GCR-INDUCED PHOTON LUMINESCENCE OF THE MOON. K. T. Lee[1] and T. L. Wilson[2], [1]Lockheed Martin Mission Services, 1300 Hercules Suite 100, Houston, TX 77058, [2]NASA, Johnson Space Center, Houston, Texas 77058 USA.

Introduction: It is shown that the Moon has a ubiquitous photon luminescence induced by Galactic cosmic-rays (GCRs), using the Monte Carlo particle-physics program FLUKA. Both the fluence and the flux of the radiation can be determined by this method, but only the fluence will be presented here. This is in addition to thermal radiation emitted due to the Moon's internal temperature and radioactivity. This study is a follow-up to an earlier discussion [1] that addressed several misconceptions regarding Moonshine in the Earth-Moon system (Figure 1) and predicted this effect. There also exists a related x-ray fluorescence induced by solar energetic particles (SEPs, <350 MeV) and solar photons at lower x-ray energies, although this latter fluorescence was studied on Apollo 15 and 16 [2-5], Lunar Prospector [6], and even EGRET [7].

The Dark of the Moon: Astronomical investigation of optical flashes on the Moon dates back centuries [8], including more recent discussions [1] that have identified these as due to meteor and micrometeorite impacts. To that, one can now add CR impacts.

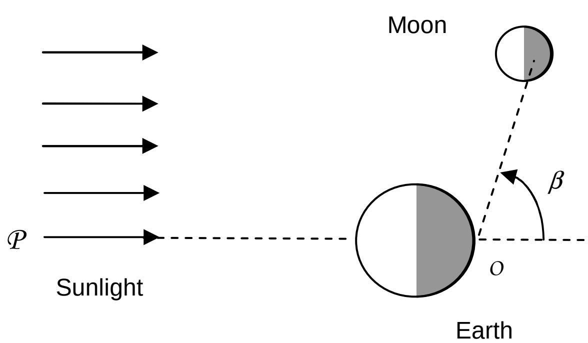

Figure 1: Earth-Moon scattering geometry

As old as the subject is, astronomers still do not understand moonlight. Referring to Figure 1, Moonshine is the term for sunlight reflected by the Moon and illuminating portions of the Earth. Earthshine is the reciprocal, being that portion of sunlight reflected by the Earth and illuminating the Moon. The latter is the basis for astronomical scattering studies of the dark portion of a crescent Moon as well as for measuring attributes of the Earth's atmospheric albedo. By symmetry, the two terms can be interchanged under reciprocity for an Earth-based optical observer *O* (Figure 1).

However, for a Moon-based observer the reciprocity fails (a broken symmetry). The reason is that the Moon has no appreciable atmosphere and is directly bombarded by a charged particle flux of CRs and solar wind material, while the Earth's surface is not. The consequence is that the lunar surface has a CR-induced albedo which is absent from the Earth's surface (although it is present at the top of Earth's atmosphere as a neutron albedo). Therefore, a lunar-based observer standing in the dark of the Moon does not see Earthshine, but rather Earthshine plus CR-induced albedo. On the dark side of the Moon when there is no Earthshine, the same observer still sees a CR-induced albedo. The spectrum (above 1 keV) of GCR-induced photon luminescence on the Moon will now be determined.

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 will be exploited here. The radiation transport code chosen for the study is FLUKA (a German acronym for "Fluctuating Cascade") used at CERN, and further details about this code are available elsewhere [9-11].

Effects of the optical properties of lunar dust upon the propagation of backscattered photons have not been taken into account below 1 keV since FLUKA has no event generator for photons below that energy.

Table 1: Lunar Surface Model

Element	Atomic Mass	Z	Percent Weight
Si	28.09	14	20.86
O	16.00	8	43.47
Ti	47.88	22	1.46
Al	26.98	13	9.63
Cr	52.00	24	0.22
Fe	55.85	26	9.08
Mn	54.94	25	0.16
Mg	24.31	12	5.54
Ca	40.08	20	8.93
Na	22.99	11	0.32
K	39.10	19	0.15
P	30.97	15	0.09
S	32.07	16	0.09

Model of the Lunar Surface: The model of the lunar surface has been taken to be the chemical composition of soils found at various landing sites during the

Apollo and Luna programs [12], averaging over all such sites to define a generic regolith. The resulting weight percentages by element have been calculated and are given in Table 1. Neglecting biogenic elements (H, C, and N), these are the 13 elemental abundances measured to be present on the Moon with more than a trace, having atomic mass A and atomic number Z. The model is assumed to have a mean density of 2.85 g cm^{-3} [13] and a negligible magnetic field.

