belts → different trapped environments
- Initial orbit is critical; radiation risk is not 1:1 with trajectory duration



Left: Modified version of Apollo 11 direct Earth-Moon transfer.

Right: Example 84-day lunar transfer orbit from a LEO polar orbit, low energy.

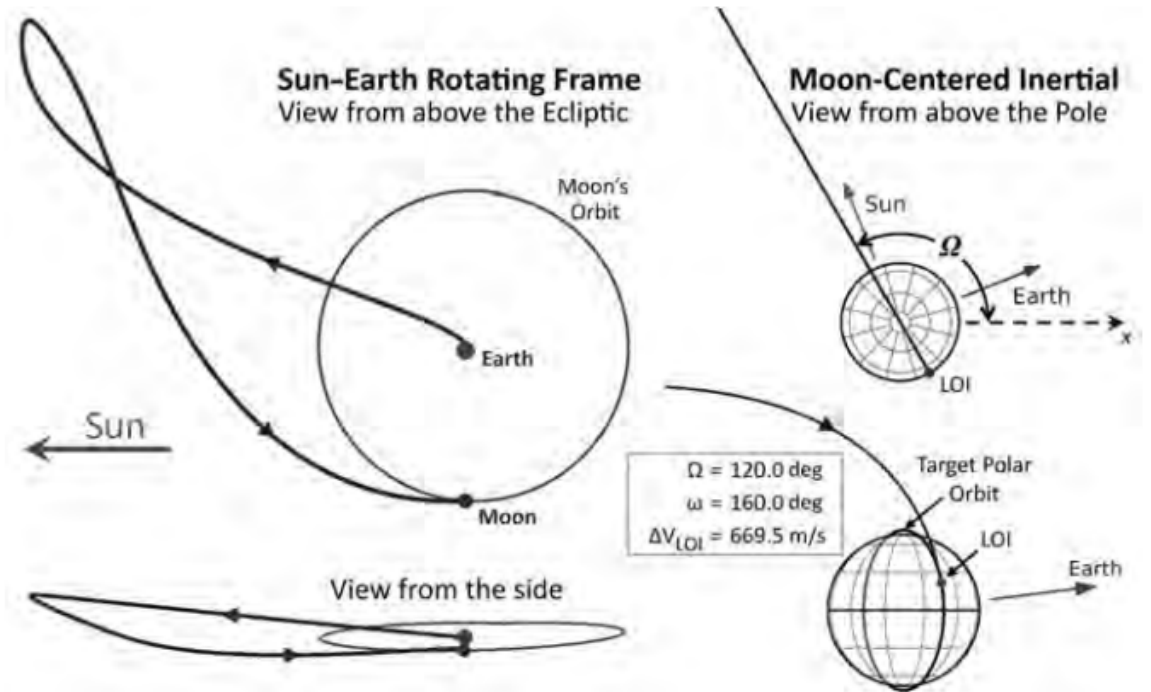
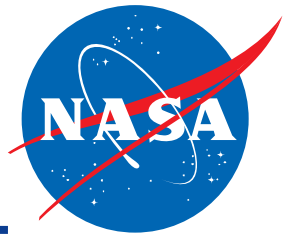


Image credit: Parker, Jeffrey S.; Anderson, Rodney L; Peterson, Andrew, 2011, "A survey of ballistic transfers to low lunar orbit", JPL Open Repository, V1; 11-0494.pdf. CC0 1.0 Available at: <https://hdl.handle.net/2014/41925>

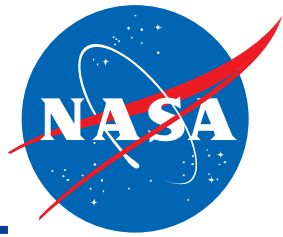


Lunar Radiation Environments – Transfer Orbits

- Effects amount of time in Van Allen Belts → different trapped environments
- Initial orbit is critical; radiation risk is not 1:1 with trajectory duration

Transfer Type	Typical Duration	Benefits	Example Missions
Direct, conventional	3 – 6 days	Well known, quick	Apollo, LRO
Direct, staging	2 – 10 weeks	Quick, many launch days	Clementine, CH-1
Direct to lunar L ₁	1 – 5 weeks	Staging at L ₁	None to date
Low-thrust	Many months	Low fuel, many launch days	SMART-1
Low-energy	2.5 – 4 months	Low fuel, many launch days	Hiten, GRAIL, ARTEMIS

