[albedo] the proportion of the incident light that is reflected by a surface

The Gamma-ray Albedo of the Moon

Igor V. Moskalenko & Troy A. Porter
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Masaki Mori

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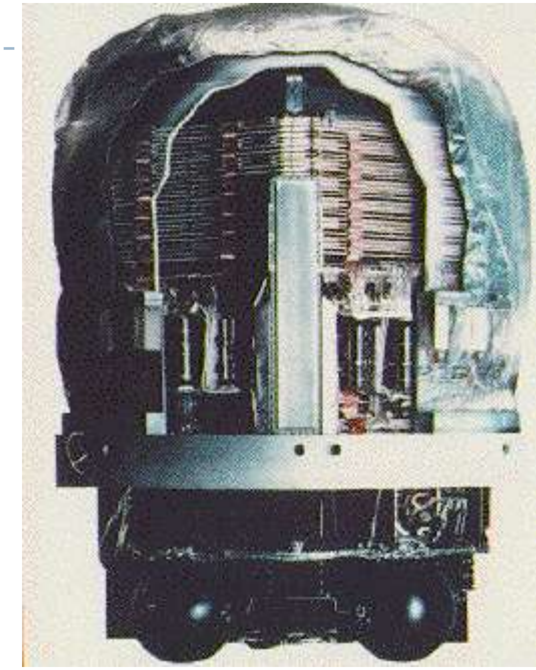
Gamma-ray albedo of the moon

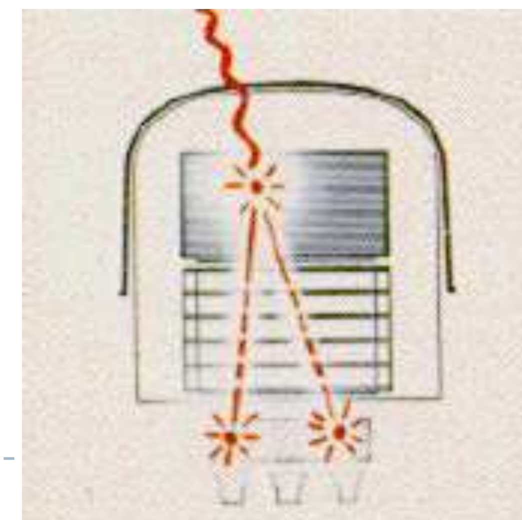
- Due to cosmic-ray interaction with moon rock (Morris 1984; Thompson et al. 1997)
  Mainly, $p + A \rightarrow \pi^0 (\rightarrow 2\gamma) + X$
- Solid surface – difficult for gamma-rays to get out from deep rock
  - Soft spectrum: small fraction from surface layer
  - High-energy gamma-rays only from tangential trajectory
- Well understood - "standard candle" for gamma-ray telescopes
- Simultaneous observations of GLAST with PAMELA can be used to test model predictions
- Monitoring CR spectrum modulation using the albedo gamma-ray flux

http://cossc.gsfc.nasa.gov/docs/cgro/egret/

EGRET

1. **Type:** spark chambers, NaI(Tl) crystals, and plastic scintillators.
2. **Energy Range:** 20 MeV to about 30 GeV.
3. **Energy Resolution:** approximately 20% over the central part of the energy range.
4. **Total Detector Area:** approximately 6400 cm^2
5. **Effective Area:** approximately 1500 cm^2 between 200 MeV and 1000 MeV, falling at higher and lower energies.
6. **Point Source Sensitivity:** varies with the spectrum and location of the source and the observing time. Under optimum conditions, well off the galactic plane, it should be approximately 6×10^{-8} $cm^{-2}s^{-1}$ for E > 100 MeV for a full two week exposure.
7. **Source Position Location:** Varies with the nature of the source intensity, location, and energy spectrum from 5 - 30 arcmin.
8. **Field of View:** approximately a Gaussian shape with a half width at half maximum of about 20. Note that the full field of view will not generally be used.
9. **Timing Accuracy:** 0.1 ms absolute
10. **Weight:** about 1830 kg
11. **Size:** 2.25 m x 1.65 m diameter
12. **Power:** 190 W (including heater power)





Thompson et al., JGR A102, 14735 (1997)

