Heliospheric Physics and NASA’s Vision for Space Exploration

Joseph Minow
NASA, Marshall Space Flight Center

The Vision for Space Exploration outlines NASA’s development of a new generation of human-rated launch vehicles to replace the Space Shuttle and an architecture for exploring the Moon and Mars. The system—developed by the Constellation Program—includes a near term (~2014) capability to provide crew and cargo service to the International Space Station after the Shuttle is retired in 2010 and a human return to the Moon no later than 2020. Constellation vehicles and systems will necessarily be required to operate efficiently, safely, and reliably in the space plasma and radiation environments of low Earth orbit, the Earth’s magnetosphere, interplanetary space, and on the lunar surface. This presentation will provide an overview of the characteristics of space radiation and plasma environments relevant to lunar programs including the trans-lunar injection and trans-Earth injection trajectories through the Earth’s radiation belts, solar wind surface dose and plasma wake charging environments in near lunar space, energetic solar particle events, and galactic cosmic rays and discusses the design and operational environments being developed for lunar program requirements to assure that systems operate successfully in the space environment.
Heliospheric Physics and NASA’s Vision for Space Exploration

Joseph I. Minow
NASA, Marshall Space Flight Center

Utah State University, Logan, UT
17 April 2007
Overview

- Constellation Program architecture
- Heliospheric physics science in design, operations of lunar programs
  - Radiation environments
    - Crew
    - Hardware (electronics), materials
  - Plasma environments
    - Spacecraft charging, surface dose
- Summary

<table>
<thead>
<tr>
<th>Environments</th>
<th>Space System Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic cosmic rays</td>
<td>SEE, crew dose</td>
</tr>
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<td>Solar particle events</td>
<td>SEE, TID, crew dose, charging</td>
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<td>Trapped radiation belts</td>
<td>SEE, TID, crew dose, charging</td>
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<td>Solar wind, magnetosheath</td>
<td>TID, charging</td>
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<td>magnetospheric plasma</td>
<td>charging</td>
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<tr>
<td>Lunar photoelectrons</td>
<td></td>
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</table>

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Constellation Program

- New human-rated space transportation system to replace Space Transportation System (Shuttle)
  - ISS support ~2014
  - Lunar exploration ~2020
  - Mars exploration

ISS Support

- Crewed Exploration Vehicle
  - Capability for transferring crew members (4-6) to ISS
  - Unmanned cargo delivery
    - Pressurized
    - Unpressurized

Service Module | Crew Module | Launch Abort System
Lunar Exploration Architecture

Composite Shroud

Lunar Surface Access Module (LSAM)

Earth Departure Stage
LOx/LH₂
1 J-2X Engine
Al-Li Tanks/Structures

Interstage

Core Stage
LOx/LH₂
5 RS-68 Engines
Al-Li Tanks/Structures

5-Segment
2 RSRB's

Lunar Surface Access Module (LSAM)

Example Lunar Reference Mission

- Lunar architecture
  - Lunar sortie (7 days)
  - Lunar outpost (~6 months)


- Current program focus is on developing an outpost at one of the lunar poles with access to other locations on lunar surface
Lunar South Pole

- >70% illumination on rim of Shakelton Crater
- \( T \approx 220 \pm 10 \) K...relatively benign
- Night temperatures near equator are \( T \approx 100 \) K
- \( T \approx 40 \) K to 50 K in permanently dark craters

[adapted from Bussey et al., LPSC 1999]

Longest period of shadow ~49 hours based on ~29.5 day/Sol or 12.2 deg/day

[Bussey et al., GRL, 1999]

