Lunar Exploration Initiative

Briefing Topic:

Ionizing Radiation on the Moon

David A. Kring

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 cm^3**
- **Proton flux is generally 1 – 8 x 10^8 protons/cm^2s**

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**

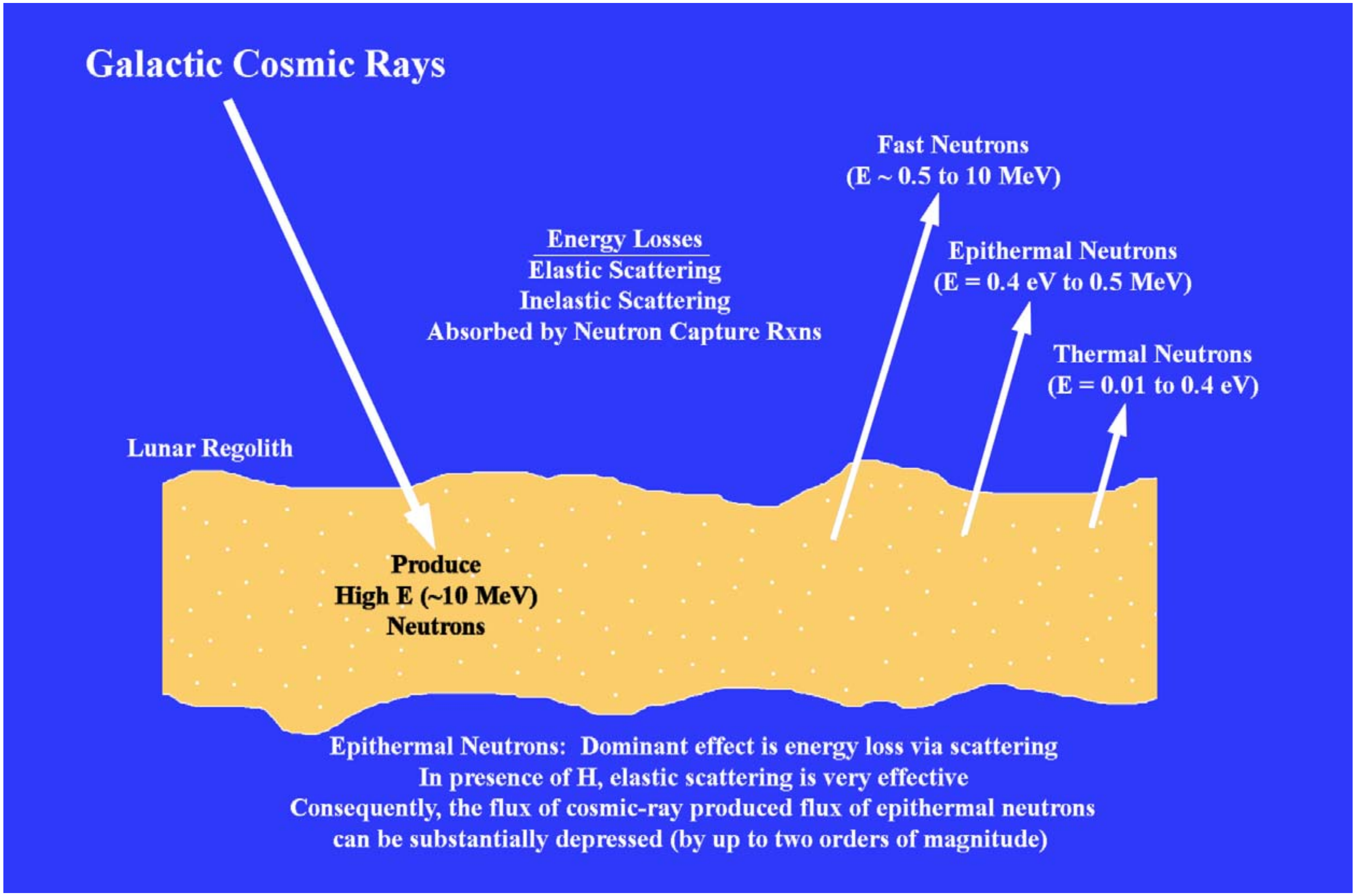
Galactic Cosmic Rays

- 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 loose energy as they penetrate the solar system
- Flux of particles ≥1 GeV/u is 2 times higher at solar minimum than at solar maximum
- Solar activity may also vary on an ~200 year cycle, producing longer periods of low solar activity (e.g., Maunder Minimum of 1645 to 1715) may permit GCR fluxes ~3 times greater than that at solar miniumum
- 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



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)

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* 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

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei energies	~0.3 to 3 keV/u*	~1 to >100 MeV/u	~0.1 to >10 GeV/u
Electron energies	~1 to 100 eV	<0.1 to 1 MeV	~0.1 to >10 GeV
Fluxes (protons/cm^{2}s)	~3 x 10^8	~0 to 10^6 **	2 to 4
Particle ratios* **			
electron/proton	~1	~1	~0.02
proton/alpha	~22	~60	~7
L ($3 \leq Z \leq 5$)/alpha	n.d.	<0.0001	~0.015
M ($6 \leq Z \leq 9$)/alpha	~0.03	~0.03	~0.06
LH ($10 \leq Z \leq 14$)/alpha	~0.005	~0.009	~0.014
MH ($15 \leq Z \leq 19$)/alpha	~0.0005	~0.0006	~0.002
VH ($20 \leq Z \leq 29$)/alpha	~0.0012	~0.0014	~0.004
VVH ($30 \leq Z$)/alpha	n.d.	n.d.	~3 x 10^6
Lunar penetration depths			
protons & alphas	<micrometers	centimeters	meters
heavier nuclei	<micrometers	millimeters	centimeters

(*) 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/cm^{2}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 great than 2 in the cosmic rays. Source: *Lunar Sourcebook* (p. 48)