EGRET observation of the moon

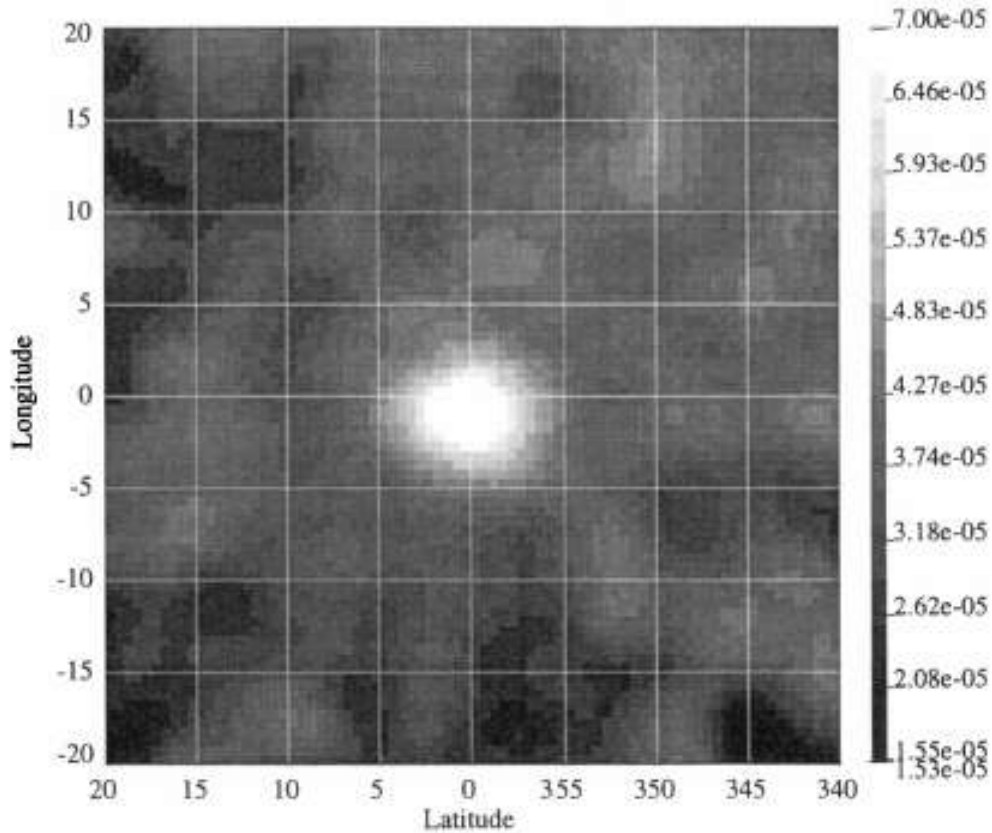


Figure 1. Combined intensity map of the energetic gamma ray experiment telescope (EGRET) observations of the Moon. The coordinate system is one which tracks the Moon, whose nominal position is (0,0). The offset of the excess from (0,0) is within the positional uncertainties of the EGRET measurement. The units are photons ($E > 100$ MeV) $cm^{-2}\ s^{-1}\ sr^{-1}$, and a 1.5° smoothing has been applied to the data. The EGRET resolution at these energies is not sufficient to resolve the lunar disk.

- Flux from the moon: $(4.7\pm0.7)\times10^{-7}cm^{-2}s^{-1}$ (>100MeV)
  Cf. Upper limit for the Sun: $<2.0\times10^{-7}cm^{-2}s^{-1}$ (>100MeV, 95% C.L.)

Thompson et al., JGR A102, 14735 (1997)

EGRET spectrum

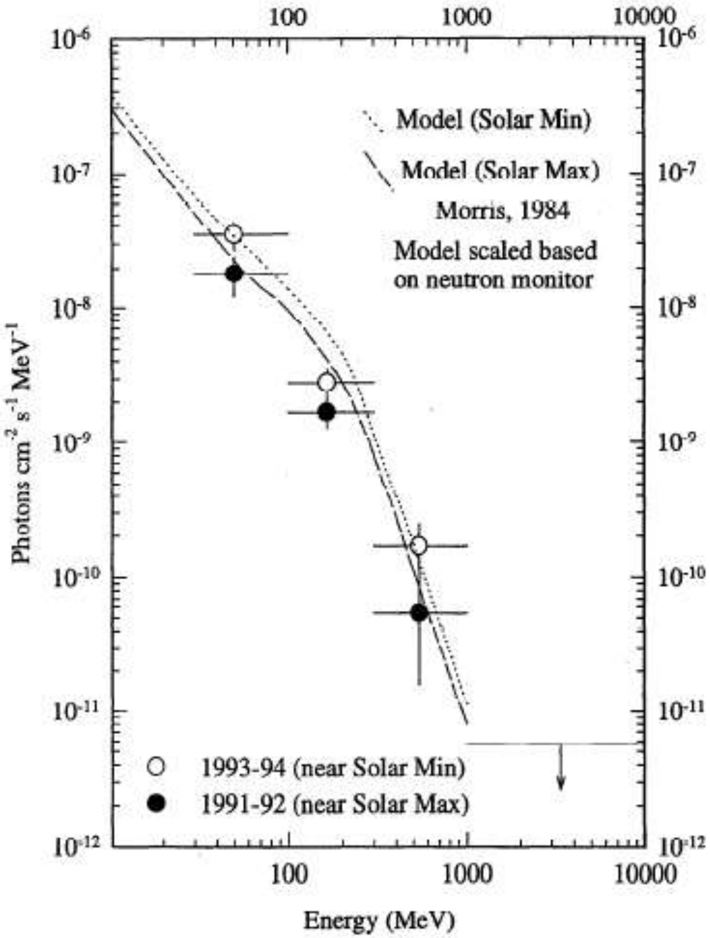


Figure 3. Energy spectrum of the lunar gamma radiation as measured by EGRET. The original calculations of *Morris* [1984] have been scaled down by 24% on the basis of the lower cosmic ray flux seen in the solar cycle of the 1990s compared to the 1970 solar cycle.