[Dale, 2nd Space Expl. Conf., 2006]
# Apollo Experience

<table>
<thead>
<tr>
<th>Mission</th>
<th>Landing Date</th>
<th>SEA(^a) (GMT)</th>
<th>SEA(^a) (deg)</th>
<th>Lunar(^c) Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>20 Jul 69</td>
<td>10.8</td>
<td>WxC, 31%</td>
<td></td>
</tr>
<tr>
<td>Apollo 12</td>
<td>19 Nov 69</td>
<td>5.1</td>
<td>WxG, 81%</td>
<td></td>
</tr>
<tr>
<td>Apollo 13</td>
<td>----</td>
<td>18.5(^b)</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Apollo 14</td>
<td>5 Feb 71</td>
<td>10.3</td>
<td>WxG, 81%</td>
<td></td>
</tr>
<tr>
<td>Apollo 15</td>
<td>30 Jul 71</td>
<td>12.2</td>
<td>1Qtr, 50%</td>
<td></td>
</tr>
<tr>
<td>Apollo 16</td>
<td>21 Apr 72</td>
<td>11.9</td>
<td>WxG, 62%</td>
<td></td>
</tr>
<tr>
<td>Apollo 17</td>
<td>11 Dec 72</td>
<td>13.0</td>
<td>WxC, 29%</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Solar elevation angle data from Orloff [2000]

\(^b\)Planned

\(^c\)http://aa.usno.navy.mil/data/docs/RS_OneDay.html

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**Waxing Crescent Quarter**
**Waxing Gibbous**
**Full Moon**
**Waning Gibbous**
**Waning Quarter Crescent**
**New Moon**

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Magnetosphere and Lunar Orbit

Moon passes through magnetotail and magnetosheath plasma environments every month

In-situ observations of plasma and radiation environments relevant to lunar exploration are available from pre-Apollo to present
Bow Shock and Magnetopause Variability

**Fraction of Month in Plasma Environments**

- ~73.5% solar wind
- ~13.3% magnetosheath
- ~13.2% magnetotail

**Graphical Data**

- **B**$_z$ (nT) $V_{sw}$ (km/s) $N_p$ (#/cc)
  - a) 0  400  8
  - b) -5  400  8
  - c) -15  400  8
  - d) 0  700  5
  - e) 5  400  70

**Legend**

- BS: bow shock
- MP: magnetopause

**Notes**

- Lunar orbit ~60 Re
- Petrinic and Russell [1993, 1996]
- Bennett et al. [1997]

**References**

- Blackwell et al., 2000

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Inclination, Departure Longitude and Dose

Single TLI orbit
perigee = 300 km
apogee = 379,867 km
Inclination, Departure Longitude and Dose

Single TLI orbit
perigee = 300 km
apogee = 379,867 km
Lunar 60 Re orbit is 
\( \sim 1 \pm 0.0026 \text{ AU} \)

--Same cosmic ray, solar energetic particle environment as Earth

--Magnetotail \( \sim 10 \text{ nT} \) field at lunar orbit weaker than the 50 nT to 100 nT at GEO

CREME 1996 [Tylka et al., 1997]
Solar Particle Event ("Flare") Environments

IMP-8 interplanetary ions from the C-N-O group
Episodic high flux solar particle events are superimposed on the slowly varying galactic cosmic ray background flux

Frequency and magnitude of solar particle events demonstrates that Shuttle exposure to a high flux solar energetic particle event (or an equivalent fluence due to a number of smaller events) is a credible event during Shuttle life

Example flux and duration of large proton solar particle event in October 1989
Flares, CME’s

- Impulsive events
  - Minutes to hours
  - Electron rich
  - ~1000/yr at solar max

- Gradual events
  - Days
  - Proton rich
  - ~100/year

[http://www.srl.caltech.edu/ACE/ACENews/ACENews55.html]
Energetic Particle Impacts on Spacecraft

- Bastille Day 2000 Storm
  - SOHO Lasco
  - Polar VIS

- Similar effects on star trackers used for attitude control can threaten spacecraft
Constellation Design Environments

- Proton SPE, GCR fluence spectra (for total dose analyses)
  - Based on October 1989 flare, solar minimum GCR environments derived from CREME96 model