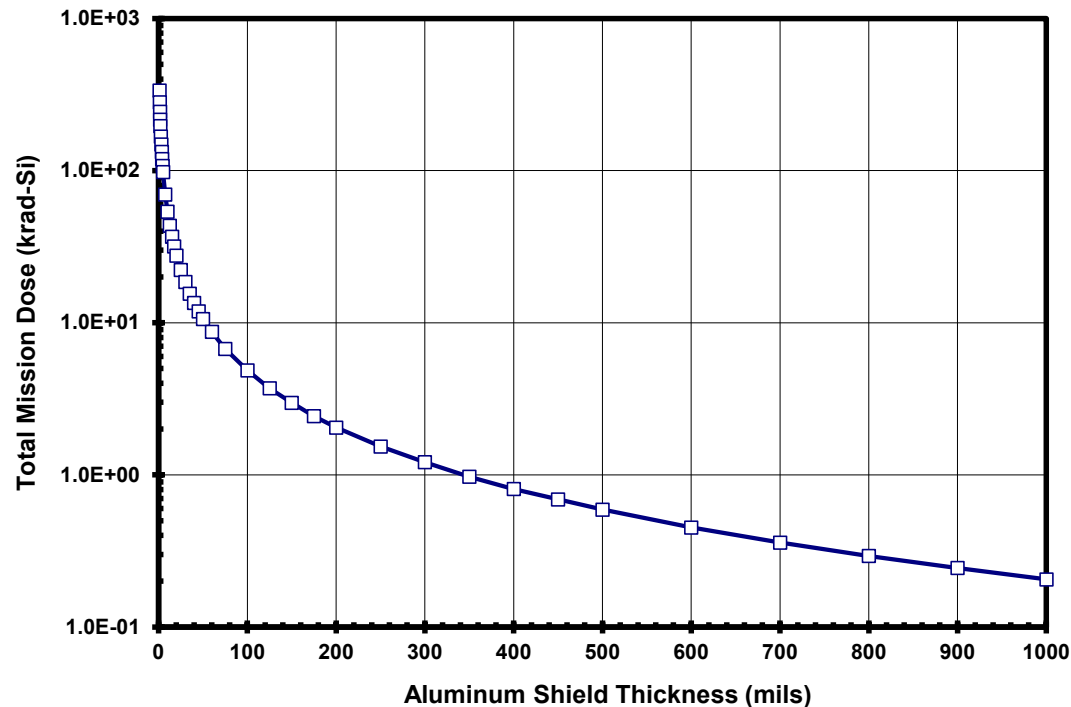
Table reproduced from: J. S. Parker and R. L. Anderson, “Title of Chapter” in *Low-Energy Lunar Trajectory Design*, Pasadena, CA, JPL, July 2013, Ch. 1, pp. 3. Available at: <https://descanso.jpl.nasa.gov/monograph/series12/LunarTraj--Overall.pdf>



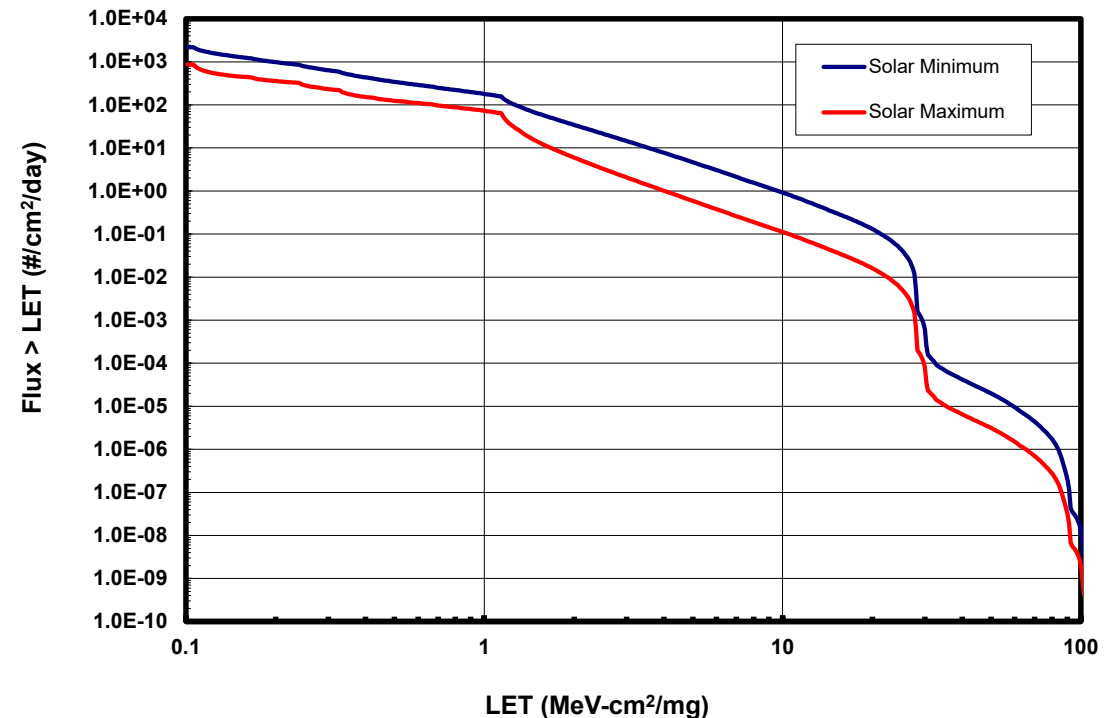
Lunar Radiation Environments – Lunar Orbit