~24% below the predictions by Morris

Prettyman et al., JGR 111, E12007 (2006)

Lunar Prospector/GRS

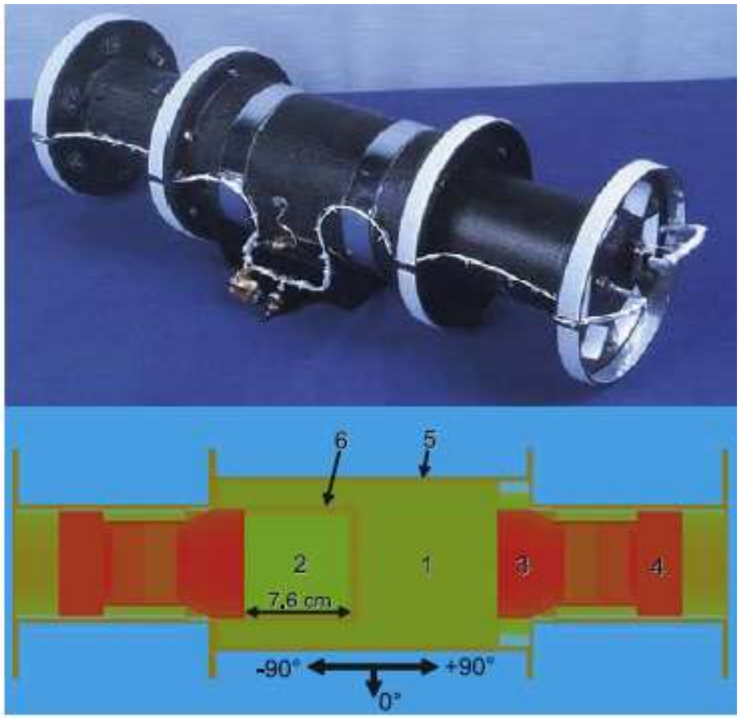


Figure 11. A photograph of the GRS is compared to the geometric model used to simulate the instrument response. The nadir direction for three latitudes (for the high-altitude spin-axis orientation) is indicated by arrows. The arrows also indicate the direction to the source in the experiments described in Appendix C. Selected zones of the geometric model are labeled as follows: (1) the anti-coincidence shield; (2) the BGO crystal; (3) a photomuliplier tube and (4) bleeder board assembly; (5) the instrument's housing; and (6) packaging material around the BGO crystal.

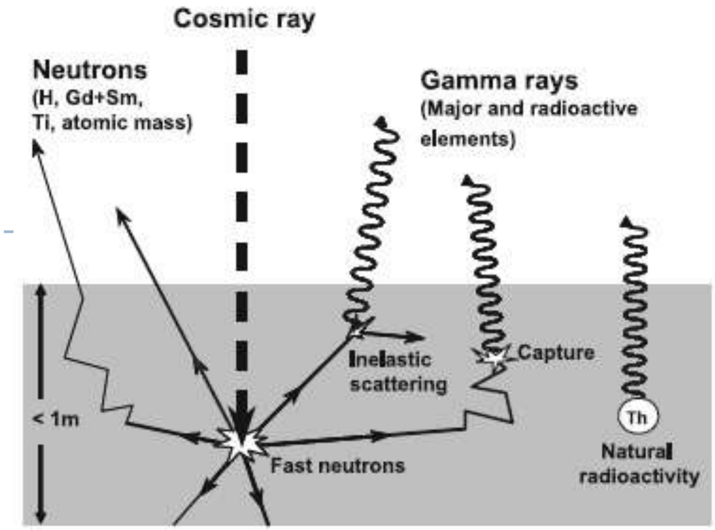


Figure 1. Schematic diagram of a galactic cosmic ray interaction with the lunar surface.

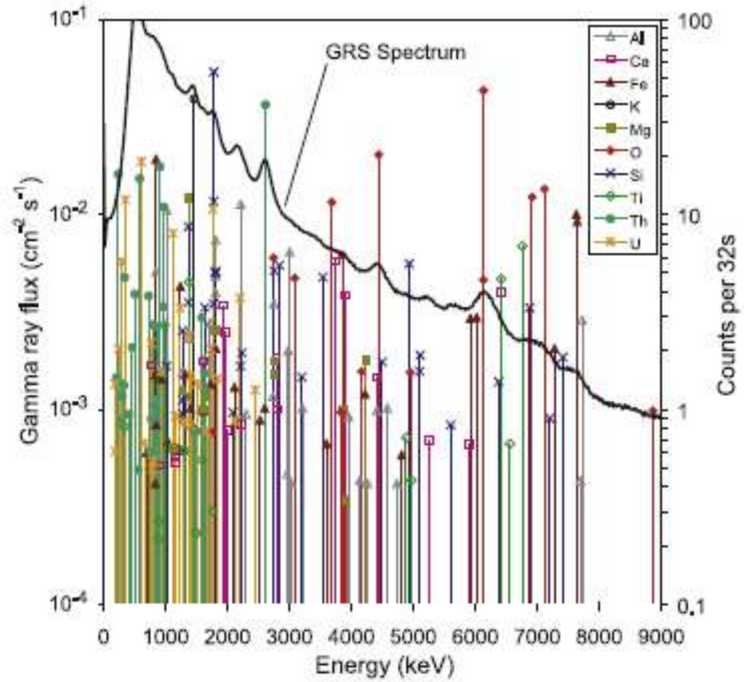


Figure 2. Discrete gamma ray lines are compared to a spectrum acquired by the GRS.