<table>
<thead>
<tr>
<th>Event</th>
<th>Max &gt;30 MeV flux (#/cm²-s-sr)</th>
<th>30 MeV fluence (#/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1859/09/01</td>
<td>5 x 10⁴</td>
<td>19 x 10⁹</td>
</tr>
<tr>
<td>1960/11/15</td>
<td>hardware</td>
<td>9 x 10⁹</td>
</tr>
<tr>
<td>1946/07/25</td>
<td></td>
<td>6 x 10⁹</td>
</tr>
<tr>
<td>1972/08/04</td>
<td>2 x 10⁴</td>
<td>5 x 10⁹</td>
</tr>
<tr>
<td>2000/07/12</td>
<td></td>
<td>4.3 x 10⁹</td>
</tr>
<tr>
<td>1989/10/19</td>
<td></td>
<td>4.2 x 10⁹</td>
</tr>
<tr>
<td>2001/11/04</td>
<td></td>
<td>3.4 x 10⁹</td>
</tr>
<tr>
<td>2003/10/28</td>
<td>4.5x10³</td>
<td>3.4 x 10⁹</td>
</tr>
<tr>
<td>2000/08/00</td>
<td></td>
<td>3.2 x 10⁹</td>
</tr>
<tr>
<td>1959/07/14</td>
<td></td>
<td>2.3 x 10⁹</td>
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<tr>
<td>1991/03/22</td>
<td></td>
<td>1.8 x 10⁹</td>
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<td>1989/08/12</td>
<td></td>
<td>1.4 x 10⁹</td>
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<tr>
<td>1989/09/29</td>
<td></td>
<td>1.4 x 10⁹</td>
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<td>2001/09/24</td>
<td></td>
<td>1.2 x 10⁹</td>
</tr>
<tr>
<td>2005/01/15</td>
<td></td>
<td>1.0 x 10⁹</td>
</tr>
</tbody>
</table>

Sources: Smart and Shea, 2002; Reedy, 2006; Smart et al., 2005

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Solar energetic particles have nearly free access to outer magnetosphere and magnetotail—no protection for Moon when in magnetotail
CREME96 Worst Week + 1 year GCR (solar min)

- Flare environment dominates at energies less than few hundred MeV
  - Particles responsible for total dose issues removed by shielding
  - Energetic (100's MeV to multiple GeV) particles difficult to shield
    - Electronics upsets
    - Crew dose
Single event effects (SEE) occur when charge deposited by an ion passing through the sensitive volume of a biased electronic device is of sufficient magnitude to change the operating state of the device. Example SEE types include:

- **Single event voltage transient (SET):** self correcting but could cause system malfunction if propagated as a signal
- **Single event upset (SEU):** operating state change (e.g. memory bit upset)-errors in data and executable output if uncorrected
- **Single event latchup (SEL):** operation ceases-effect may be correctible by power cycling or part may be destroyed
- **Single event burnout (SEB):** part is destroyed by over-current

SEE typically produced by heavy ions ($Z=2-92$)
Protons produce insufficient ionization to generate upsets directly

--Minor contribution from protons to SEE rates due to (small) cross section for proton induced nuclear reactions generating secondary heavy ions
GCR Dose

<table>
<thead>
<tr>
<th>Shielding (Apollo-16 soil)</th>
<th>GCR Dose (FLUKA) $(1 \leq Z \leq 28)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cm</td>
<td>15.9 cGy/yr</td>
</tr>
<tr>
<td>25 cm</td>
<td>9.3 cGy/yr</td>
</tr>
<tr>
<td>50 cm</td>
<td>5.6 cGy/yr</td>
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Deterministic LEO Dose Limits*

<table>
<thead>
<tr>
<th></th>
<th>BFO</th>
<th>Ocular Lens</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-day</td>
<td>25</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Annual</td>
<td>50</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Career</td>
<td>100-400</td>
<td>400</td>
<td>600</td>
</tr>
</tbody>
</table>

* [NCRP-98-1989] (from Wilson et al., 1997)

Mission Dose (cSv) Estimates
(50 cm regolith shielded cylinder)

GCR Feb 56 Flare Mission Dose

<table>
<thead>
<tr>
<th></th>
<th>GCR Solar Minimum</th>
</tr>
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<tbody>
<tr>
<td>30-days</td>
<td>1</td>
</tr>
<tr>
<td>6 months</td>
<td>6</td>
</tr>
<tr>
<td>1 year</td>
<td>12</td>
</tr>
</tbody>
</table>

(From Simonson et al., 1997)

Evaluating stochastic human dose risk requires more detailed analysis!
Regolith Shielding Properties for GCR