- Interplanetary space → no trapped environment, no geomagnetic shielding
- Radiation environment dominated by solar protons, GCRs
- No protection from very high flux solar particle events (SPEs)

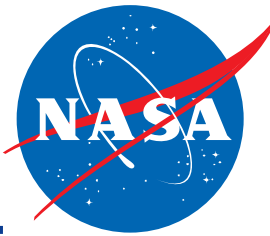
Solar Max Dose-Depth Curves (Conf. Level 95%)



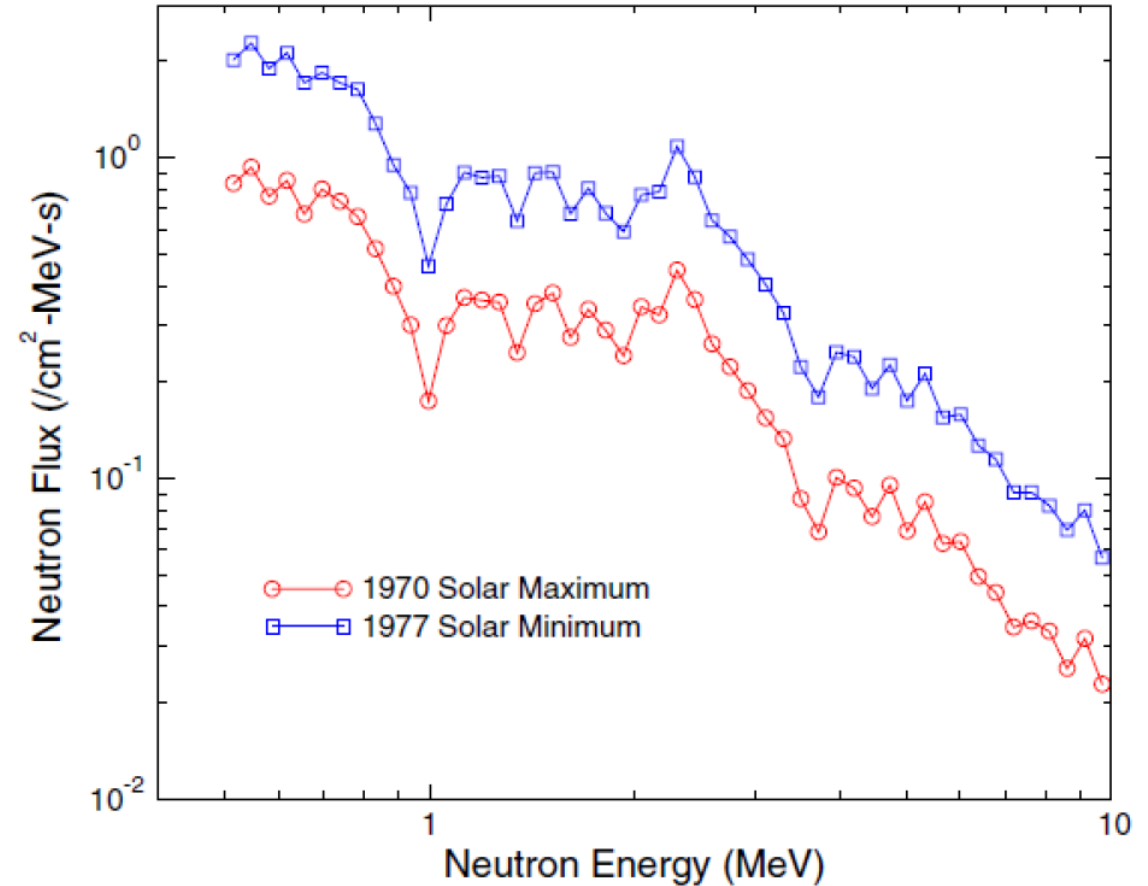
Lunar LET Spectra
(Behind 100 mils(Al))