Simulation geometry

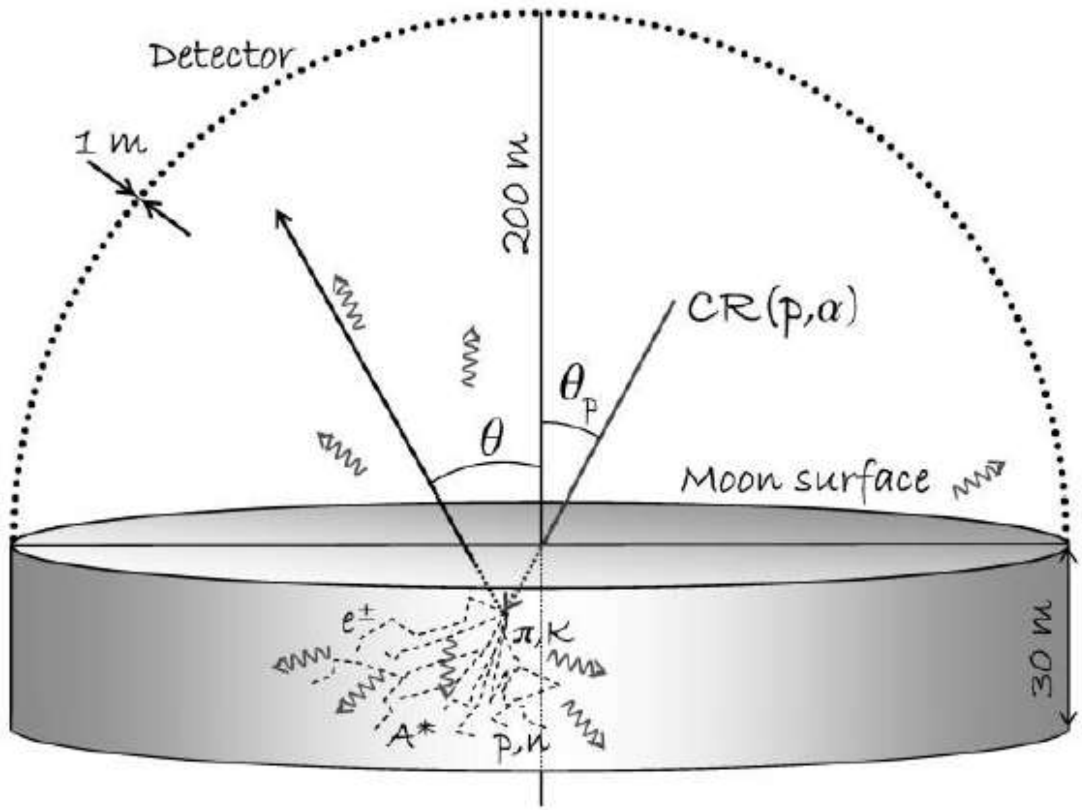


FIG. 1.— Beam/target/detector setup for simulating CR interactions in moon rock. The primary beam enters the moon rock target with incident polar angle θ_p. Secondary γ-rays are emitted with polar angle θ. The detection volume surrounds the target.

GEANT4 Monte Carlo (version 8.2.0)

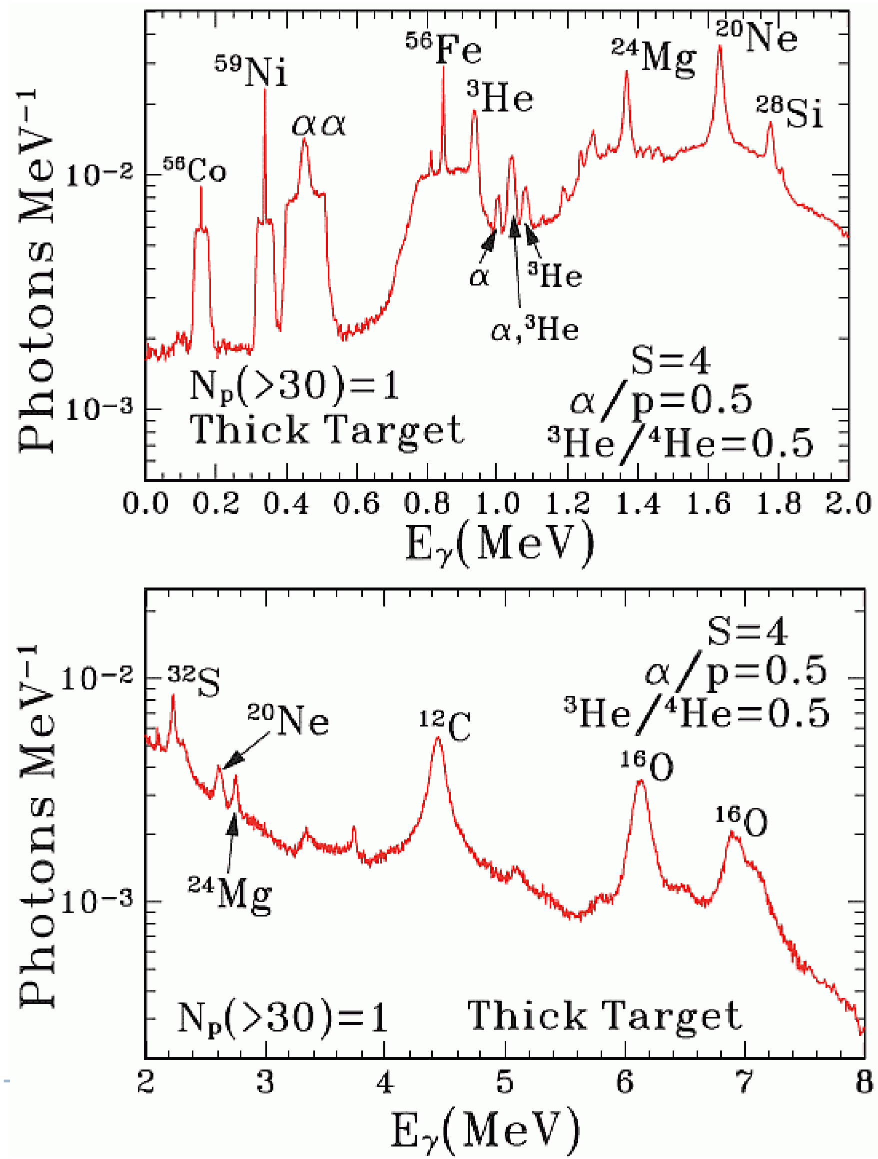
Moon rock:
- 45% SiO_2
- 11% CaO
- 10% Al_2O_3
- 9% MgO
- 3% TIO_2