- FLUKA transport code
- Shield with Apollo-16 lunar soil composition
- CREME96 GCR Z=1 solar minimum
  - Isotropic incident flux over hemisphere

<table>
<thead>
<tr>
<th>Compound</th>
<th>Percent A-16</th>
<th>Percent JSC-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂O</td>
<td>0.46</td>
<td>2.70</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>27.30</td>
<td>15.02</td>
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<tr>
<td>FeO</td>
<td>5.10</td>
<td>7.35</td>
</tr>
<tr>
<td>CaO</td>
<td>15.70</td>
<td>10.42</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.07</td>
<td>3.44</td>
</tr>
<tr>
<td>MnO</td>
<td>0.30</td>
<td>0.18</td>
</tr>
<tr>
<td>MgO</td>
<td>5.70</td>
<td>9.01</td>
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<tr>
<td>SiO₂</td>
<td>45.00</td>
<td>47.71</td>
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<tr>
<td>K₂O</td>
<td>0.17</td>
<td>0.82</td>
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<tr>
<td>TiO₂</td>
<td>0.54</td>
<td>1.59</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.11</td>
<td>0.66</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.33</td>
<td>0.04</td>
</tr>
</tbody>
</table>
GCR Dose

Shielding (Apollo-16 soil)  GCR Dose (FLUKA)  
(1 ≤ Z ≤ 28)

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Mission Dose (cSv) Estimates
(50 cm regolith shielded cylinder)

GCR Feb 56 Flare Mission Dose

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</thead>
<tbody>
<tr>
<td>30-days</td>
<td>1 7.5 8.5</td>
</tr>
<tr>
<td>6 months</td>
<td>6 7.5 13.5</td>
</tr>
<tr>
<td>1 year</td>
<td>12 7.5 19.5</td>
</tr>
</tbody>
</table>

(from Simonson et al., 1997)

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Total Ionizing Dose Comparison

- ESP solar proton model [Xapsos et al., 2000]
- AE-8/AP-8 trapped radiation environments

- Mission:
  1 TLI trajectory to Moon
  1 TEI trajectory from Moon
  Single flare during 1 year on Moon
  Neglect GCR

- ISS 1 year
- GEO 1 year

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Free Field Plasma Environments

- Moon spends
  - \( \sim 73.5\% \) solar wind
  - \( \sim 13.3\% \) magnetosheath
  - \( \sim 13.2\% \) magnetotail

- Solar wind fluence
  - \( \sim (3 \times 10^8 \text{ protons/cm}^2\text{-sec})(3 \times 10^7 \text{ sec/yr}) \)
  - \( \sim 9 \times 10^{15} \text{ protons/cm}^2\text{-yr} \)
Solar Wind as Radiation Environment

- Solar wind is generally considered a benign radiation environment
  - Solar wind velocity ~400 km/sec to 800 km/sec, mean ~450 km/sec
    - Kinetic energy of $H^+$ ~ 0.21 keV to 3.3 keV, mean 1.1 keV
    - Kinetic energy of $He^{++}$ ~ 0.84 keV to 13 keV, mean 4.2 keV
  - $H^+$ flux ~ NV ~ $(7 \frac{H^+}{cm^3})(450 \times 10^3 \frac{m}{s})$ ~ $3.2 \times 10^8 \frac{H^+}{cm^2-sec}$
  - $He^{++}/H^+ \sim 0.038$  $He^{++}$ flux ~ $0.12 \times 10^8 \frac{H^+}{cm^2-sec}$
  - Fluence
    - $H^+$ ~ $9.9 \times 10^{15} \frac{H^+}{cm^2-year}$
    - $He^{++}$ ~ $3.8 \times 10^{14} \frac{H^+}{cm^2-year}$
- Solar wind penetration depths are only fractions of a micron
  - Bulk materials impacted only on "surfaces"
  - 1000 Å (0.1 μm) coating is impacted throughout the material
Lunar Radiation Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

- April 1998
  - Earth's magnetotail
  - Solar energetic particle event

![Graph showing electron flux over time](image-url)
Lunar Wake

Lunar Prospector Electron Reflectometer

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Lunar Radiation Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

