

PHOTON LUMINESCENCE OF THE MOON. T. L. Wilson¹ and K. T. Lee², ¹T. L. Wilson, NASA, Johnson Space Center, Houston, Texas 77058 USA, ²Lockheed Martin Mission Services, 1300 Hercules Suite 100, Houston, TX 77058.

Introduction: Luminescence is typically described as light emitted by objects at low temperatures, induced by chemical reactions, electrical energy, atomic interactions, or acoustical and mechanical stress. An example is photoluminescence created when photons (electromagnetic radiation) strike a substance and are absorbed, resulting in the emission of a resonant fluorescent or phosphorescent albedo. In planetary science, there exists X-ray fluorescence induced by sunlight absorbed by a regolith – a property used to measure some of the chemical composition of the Moon’s surface during the Apollo program.

However, there exists an equally important phenomenon in planetary science which will be designated here as photon luminescence. It is not conventional photoluminescence because the incoming radiation that strikes the planetary surface is not photons but rather cosmic rays (CRs). Nevertheless, the result is the same: the generation of a photon albedo. In particular, Galactic CRs (GCRs) and solar energetic particles (SEPs) both induce a photon albedo that radiates from the surface of the Moon. Other particle albedos are generated as well, most of which are hazardous (e.g. neutrons).

The photon luminescence or albedo of the lunar surface induced by GCRs and SEPs will be derived here, demonstrating that the Moon literally glows in the dark (when there is no sunlight or Earthshine). This extends earlier work on the same subject [1-4]. A side-by-side comparison of these two albedos and related mitigation measures will also be discussed.

Method – the Monte Carlo: Monte Carlos have the distinct advantage that certain physics can be turned on and off. In this respect, they are a “mathematical experiment” which can isolate specific physical phenomena that actual experiment cannot. This feature has been exploited here.

The radiation transport code chosen for the study is FLUKA, which has already been described [1-5]. It has been benchmarked against experiment at the world’s largest accelerators and is currently used to support the Large Hadron Collider (LHC) at CERN.

Lunar Surface Model: The chemical composition of soils found at various landing sites during the Apollo and Luna programs [7] has been taken to be the model of the lunar surface, averaging over all such sites to define a generic regolith for the present analysis. This is the same model as used in other studies [1-4]. The lunar regolith is assumed to have a mean density of 2.85 g cm^{-3} and a negligible magnetic field [1-3].

GCR-Induced Photon Albedo of the Moon: For the case of the GCR-induced photon luminescence, the differential GCR flux was taken from Simpson [7], obeying a power-law spectrum $dN \sim E^{-\gamma} dE$ with $\gamma = 2.75$. This was modulated for solar activity ($<10 \text{ GeV/nucleon}$) using the model of O’Neill [8]. The modulation is accomplished by adopting appropriate modulation potentials Φ (MV) in the solar magnetic field for the given epoch.

The result for GCRs is given in Figure 1 [1], necessary for generation of and comparison with the SEP-induced case that follows in Figure 2. The luminescent albedo produced by the lunar regolith model is given as a fluence (the time-integral of flux) with the abscissa in GeV’s as well as wavelength in meters [$\lambda = 1.23984 \times 10^{-6} \text{ m/E(eV)}$]. First protons (H), then α -particles (He), and finally everything else ($Z > 2$) have been analyzed. The term “pr” on the ordinate axis represents primary GCR component (ionized H, He, etc.). That is to say, Figure 1 represents the fluence per primary particle.

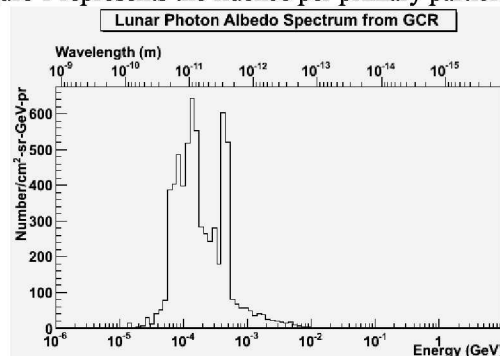


Figure 1: Photon luminescence of the Moon [1].

SPE+GCR-Induced Photon Albedo: The principal purpose of the study presented here is to extend the results in Figure 1 to account for all particle-induced lunar luminescence, save for solar photon-induced fluorescence. This provides a source-by-source comparison of respective albedos. The “pr” units must be eliminated and rescaled to give the total number of photons in one day’s worth of GCRs. Then the SEP total must be determined for the respective solar-particle-event (SPE) for side-by-side comparison.

The Badhwar-O’Neill GCR proton differential spectrum [8] was integrated over energy from 0.01 to 50000 MeV, giving the proton flux in units of days ($\text{number/cm}^2\text{-day}$). Since the protons represent only 86.5% of the total GCR flux, this result was scaled up 13.5% to give the total GCR flux. Dividing by a factor of two (the lunar surface occludes one-half of the celes-

tial sphere, 2π instead of 4π radians), the GCR flux became 282,189 (number/cm²-day). That is the conversion factor for the ordinate flux appearing in Figure 1.

The King [9] solar proton model was used to generate the SPE-induced albedo for the great proton event of August 1972. The integral proton fluxes for this event are shown in Figure 2 (a, upper). It was assumed that most of the energetic SPE flux came in the first 24 hours (1 day). The King model fit to these events was integrated over that period of time, giving a total of 2.45×10^{10} particles striking a 1 cm² area. Because FLUKA produces flux in units of number/cm²-sr-GeV-pr, the SPE output was rescaled by that total number of primaries in a day (2.45×10^{10}).

