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GCR-induced Photon Luminescence of the Moon: The Moon as a CR detector

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Abstract: We report on the results of a preliminary study of the GCR-induced photon luminescence of the Moon using the Monte Carlo program FLUKA. The model of the lunar surface is taken to be the chemical composition of soils found at various landing sites during the Apollo and Luna programs, averaged over all such sites to define a generic regolith for the present analysis. This then becomes the target that is bombarded by Galactic Cosmic Rays (GCRs) in FLUKA to determine the photon fluence when there is no sunlight or Earthshine. From the photon fluence we derive the associated energy spectrum. This is to be distinguished from the γ-ray spectrum produced by the radioactive decay of radiogenic constituents lying in the surface and interior of the Moon and the X-ray fluorescence induced by sunlight. Also, we will discuss transient optical flashes from high-energy CRs impacting the lunar surface (boulders and regolith). One goal is to determine to what extent the Moon could be used as a rudimentary CR detector. Meteor impacts on the Moon have been observed for centuries to generate such flashes, so why not CRs?

Introduction

The production rates of various particles and elemental species by planetary surfaces when bombarded with GCR fluxes are of interest in space exploration as well as albedo physics. Many groups have addressed the subject and the Moon in particular. Theoretical analyzes [1, 2], simulations using Monte Carlo transport codes [3-5], and experimental observations [6-9] have investigated the lunar radiation environment during and since the Apollo program. The analysis of planetary regoliths for their CR-induced backscatter albedos is important for its potential contributions to science investigations in fundamental physics and astrophysics in space [10]. All such albedos produced in the secondary backscatter affect science experiments and the personnel that operate them. Here we investigate an intrinsic physical property of objects in space, that they necessarily have a GCR-induced (and solar-particle-induced, <350 MeV) photon luminescence and fluence. This is in addition to thermal radiation emitted due to their internal temperature and radioactivity. The study will address the Moon in particular.

The Dark of the Moon

Astronomical investigation of optical flashes on the Moon dates back centuries [11], including more recent discussions [12-18] that have identified these as due to meteor and micrometeorite impacts.

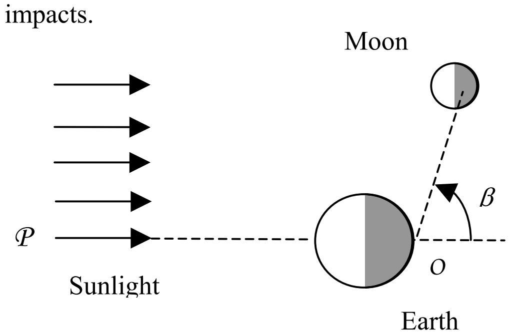

Figure 1: Earth-Moon scattering geometry

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 are 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 [19], a property since corroborated by AMS [20]). 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 far side of the Moon where there is no Earthshine, the same observer still sees a CR-induced albedo. The measurements on Apollo 15 and 16 [6-8], Lunar Prospector [9], and even EGRET [21] studied the total spectrum and not the component addressed here – although the effect should exist in the Lunar Prospector data. 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") [22-24]. It is executed via a user-friendly interface known as Flair [25]. Version 2006.3b of the FLUKA simulation package has been launched on a Linux-based architecture. 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. Because heavy-ions will be transported in the simulation, the full range from low-energy neutrons up to 10^{20} eV will be available. This entails the dual-parton model feature for hadron physics in FLUKA known as DPMJET-3 [26].

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 [27], averaging over all such sites to define a generic regolith for the present analysis. This is the same model as used in [4-5]. 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} [28] and a negligible magnetic field.

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

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 [29], 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 [30] at an epoch of October 2003, on the way to solar minimum.
The incident flux (having 4-momenum p_μ whose energy is E) impacts the regolith at an angle Θ with respect to the zenith. For these initial runs, the incoming radiation has been assumed to be along the lunar zenith (Θ=0) and 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

There are several caveats that must be given regarding the period of time allocated for this study and subtleties in the Monte Carlo. Because FLUKA can be used to investigate many realms of physics, it has a number of cutoffs for bypassing details that are not needed for every application. There is a global cutoff for all particle propagation < 100 keV. This can be overridden on a particle basis. For the case of proton propagation, the momentum cutoff is set per region – with a default of 0.03 MeV/c. Similarly for proton energy E the default is 0.6 MeV. These default cutoffs have all been removed in the simulation code for the present investigation.

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 [λ=1.23984x10^{-6} m/E(eV)]. The term "pr" on the ordinate axis represents primary GCR component (H, He, etc.).

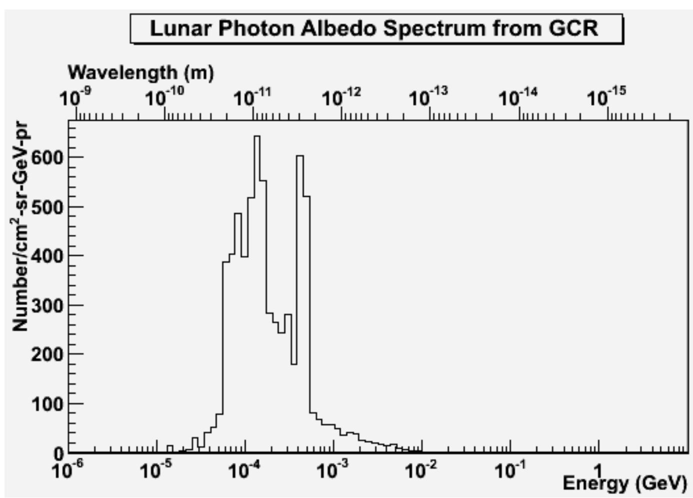

Figure 2: Photon luminescence of the Moon

Moon Glow

We have demonstrated that the Moon has a fluence with the GCR-induced spectrum indicated in Figure 2. One can see the spectroscopic features of the elemental composition in Table 1. A fluence is time-independent. It is a glow. The Moon glow continues on 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 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.

The Moon as a Calorimeter

As with the historical optical flashes discussed earlier, transient GCR-induced optical flashes will occur. Given the ubiquitous fluence or Moon glow shown above, however, this represents a background that will conflict with the observation of transient events. As with all backgrounds, this will place limits on observational results.

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. Optical flashes as transient phenomena are produced by GCR, meteor, and debris impacts, and those will have to be distinguished from the GCR-induced background albedo.

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