- 4-5 April 1998
  - Moon in solar wind
  - Plasma wake
  - Solar particle event and wake
Surface Charging

- Time dependent current balance on surfaces

\[ \frac{dQ}{dt} = C \frac{dV}{dt} = \sum_k I_k \quad (\sim 0 \text{ at equilibrium}) \]

\[ \sum_k I_k = \]

+ \( I_i(V) \)  
- \( I_e(V) \)  
+ \( I_{bs,e}(V) \)  
+ \( I_{se}(V) \)  
+ \( I_{si}(V) \)  
+ \( I_{ph,e}(V) \)  
+ \( I_C(V) \)  
+ \( I_B(V) \)  

incident ions  
incident electrons  
backscattered electrons  
secondary electrons due to \( I_e \)  
secondary electrons due to \( I_i \)  
photoelectrons  
conduction currents  
active current sources (beams, electric thrusters, etc.)

\[ C \frac{dV}{dt} = \sum_{k'} I_{k'} + \sigma V \]

(Garrett and Minow, 2004)
Bulk (Deep Dielectric) Charging

- Radiation charging of insulators, isolated conductors

\[ \nabla \cdot \mathbf{D} = \rho \]

\[ \mathbf{D} = \varepsilon \mathbf{E} \]

\[ \varepsilon = \kappa \varepsilon_0 \]

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{J} \]

\[ \mathbf{J} = \mathbf{J}_0 + \mathbf{J}_C \]

\[ \mathbf{J} = \sigma \mathbf{E} \]

\[ = (\sigma_{\text{dark}} + \sigma_{\text{radiation}}) \mathbf{E} \]

\[ \sigma_{\text{radiation}} = k \left( \frac{d\gamma}{dt} \right)^\alpha \quad 0.5 < \alpha < 1.0 \]

(Garrett and Minow, 2004)
Lunar Plasma Environments

- Plasma/radiation environments relevant to surface and bulk charging due to electrons, ions from thermal to \(~\text{MeV}\) energies

![Graph showing differential flux vs. energy for electrons and ions in various conditions.](image-url)
Charging in Lunar Relevant Environments

ATS-6 8 Oct 1975
ATS-6 record: $\Phi \sim -19\,\text{kV}$

Olsen [1983]

Lunar Prospector
Diff. Energy Flux ($\text{eV}/(\text{s cm}^2\text{ ster eV})$)

$\Phi \sim -51\,\text{V}$
geotail, shadow

Halekas et al., 2002

Spacecraft Potential

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[Cluster C1 LEEA PAD zone 5]
[from Szita et al., 2001]

$+8\,\text{V}$

Magnetosheath, Bow Shock, Solar Wind

[from Minow et al., 2005]
Near Earth plasma regimes are well ordered at low energies. Relatively easy to identify bow shock and magnetopause, plasma regimes by plasma characteristics.
Magnetotail Plasma at Lunar Distances

- Lunar plasma environment includes encounters with magnetotail and magnetosheath
  - Variability due to solar wind driven motion of magnetotail
- High temperature, low density plasma environments in magnetotail

Lunar orbit

4 AUGUST through 8 AUGUST 1993

IONS

<table>
<thead>
<tr>
<th>2</th>
<th>10</th>
<th>10^2</th>
<th>10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>10^2</td>
<td>10^3</td>
</tr>
</tbody>
</table>

ELECTRONS

<table>
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<tr>
<th>10^4</th>
<th>10^5</th>
<th>10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/4</td>
<td>8/5</td>
<td>8/6</td>
</tr>
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</table>

8/7

8/8

E/V, VOLTS

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E/V, VOLTS

GEOTAIL CPI - HOT PLASMA ANALYZER

16 JANUARY THROUGH 20 JANUARY 1993

IONS

ELECTRONS

1/16

1/17

1/18

1/19

1/20

ELECTRONS

COUNTS

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Surface Charging

Environment | Spacecraft Potential
-------------|----------------------
LEO          | -0.1 to 0.5 V        
GEO          | -100 to -20,000 V    
Auroral zone | -100 to -3000 V      
Magnetotail at lunar orbit
--eclipse   | -100 to -4500 V      
--sunlight   | +10’s V              
Solar wind   | +10’s V              