Lunar Radiation Environments – Lunar Surface

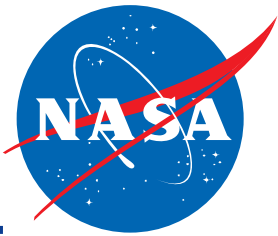


- Interplanetary space → no trapped environment, no geomagnetic shielding
- Radiation environment dominated by solar protons, GCRs
 - Divide fluxes by a factor of 2 (2π steradians) to account for presence of Moon
- Albedo neutrons generated by GCR interactions with lunar surface
 - Solar cycle dependent



Adams, J.H. *et al.*, 2007. The ionizing radiation environment on the moon. *Advances in Space Research*, 40, issue 3, 338-341.

Radiation Environment Modeling Tools



- Space Environment Information System (SPENVIS):
 - Trapped particle environment, solar protons, solar cycle effects
 - Transport radiation environment through materials (TID, DDD dose-depth curves)
 - Hosted by the European Space Agency (ESA)
 - <https://www.spennis.oma.be/intro.php>
- CRÈME96:
 - LET flux spectra from trapped particle environment, GCRs, solar protons, solar cycle effects
 - Transport radiation environment through materials (flux spectra behind shielding)
 - SEE rate calculations
 - Hosted by Vanderbilt University
 - <https://creme.isde.vanderbilt.edu/>
- Others:
 - OMÈRE, NOVICE, FastRAD
 - Cross-Program Design Specification for Natural Environments (DSNE)

Spacecraft Charging Overview

- Buildup of charge on surfaces of spacecraft from plasma environments
- Electrons are primary contribution in lunar environment
 - Transit through radiation belts carries more charging risk
- Triboelectric charging of lunar dust may be problematic on lunar surface
- Lunar surface can become charged
 - Potential difference between dayside/nightside
 - Charge separation in lunar craters and mountains

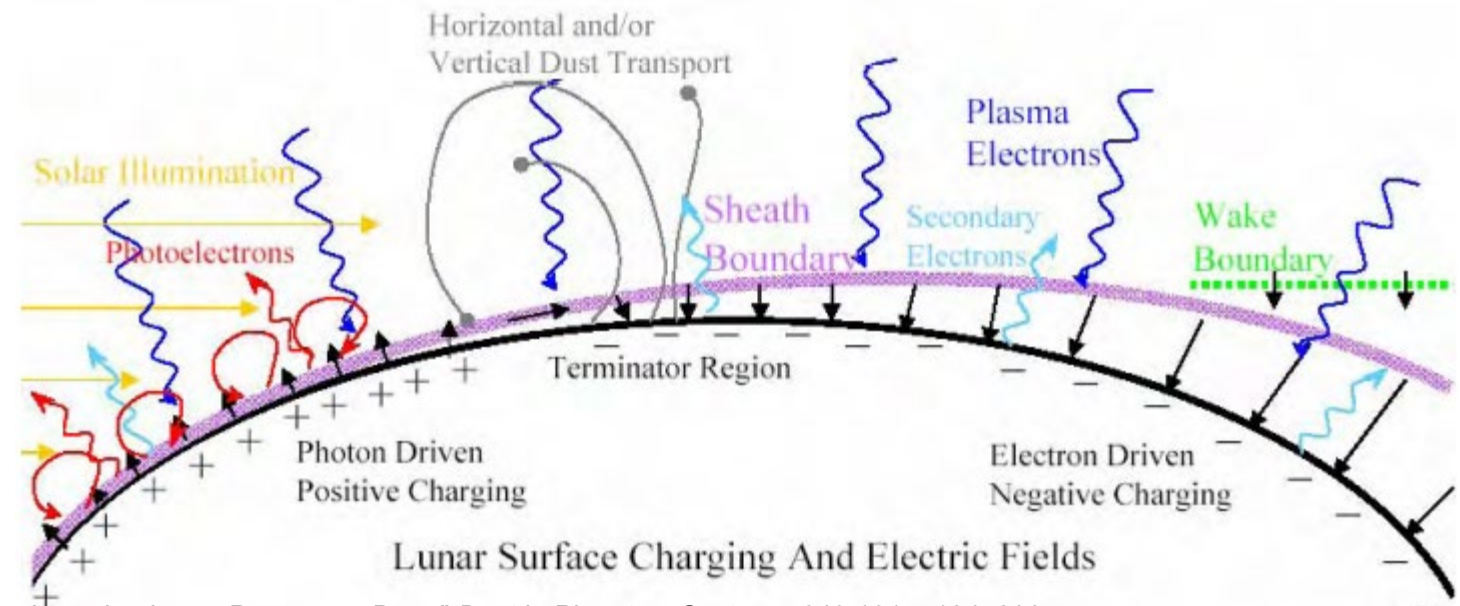
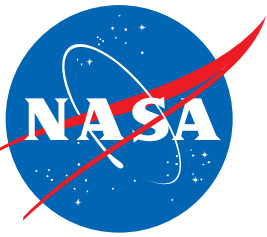