Gamma-ray emission processes

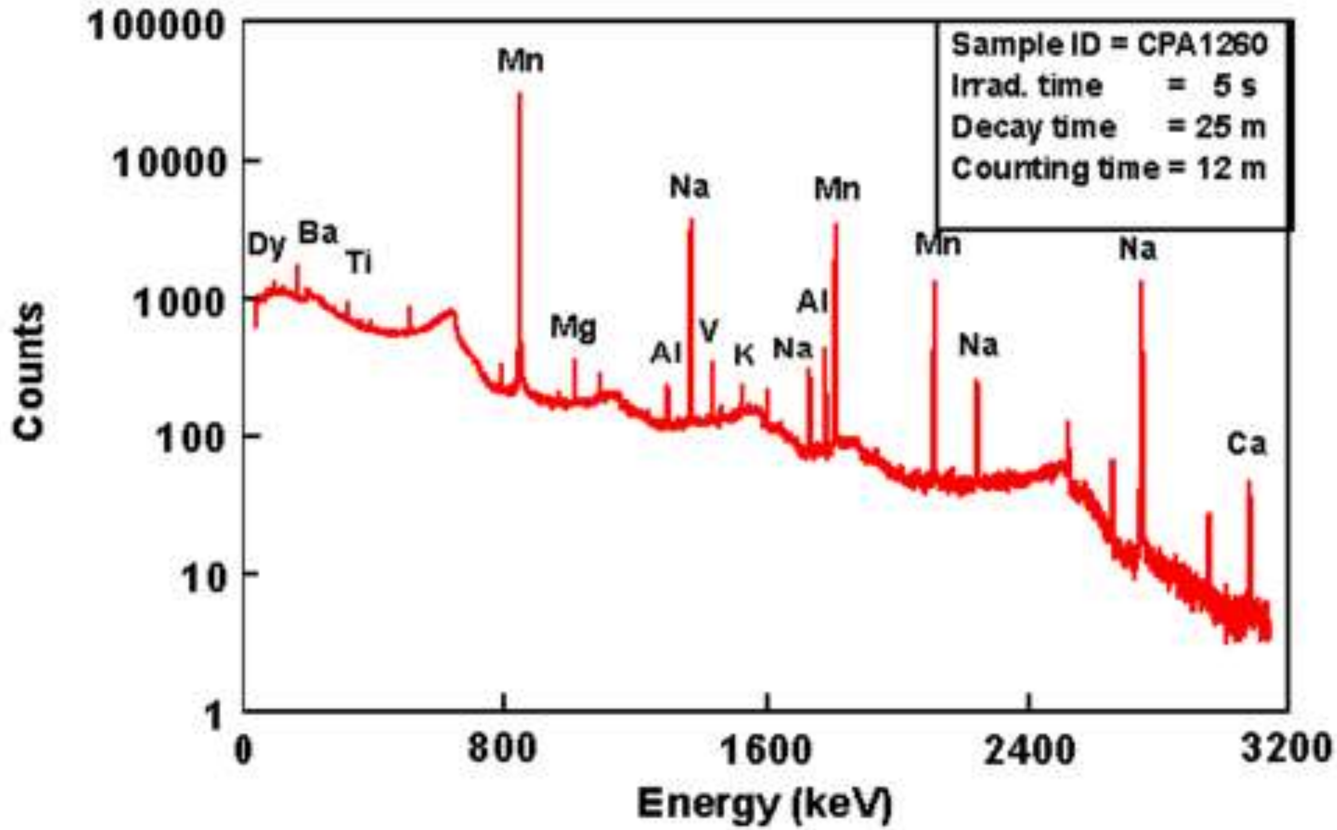
- Electron primary – Electromagnetic
  - Synchrotron (magnetic field)
    - $e + B \rightarrow e + \gamma$
  - Bremsstrahlung (Coulomb field)
    - $e + Z \rightarrow e + \gamma$
  - Inverse Compton (low energy photon)
    - $e + \gamma \rightarrow e + \gamma$
- Proton primary - Hadronic
  - $p + A$ (or $p + \gamma$) $\rightarrow (\pi^0 \rightarrow \gamma\, \gamma) + X$
- Photo-disintegration/de-excitation (A^*)
  - Photonuclear process $A + \gamma \rightarrow A'^* + X$
  - De-excitation $A'^* \rightarrow A' + \gamma$ (ex. ^{16}O: 6.13, 6.92 & 7.12 MeV)
- Neutron capture
  - $n + A \rightarrow A' + \gamma$ (ex. ^{16}O: 0.871, 1.088, 2.184 & 3.271 MeV)