The Monte Carlo target geometry for the lunar surface consists of a collisional tracking volume in the form of a rectangular parallelepiped, basically a "flat Moon" without curvature. A layer of vacuum above the regolith (tracking medium 1) is followed by a homogeneous mixture of the lunar surface material in Table 1 (tracking medium 2) comprising a 200 m by 200 m slab of regolith that is 50 m thick. The differential GCR flux is taken from Simpson [14], obeying a power-law spectrum $dN \sim E^{-\gamma} dE$ with $\gamma = 2.75$. This is modulated for solar activity (<10 GeV/nucleon) using the model of O'Neill [15] at an epoch of October 2003, on the way to solar minimum.

The incident flux of energy *E* impacts the regolith along the zenith and is limited to energies 10 MeV-to-10 GeV. First protons (H, hydrogen), then α–particles (He, helium), and finally everything else (Z>2) have been analyzed.

GCR-Induced Albedo of the Moon: The results of this study are shown in Figure 2. The photoluminescent albedo of the lunar regolith model (Table 1) is given as a fluence (the time-integral of flux) with the abscissa in GeV's as well as wavelength in meters [$\lambda = 1.23984 \times 10^{-6}$ m/E(eV)].

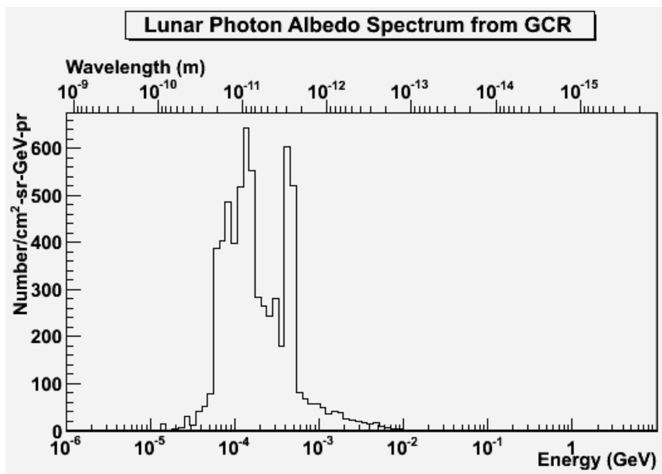

Figure 2: Photon luminescence of the Moon

Moon Glow: A fluence is time-independent. It is a glow. In Figure 2, the Moon glow begins to the left with a threshold around 10 keV (10^{-5} GeV) based upon the 1 keV threshold existing in the Monte Carlo. From the wavelength, one sees that the spectrum is in the upper (hard) X-ray and extends into the lower γ-ray portion of the electromagnetic spectrum. Note carefully that the spectrum is induced entirely by GCRs since no radioactivity of the Moon was simulated and solar radiation was not introduced.

Conclusions: It has been shown that the entire Moon glows due to a GCR-induced photon luminescence, with a fluence whose spectrum extends from X-rays to γ–rays. An instrumented photodetector array on the lunar surface or in lunar orbit could serve as a means for observing this albedo during the lunar night. When free of Earthshine, the dark side of the Moon (based upon the solar ephemeris in Figure 1) would be particularly suited for such observations. The effect should exist in Lunar Prospector data.

References: [1] T. Wilson (2005), *LPS XXXVI*, 1201. [2] R.C. Reedy et al. (1973), *JGR 78*, 5847. [3] A.E. Metzger et al. (1973), *Science 179*, 800. [4] I. Adler et al. (1973), *LPS 4.3*, 2783. [5] G. Heiken et al. (1991) *Lunar Sourcebook*, Cambridge UP, NY, 56; 603; Plates 10.1-10.5. [6] T. H. Prettyman et al. (2006), *JGR 111*, E12007. [7] D.J. Thompson et al. (1997), *Geophys. Res. A 102*, 14,735. [8] F. W. Hershel (1787), *Scientific Papers of Sir William Hershel 1*, p38, London. [9] FLUKA website: http://www.fluka.org. [10] Wilson T.L. and Lee K. (2007), *Proc. 30th ICRC*, 0209. [11] Wilson T.L. (2007), *Proc. 30th ICRC*, 212. [12] Ref. 5, Table 7.15. [13] T. Wilson (1992), *LPS XXIII*, 1539. [14] J. A. Simpson (1983), *Ann. Rev. Nucl. Part. Sci. 33*, 323. [15] P.M. O'Neill (2006), *Adv. Spa. Res. 17*, 1727.