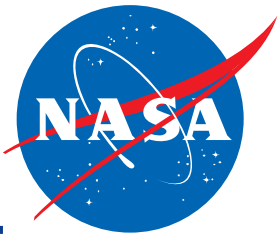
Image credit: T. J. Stubbs *et. al*, "Lunar Surface Charging: A Global Perspective using Lunar Prospector Data," *Dust in Planetary Systems*, 643:181 – 184, 2007.
 Available at: https://www.nasa.gov/centers/johnson/pdf/486015main_StubbsSurfaceCharging.4070.pdf



Types of Spacecraft Charging

- Surface charging – charges accumulate on the surface of the spacecraft
- Deep dielectric charging – charges accumulate deep within spacecraft dielectrics
- Absolute charging – entire spacecraft potential is changed relative to ambient space plasma
- Differential charging – parts of spacecraft are charged to different potentials relative to each other

Effects of Spacecraft Charging



Concerns

- Arcing
- Electrostatic discharge
- Enhanced surface contamination
- Local dielectric breakdown
- Cracked plastics
- Unknown concern for astronauts on EVAs

Mitigation techniques

- Good spacecraft design
 - Selection of insulators
 - Use of conductive surfaces and coatings
- Ground external conductors together
- Minimize energy stored in capacitance
- Electrically isolating astronauts from suit (theoretical possibility)

Nuclear Power Solutions

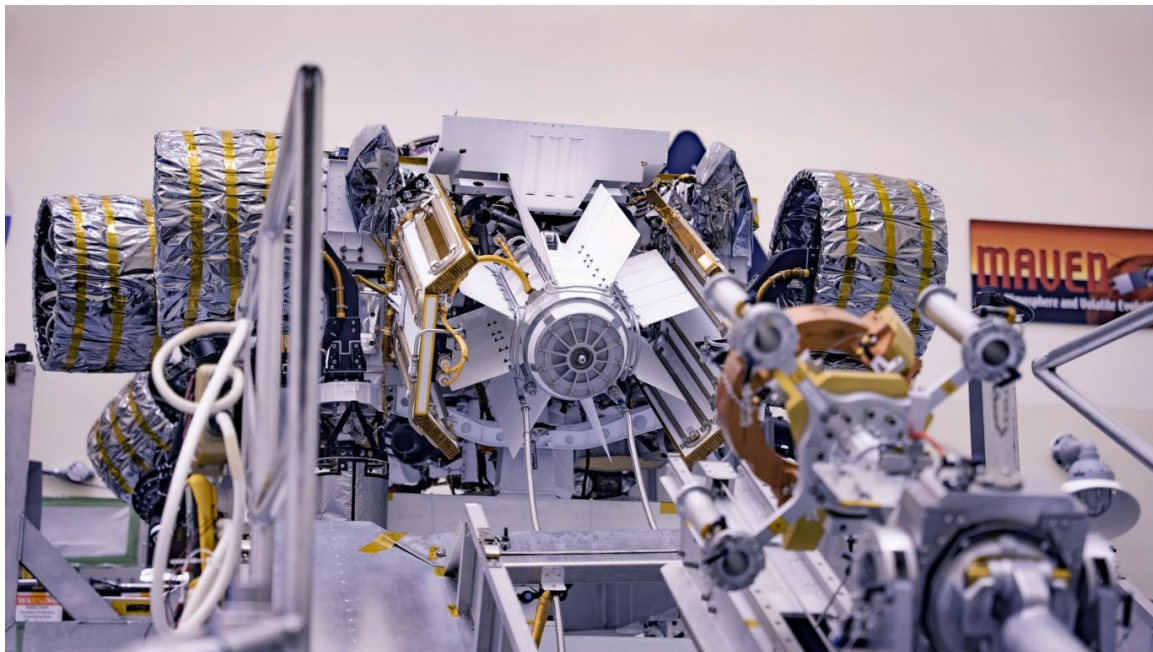
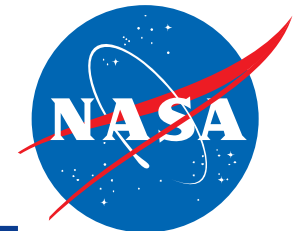