Ramaty, Kozlovsky & Lingenfelter 1979

De-excitation gamma-ray lines: an example



Neutron capture gamma-rays: an example



Gamma Spectra from a Sample of Pottery Irradiated for 5 Seconds, Decayed for 25 Minutes, and Counted for 12 Minutes with an HPGe Detector.

Gamma-ray spectrum from moon surface

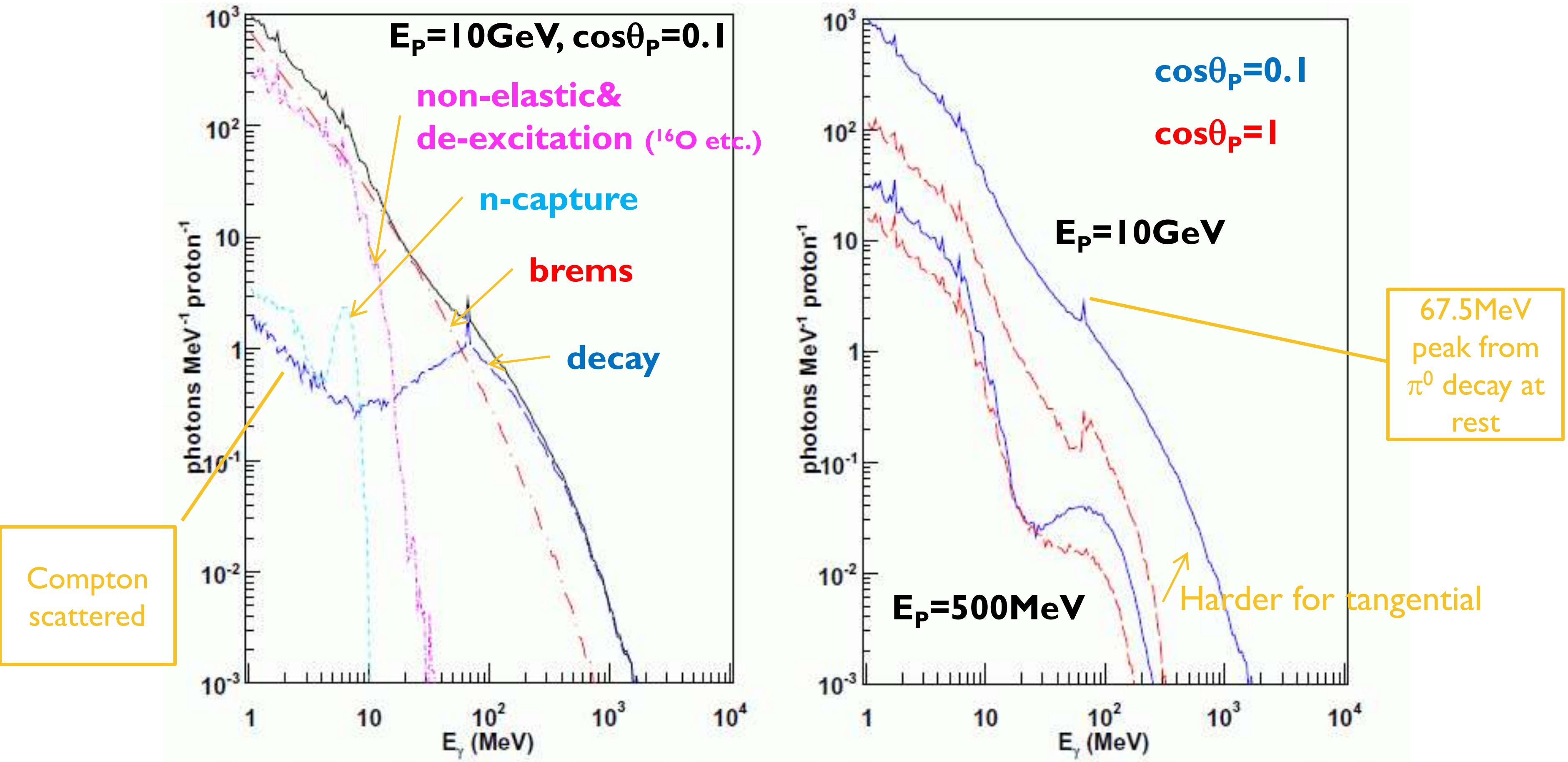


FIG. 2.— γ-ray yield per proton interaction integrated over all emission angles from the Moon surface. Left panel: yield calculated for $E_p = 10000$ MeV and $\cos\theta_p = 0.1$ with components shown. Line styles: blue-dashed, decay; red-long-dash-dot, bremsstrahlung; magenta-short-dash-dot, non-elastic scattering and de-excitation; cyan-dot, low energy neutron capture; black-solid, total. For each component, the initial process responsible for the production of the γ-ray secondary is given by the line style but the yield distribution includes also processes such as Compton scattering. Right panel: yield calculated for two different energies and incident angles. Line styles: blue-solid, $\cos\theta_p = 0.1$; red-dashed, $\cos\theta_p = 1$. Line-sets: lower, $E_p = 500$ MeV; upper, $E_p = 10000$ MeV.