Orbit inclination, departure local time (longitude) important for surface charging
Internal (Bulk) Charging

- Translunar and trans-Earth injection trajectories transit the radiation belts
- TLI/TEI orbits are similar to the geostationary transfer orbit environments encountered by CRRES
  - CRRES T~10 hours
    10 hours in radiation belt
  - TLI/TEI T~8 days
    ≤4 hours in radiation belt
- CRRESELE Ap dependent (a-c), worst case (d) orbit averaged environments
- Fennell et al. 2000 (e) lunar transfer orbit charging environment

Energy (MeV)

0 deg (solid) 30 deg (dash)

Integral Flux (#/cm² - sec)

(a) Ap = 5.0 - 7.5 nT
(b) Ap = 10.0 - 15.0 nT
(c) Ap = 25.0 - 55.0 nT
(d) Maximum flux
(e) Fennell et al, 2000

2x10¹⁰ e⁻/cm² in 10-hrs
Lunar Wake

\[ \theta_{sw} \sim 45 \text{ deg} \]

a) Density

b) \( T_{//}/T_{perpendicular} \)

Earth-Moon
L1, L2 \sim 33.12 \( R_L \)

ION WAKE DENSITY

Low Density Streamers

Wake Fill-in via ES Instability

Earth-Moon
L1, L2 \sim 33.12 \( R_L \)

[Trávníček et al., 2005]

[Bale et al., 1997]

[Farrell et al., 1998]

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17 Apr 2007
Analytical Lunar Wake Model

- Analytical models useful for first order estimate of wake plasma environments
  - Analytical models to be imbedded in Luna-CPE model to scale plasma flux to spacecraft surface for surface dose evaluation

- Numerical electrostatic codes required to evaluate details including
  - Particle distribution functions
  - Energetic solar particle events
  - Backflow from distant magnetotail

[Blackwell et al., 2007]
Lunar Plasma Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

- April 1998
  - Earth's magnetotail
  - Solar energetic particle event
Lunar Plasma Environments

- Lunar Prospector Electron Reflectometer
  - Spin average electron flux
  - ~40 eV to ~20 keV

- 4-5 April 1998
  - Moon in solar wind
  - Plasma wake
Lunar Plasma Environments

- **Lunar Prospector Electron Reflectometer**
  - Spin average electron flux
  - ~40 eV to ~20 keV

- **4-5 April 1998**
  - Moon in solar wind
  - Plasma wake
  - Solar particle event and wake
Wind Magnetotail Passage

- Wake plasma environments
  - Cold ion depletions
  - keV electron access to wake produces strong charging environment
Charging in Lunar Wake

Lunar Prospector
20-115 km

Wake properties relative to ambient solar wind

[Halekas et al. 2005]

Spacecraft potentials
day +10 V to +50 V
night -100 V to -300 V
Charging in Lunar Environments

- Solar wind
  - Quiet solar wind $T_{eo} \sim 12.15 \pm 3.27$ eV [Newbury, 1996; Newbury et al., 1998]
    $N_{eo} \sim 5.87 \pm 5.25$ #/cm$^3$ [3 years Genesis L1 ion moments]
  - Wake 6x to 10x $T_e$ enhancements yield $\sim$72 to $\sim$122 eV
  - Surface charging rule of thumb
    - Darkness $\Phi_{s/c} \sim$ few kTe [Moore et al., 1998]
    - Sunlight $\Phi_{s/c} \sim +9 [\text{Ne, #/cm}^3]^{-0.44}$ [Pederson, 1995]
    - low mean high
      - $-307 \text{ V} < -194 \text{ V} < -107 \text{ V}$
      - $+3 \text{ V} < +4 \text{ V} < +11 \text{ V}$

- Recent analysis of Lunar Prospector records [Halekas et al., 2007] suggest lunar surface potentials $\sim 4.5 \text{ kV}$
Lunar Plasma Environments/Interactions

[Caption: Diagram showing the interaction of the Sun with the lunar surface, highlighting key features such as the terminator region, photon-driven positive charging, and dipolar E-fields.]