Image credit: Rover Power Source, JPL.
Courtesy of NASA/JPL-Caltech
Available at: <https://www.jpl.nasa.gov/images/pia23981-rover-power-source>

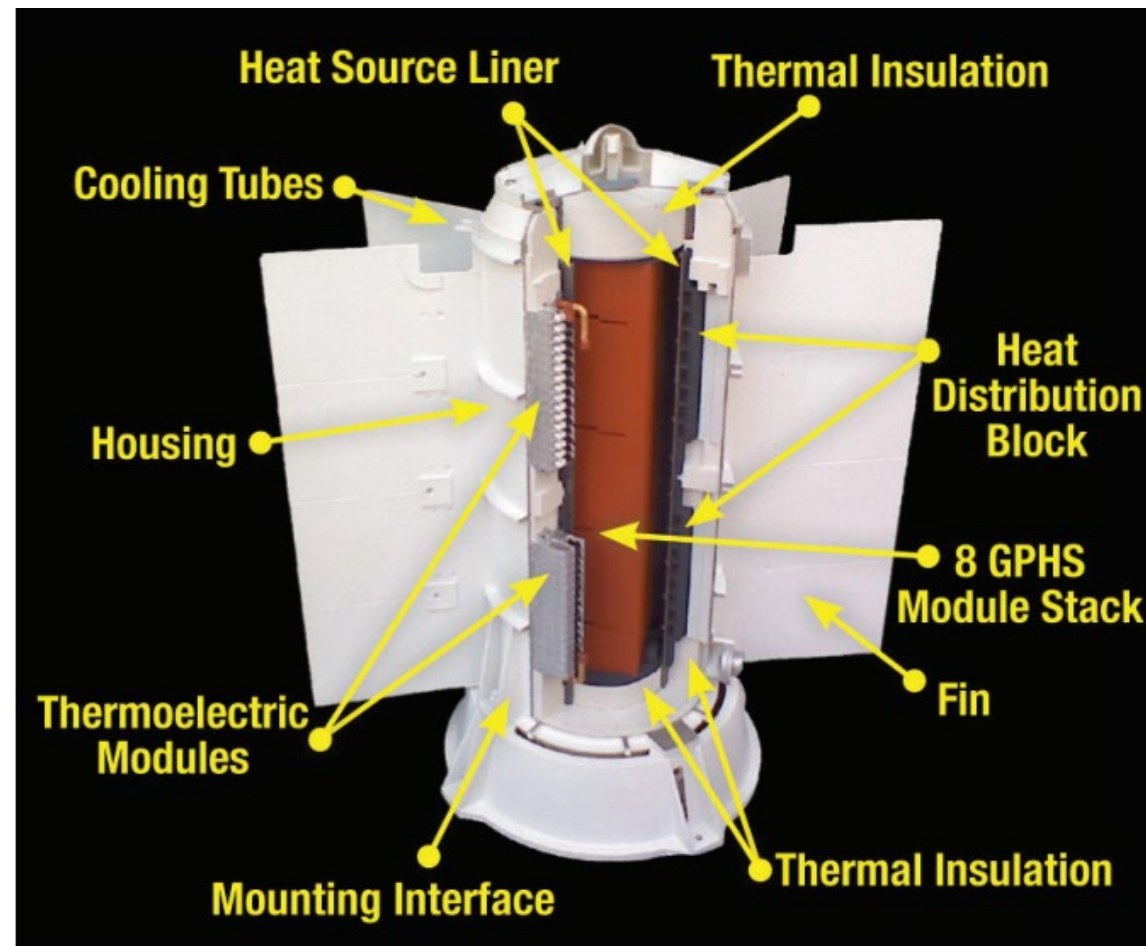
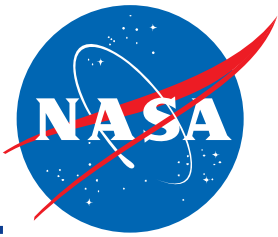
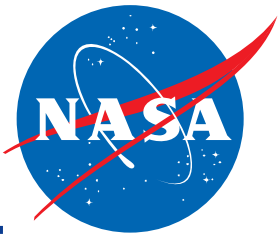