Calculations

- CR flux (at modulation potential Φ)

$$\frac{dJ_p(E_k)}{dE_k} = \frac{dJ_p^{\infty}(E_k + \Phi Z/A)}{dE_k} \frac{E^2 - M^2}{(E + \Phi Z/A)^2 - M^2}$$

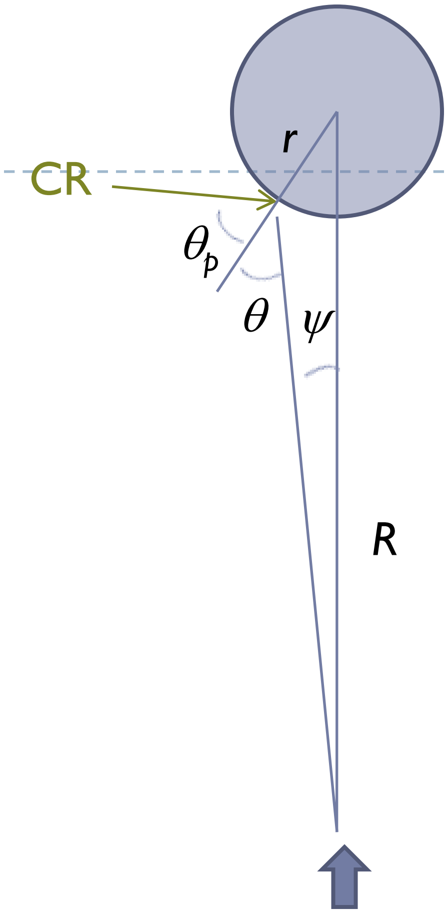
- Gamma-ray albedo flux at the earth

$$\frac{dF_\gamma}{dE_\gamma \, d\cos\psi} = \frac{1}{\cos\theta} \int dE_k \frac{dJ_p}{dE_k} \frac{d\tilde{Y}_\gamma(E_k, \cos\psi)}{dE_\gamma \, d\cos\theta}$$

ψ: angular distance from the moon center

$$\cos\theta = \sqrt{1 - \frac{R^2}{r^2}\sin^2\psi}$$

$$\frac{d\tilde{Y}_\gamma(E_k)}{dE_\gamma \, d\cos\theta} = 2\pi \int_0^1 d(\cos\theta_p) \, \cos\theta_p \frac{dY_\gamma(E_k, \cos\theta_p)}{dE_\gamma \, d\cos\theta}$$



R=1738.2km (moon radius), *r*=384,401km (distance to moon)

- Lower (Φ=500MV) and higher (Φ=1500MV) solar activity

Cosmic-ray proton spectrum

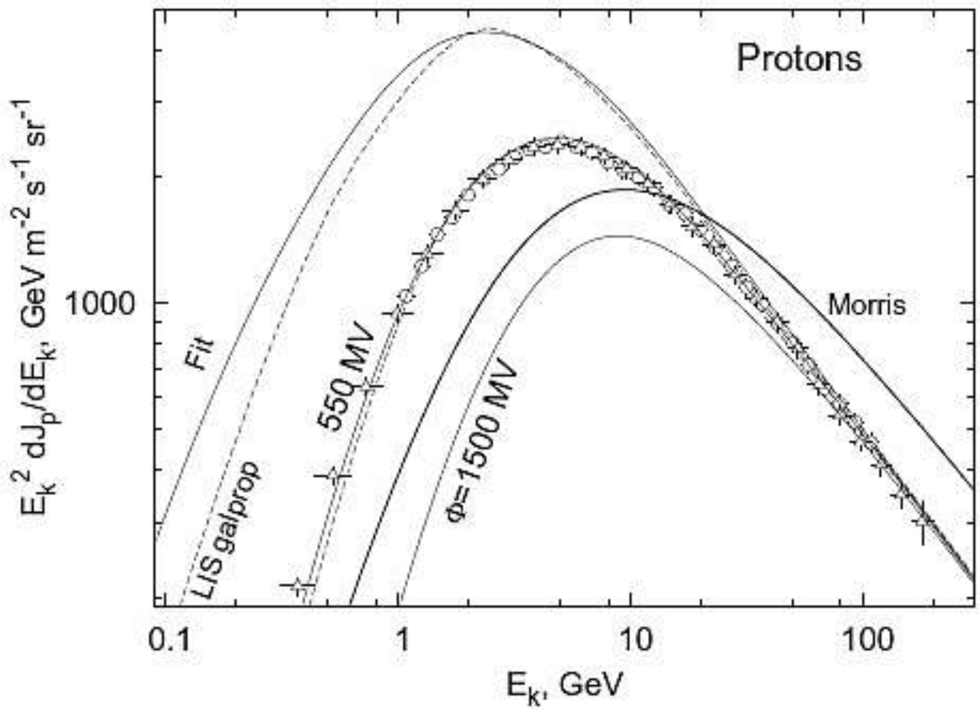


FIG. 3.— The CR proton spectrum. The dashed lines are the LIS spectrum (upper) and modulated one (lower, $\Phi = 550$ MV) as calculated by GALPROP in the plain diffusion model 44_999726 (Ptuskin et al. 2006). The thin solid lines are the fit to the LIS spectrum (upper) and modulated spectra (middle, $\Phi = 550$ MV; lower $\Phi = 1500$ MV). The thick solid line is the CR proton spectrum used by Morris (1984). Data: circles — BESS (Sanuki et al. 2000), triangles — AMS (Alcaraz et al. 2000a).

