Lunar Exploration Initiative

Briefing Topic:

Ionizing Radiation on the Moon

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Ionizing Radiation on the Moon

- Low-E solar wind particles (dominant source)
- High-E galactic cosmic rays (smaller source)
- Solar flare particles (rare, but briefly intense)
  - Also called solar energetic particles or solar cosmic rays
- Interaction with lunar soils and regolith:
  - Solar wind implantation
  - Heavy-nuclei tracks
  - Spallation reactions
  - Generation of secondary neutrons and gamma rays
- Eight orders of magnitude variation in energy
Solar Wind

- Streams outward from Sun
- Creates interplanetary magnetic field lines
- Electrically neutral
- Mean energy at 1 AU is ~1 keV/u
- Velocity is generally 300 to 700 km/s
- Particle concentrations are generally 1 to 20 per cm³
- Proton flux is generally 1 – 8 x 10⁸ protons/cm²s

Feldman et al. (1977) and the Lunar Sourcebook.
Solar Cosmic Rays

- Pulse of particles generated by solar flares
- Reach the Moon in less than 1 day
- Electrons with energies of ~0.5 to 1 MeV arrive at Moon, usually traveling along interplanetary field lines, within tens of minutes to tens of hours
- Protons with energies of 20 to 80 MeV arrive within a few to ~10 hours, although some high-E protons can arrive in as little as 20 minutes
- Some electrons and nuclei can be accelerated to relativistic velocities
- Very few SCR are present at Moon during lulls in solar activity
- SCR peak during the maximum period of activity during each solar cycle.
- Most nuclei are protons and alpha particles; most particles have energies less than ~30 MeV
Solar Cosmic Rays

• Most events have “soft” spectra, with very few high-E particles.

• Large, high-E events are possible, however, producing particles with GeV and higher energies

• These infrequent events pose a serious hazard to human and robotic exploration

• Most serious storms in recent history:
  – February 23, 1956
  – August 4, 1972

• GeV storms produce:
  – Nausea and vomiting within 1 hr
  – Death with a few days exposure

• Astronauts will likely be required to maintain ready access to shelter in case these types of storms occur
Galactic Cosmic Rays

- Isotropic field of GCR exist at Earth, although it can be modified by solar activity

- GCR are the most penetrating of the major types of ionizing radiation

- Enhanced solar winds and interplanetary magnetic field during solar maximum causes GCR to lose energy as they penetrate the solar system

- Flux of particles $\geq 1$ GeV/u is 2 times higher at solar minimum than at solar maximum

- Solar activity may also vary on an $\sim 200$ year cycle, producing longer periods of low solar activity (e.g., Maunder Minimum of 1645 to 1715) may permit GCR fluxes $\sim 3$ times greater than that at solar minimum

- Solar activity effect is greatest for 10 MeV to 1 GeV GCR; GCR with energies $>10$ GeV are hardly effected
Galactic Cosmic Rays

- The flux of GCR protons is almost always less than that from interstellar space, although the fluxes are similar for energies >10 GeV

- The flux of GCR protons is less than that of SCR protons in the 10 MeV to ~1 GeV, but is much greater than that of SCR protons above ~700 MeV

- GCR also create a cascade of secondary particles (mostly neutrons), which are created when GCR protons and alpha particles penetrate meters into the lunar surface
Galactic Cosmic Rays

Epithermal Neutrons: Dominant effect is energy loss via scattering
In presence of H, elastic scattering is very effective
Consequently, the flux of cosmic-ray produced flux of epithermal neutrons can be substantially depressed (by up to two orders of magnitude)

Fast Neutrons (E ~ 0.5 to 10 MeV)
Epithermal Neutrons (E = 0.4 eV to 0.5 MeV)
Thermal Neutrons (E = 0.01 to 0.4 eV)

Produce High E (~10 MeV) Neutrons
Elastic Scattering
Inelastic Scattering
Absorbed by Neutron Capture Rxns

Lunar Regolith
Evaluating Exploration Hazards

- Low-E solar wind ions (which dominate the ionizing flux) should not pose a serious threat*

- Energetic particle fluxes produced by solar flares are much more hazardous

- Measurements of the ~1 MeV to >1 GeV particle flux in a polar environment during solar max will greatly aid any assessment of that threat

- These measurements should be supplemented with models of short-term GeV storms (which may not occur during a specific lunar mission) and longer-term variations of solar activity that may occur over time periods of hundreds of years (for future human exploration endeavors)

* The solar wind is the source of several volatile elements (like H) in the lunar regolith, so one may want to measure this radiation for purposes other than hazard assessment
# Summary of Major Forms of Ionizing Radiation on the Moon

<table>
<thead>
<tr>
<th>Type</th>
<th>Solar Wind</th>
<th>Solar Cosmic Rays</th>
<th>Galactic Cosmic Rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclei energies</td>
<td>~0.3 to 3 keV/u*</td>
<td>~1 to &gt;100 MeV/u</td>
<td>~0.1 to &gt;10 GeV/u</td>
</tr>
<tr>
<td>Electron energies</td>
<td>~1 to 100 eV</td>
<td>&lt;0.1 to 1 MeV</td>
<td>~0.1 to &gt;10 GeV</td>
</tr>
<tr>
<td>Fluxes (protons/cm²/s)</td>
<td>~3 x 10⁸</td>
<td>~0 to 10⁶ **</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Particle ratios***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron/proton</td>
<td>~1</td>
<td>~1</td>
<td>~0.02</td>
</tr>
<tr>
<td>proton/alpha</td>
<td>~22</td>
<td>~60</td>
<td>~7</td>
</tr>
<tr>
<td>L (3 ≤ Z ≤ 5)/alpha</td>
<td>n.d.</td>
<td>&lt;0.0001</td>
<td>~0.015</td>
</tr>
<tr>
<td>M (6 ≤ Z ≤ 9)/alpha</td>
<td>~0.03</td>
<td>~0.03</td>
<td>~0.06</td>
</tr>
<tr>
<td>LH (10 ≤ Z ≤ 14)/alpha</td>
<td>~0.005</td>
<td>~0.009</td>
<td>~0.014</td>
</tr>
<tr>
<td>MH (15 ≤ Z ≤ 19)/alpha</td>
<td>~0.0005</td>
<td>~0.0006</td>
<td>~0.002</td>
</tr>
<tr>
<td>VH (20 ≤ Z ≤ 29)/alpha</td>
<td>~0.0012</td>
<td>~0.0014</td>
<td>~0.004</td>
</tr>
<tr>
<td>VVH (30 ≤ Z)/alpha</td>
<td>n.d.</td>
<td>n.d.</td>
<td>~3 x 10⁶</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lunar penetration depths</th>
<th>protons &amp; alphas</th>
<th>heavier nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;micrometers</td>
<td>&lt;micrometers</td>
</tr>
<tr>
<td></td>
<td>centimeters</td>
<td>millimeters</td>
</tr>
<tr>
<td></td>
<td>meters</td>
<td>centimeters</td>
</tr>
</tbody>
</table>

(*) eV/u = electron volts per nucleon; (**) Short term SCR fluxes above 10 MeV; maximum is for the peak of the 4 August 1972 event. Flux above 10 MeV as averaged over ~1 m.y. is ~100 protons/cm²/s; (***): Ratios often vary considerably with time for solar wind and SCR particles and with E for SCR and GCR. The symbols L (light), M (medium), H (heavy), VH (very heavy), etc., are historical terms for nuclei charge (Z) groups greater than 2 in the cosmic rays. Source: *Lunar Sourcebook* (p. 48)