Image credit: Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), NASA, Fact Sheet.
Available at: https://rps.nasa.gov/resources/86/multi-mission-radioisotope-thermoelectric-generator-mmrtg/?category=fact_sheets

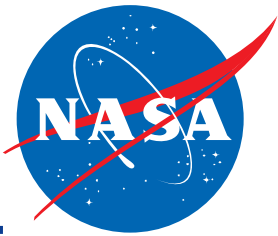
Nuclear Power Solutions



- Has power density advantages over solar/chemical power solutions
- Common nuclear sources:
 - Radioisotope thermal electric generators (RTGs)
 - Radiation heater units (RHUs)
- Radiation by-products:
 - Gamma radiation, alpha decay from plutonium-238 decay, other plutonium isotopes, and alpha reactions with light elements
- Radiation effects:
 - TID from gamma radiation
 - SEEs from secondary products from proton, neutron interactions
 - DDD from proton, neutron interactions, gamma radiation
- Location of nuclear power sources, shielding of sensitive electronics needs to be considered

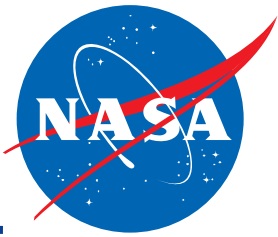


- CRÈME96 – <https://creme.isde.vanderbilt.edu/>
- RGENTIC – <https://vanguard.isde.vanderbilt.edu/RGentic/>
- Spenvis – <https://www.spenvis.oma.be/intro.php>
- Cross-Program Design Specification for Natural Environments (DSNE) – (available in NTRS) <https://ntrs.nasa.gov/citations/20190027643>
- Avionics Radiation Hardness Assurance (RHA) Guidelines – (available in NTRS) <https://ntrs.nasa.gov/citations/20210018053>
- J. S. Parker and R. L. Anderson, “Title of Chapter” in *Low-Energy Lunar Trajectory Design*, Pasadena, CA,: JPL, July 2013. Available at: <https://descanso.jpl.nasa.gov/monograph/series12/LunarTraj--Overall.pdf>
- Design guidelines for assessing and controlling spacecraft charging effects – (available in NTRS) <https://ntrs.nasa.gov/citations/19840025381>



- J. S. Halekas *et. al*, “Electrons and magnetic fields in the lunar plasma wake,” *Journal of Geophysical Research*, vol. 110, A07222, doi:10.1029/2004JA010991, 2005.
- J. S. Halekas *et. al*, “Lunar surface charging during solar energetic particle events: Measurement and prediction,” *Journal of Geophysical Research*, vol. 114, A07222, doi:10.1029/2009JA014113, 2009.
- E. L. Noon, G. H. Anno and M. A. Dore, "Nuclear Radiation Sources on Board Outerplanet Spacecraft," in *IEEE Trans. on Nucl. Sci.*, vol. 18, no. 5, pp. 50-57, Oct. 1971, doi: 10.1109/TNS.1971.4326395.

Summary



- Goal is to bound risk from the environment to the system
 - Is the system exposed to a threat?
 - What is the worst-case result of that threat?
 - Can the threat be lived with, or does it need mitigated?
- Radiation environment changes as spacecraft move from Earth to the Moon
 - Initial trajectory is extremely important in determining Van Allen Belt environment
 - Nominal lunar environments are benign compared to transits through Van Allen Belts
 - No protection from SPEs in lunar orbit, on lunar surface
- Lunar environments are understood from historical events and missions
 - Steady-state concerns are understood, perturbations are more complex