Gamma-ray albedo spectrum

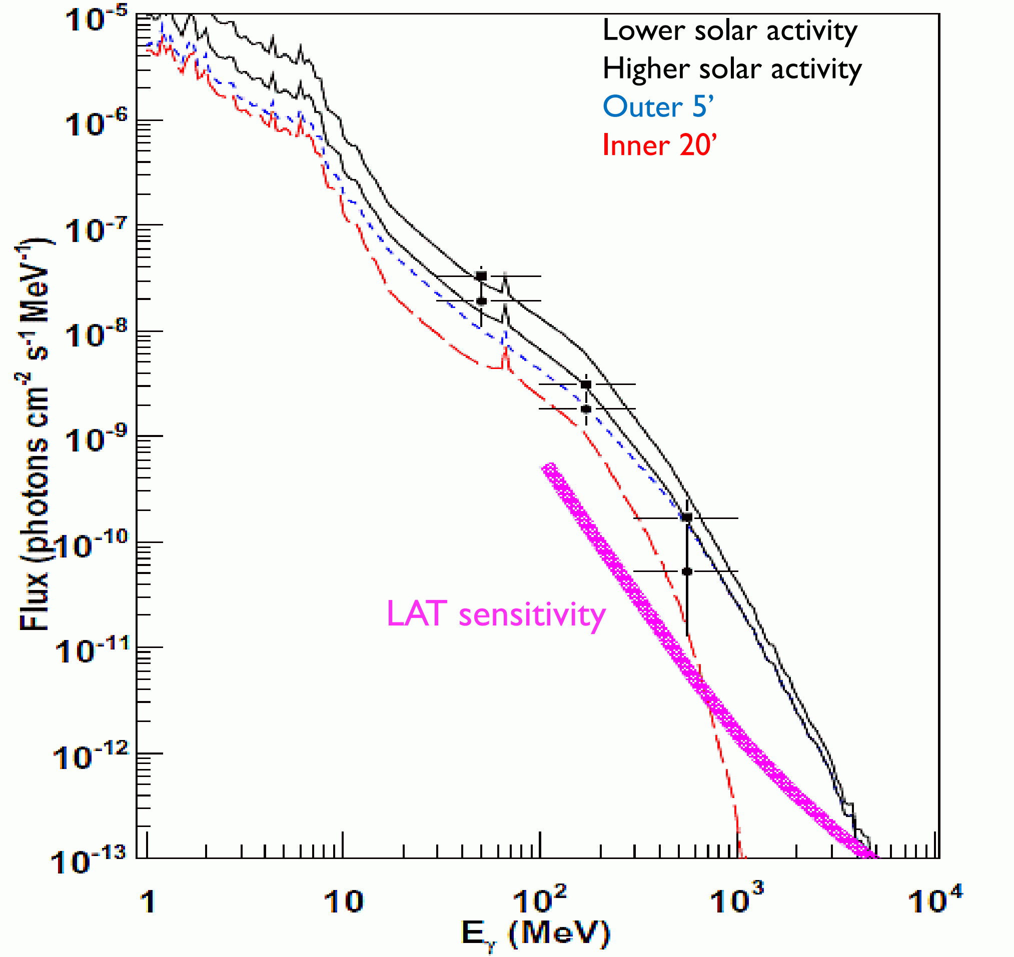


FIG. 4.— Calculated γ-ray albedo spectrum of the Moon. Line-styles: black-solid, total; blue-dotted, limb – outer 5′; red-dashed, center – inner 20′. Upper solid line: Φ = 500 MV; lower solid line: Φ = 1500 MV. Limb and center components are only shown for Φ = 1500 MV. Data points from the EGRET (Thompson et al. 1997) with upper and lower symbols corresponding to periods of lower and higher solar activity, respectively. The differential 1 year sensitivity of the LAT is shown as the shaded region.

Discussion

- GLAST/LAT: moon is in FOV for about 20% of time
  - 5000 (>100MeV), 600 (>1GeV), ~5 (>4 GeV)photons per year
  - Moon is a moving target passing through high Galactic latitudes and the Galactic center region.
  - Useful "standard candle" for LAT where PSF is comparable to the moon size (30').
  - At lower energies, gamma-ray flux depends on solar modulation, and can be used to infer CR spectrum.
  - Simultaneous observation of H and He by PAMELA provide input for albedo calculation.
  - 67.5MeV line is unique and could be used for in-orbit calibration.
  - Above a few GeV, the moon is a black spot on the gamma-ray sky which screens out a piece of the sky.