[Source: Lin et al., 2007]

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Material Electrical Properties

- Charging analyses require electrical properties of materials as a function of temperature
  - \( \sigma(T) \) conductivity
  - \( \kappa \) dielectric constant
  - Radiation induced conductivity parameters \( k_p, \Delta \)
  - Secondary electron yields
- Properties of terrestrial materials measured in laboratory
- Some information is available for lunar regolith
Electrical Properties of Lunar Regolith

- Information on secondary electron emission properties of lunar regolith is available from materials returned by Apollo
- Biased towards low lunar latitudes

\[ \delta(E) = 7.4 \delta_M \left( \frac{E}{E_M} \right) \exp\left( -2 \left( \frac{E}{E_M} \right)^{1/2} \right) \]

[Horyani et al., 1998]

[Sternglass, 1954]

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Lunar Secondary Electron Environments

- Lunar photoelectron sheath
  - Vysklov (1976) reported lunar "ionosphere" using radio occultation technique from Luna 22 with peak electron densities of 500-1000 \#/cm^3 at altitudes of 5-10 km above sunlit lunar surface
  - In-situ measurements from Apollo 12, 15, 15 Suprathermal Ion Detector Experiment (SIDE) and Apollo 14 Charged Particle Lunar Environment Experiment (CPLEE) show $10^4 \#/\text{cm}^3$ up to altitudes of 100 m (Reasoner and Burke, 1972)
  - For comparison...
    - Solar wind ~6 e-/cm^3, large values of 50 e-/cm^3 to 100 e-/cm^3 in shocks (CME's, CIR, etc)
    - Magnetosheath at lunar distances Ne ~ 1 to 100 e-/cm^3
    - Magnetotail at lunar distances Ne ~ 0.01 to 10 e-/cm^3

- Lunar Debye length ~1 meter
  - ~130 electrons/cm^3 density at surface (Feuerbacher et al., 1972)
  - Photoelectrons dominate daytime charging environments within a few meters of surface

Radio occultation (Vysklov, 1976)
Lunar environments can be very cold
- ~85K in night just before sunrise
- ~40K to 50K in permanently dark polar craters

Insulator charging in these environments will integrate charge for extended periods of time

\[ T \sim 300K \]
\[ \sigma \sim 10^{-16} \text{ S/m} \]
\[ \kappa \sim 3.706 \]
\[ \sigma_{RIC} \sim 2.76 \times 10^{-16} [d\gamma/dt]^{1.0} \text{ S/m} \]
Charging in Cold Environments

- Lunar environments can be very cold
  ~85K in night just before sunrise
  ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time

\[ T \sim 100K \]
\[ \sigma \sim 10^{-19} \text{ S/m} \]
\[ \kappa \sim 7.412 \]
\[ \sigma_{RIC} \sim 2.76 \times 10^{-16} \left[ \frac{\text{d} \gamma}{\text{d} t} \right]^{1.0} \text{ S/m} \]
Charging in Cold Environments

- Lunar environments can be very cold
  ~85K in night just before sunrise
  ~40K to 50K in permanently dark polar craters
- Insulator charging in these environments will integrate charge for extended periods of time

\[ T < 50K \]
\[ \sigma \sim 10^{-25} \text{ S/m} \]
\[ \kappa \sim 7.412 \]
\[ \sigma_{RIC} \sim 2.76 \times 10^{-16} [d\gamma/dt]^{1.0} \text{ S/m} \]

No further change in fields once insulator becomes a "charge integrator"
Constellation Design Environments

- Charging design environments:
  - Geostationary orbit extreme surface charging environments [Purvis et al., NASA TP-2361, 1984]
  - Trans-lunar injection orbit [Fennell et al., 2000]

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- Lunar specific environments are pending, but these cases will certainly drive design
Summary

- Plasma environments encountered during lunar missions similar to environments encountered in LEO, GEO missions

- Charging environments will need to be evaluated:
  - Radiation belt transit
  - Lunar wake environments

- Charging design environments in place for LEO, magnetosphere transit

- Further exploration of lunar charging environments is warranted