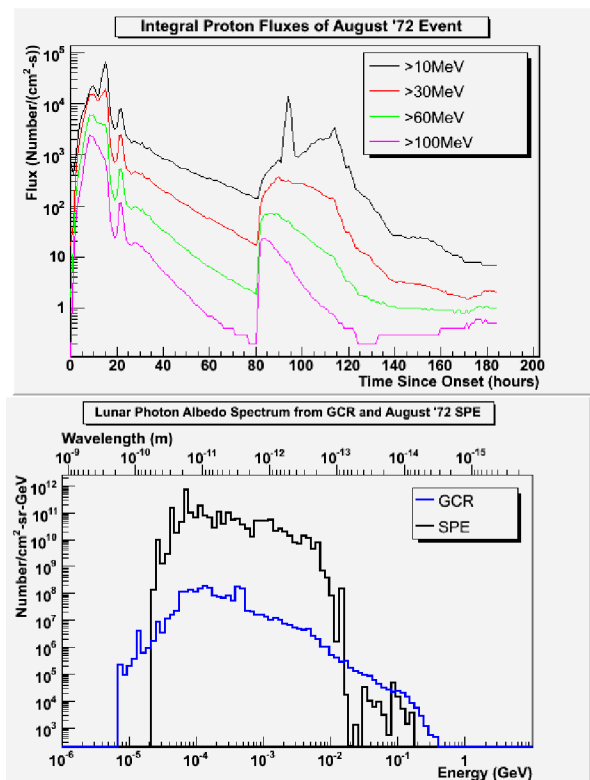


Figure 2. (a) 1972 Source for SPEs; (b) GCR Moon glow measurable in total lunar darkness.

The side-by-side results are shown in Figure 2 (b, lower). The onset of the GCR-induced photon luminescence is again in the X-ray region near 7 keV, peaking at 60 keV through 500 keV, and vanishing at 400 MeV. The onset of the SPE-induced photon luminescence is at 20 keV, peaking at 60 keV, and disappearing at 180 MeV. It still ranges from X-rays to γ -rays in the electromagnetic spectrum. The SPE-induced photon luminescence (black curve) only occurs on the side of the Moon heading into the solar wind during the period of time that the Moon is not passing through the tail of the Earth's magnetosphere ($\sim 75\%$ of the time). On the leeward or opposite side of the Moon, there exists a

plasma void or wake [10-11] and hence no SPEs or SPE albedo. The GCR-induced photon luminescence (blue curve), on the other hand, is present everywhere and all of the time (lunar day and night). Their relative amplitudes are approximately 1000:1 (worst case) except above 20 MeV where the GCR albedo dominates.

Relevance to Space Radiation Mitigation: Space radiation is background-limiting for science investigations, and hazardous for space operations. One might conclude, based upon a linear-dose model of radiation hazard, that the GCR-induced albedo in Figure 2b is nothing to be concerned about compared to the SPE-induced albedo. The linear-dose model basically assumes that increasing radiation intensity means greater risk, and a lower intensity means less risk.

However, a recent result has shown that low doses of radiation such as X-rays experienced in a dentist's chair may do more long-lasting damage than higher doses [12-13], a publication that has inspired 83 important papers in the last five years. It is clear that the hazardous effects of even modest radiation are not understood at the present time. Therefore, the space exploration community cannot assume that any form of radiation can be neglected if the widely-assumed linear-dose model is in fact not true. Present everywhere all the time on the Moon, the GCR-induced hard X-ray and lower γ -ray radiation in Figure 2b may have significance for lunar exploration, given the possible nonlinear dose-effect due to the Rothkamm-Löbrich effect.

Conclusions: It has been shown that the entire Moon glows due to a GCR-induced albedo, with a fluence whose spectrum extends from X-rays to γ -rays. In conjunction with the SPE-induced luminescence, this is yet another possible source of radiation hazard on the Moon in view of the Rothkamm-Löbrich effect. When free of Earthshine, the dark side of the Moon would be particularly suited for observing this luminescence. The effect should exist in Lunar Prospector data.

References: [1] Lee K. T. and Wilson T. L. (2008) *LPS XXXIX*, 1150. [2] Wilson T. L. and Lee K. T. (2007) *Proc. 30th ICRC*, 0209. [3] Wilson T. (2005) *LPS XXXVI*, 1201. [4] Wilson T. et al. (2003) *Proc. 28th ICRC*, 1447-1450. [5] Ballarini F. et al. (2007) *Adv. Spa. Res.* 40, 1339-1349. [6] Heiken G. et al. (1991) *Lunar Sourcebook*, Cambridge UP, NY, Table 7.15. [7] Simpson J. A. (1983) *Ann. Rev. Nucl. Part. Sci.* 33, 323-381. [8] O'Neill P. M. (2006) *Adv. Spa. Res.* 17, 1727-1733. [9] King J. H. (1974) *J. Spacecraft Rockets* 11, 401-408. [10] Wolf R. A. (1968) *J. Geophys. Res.* 73, 4281-4289. [11] Oglivie K. W. et al. (1996) *Geophys. Res. Lett.* 23, 1255-1258. [12] Rothkamm K. and Löbrich M. (2003) *Proc. Nat'l. Acad. Sci.* 100, 5057-5062. [13] Bonnor W. M. (2003) *Proc. Nat'l. Acad. Sci.* 100, 4973-4975.