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THE GAMMA-RAY ALBEDO OF THE MOON. I. V. Moskalenko[1,2], T. A. Porter[3], [1]Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305 (imos@stanford.edu), [2]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94309, [3]Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064 (tporter@scipp.ucsc.edu).

Introduction: We use the GEANT4 Monte Carlo framework to calculate the γ-ray albedo of the Moon due to interactions of cosmic ray (CR) nuclei with moon rock. Our calculation of the albedo spectrum agrees with the EGRET data. We show that the spectrum of γ-rays from the Moon is very steep with an effective cutoff around 3 – 4 GeV (600 MeV for the inner part of the Moon disk) and exhibits a narrow pion-decay line at 67.5 MeV, perhaps unique in astrophysics. Apart from other astrophysical sources, the albedo spectrum of the Moon is well understood, including its absolute normalisation; this makes it a useful "standard candle" for γ-ray telescopes. The steep albedo spectrum also provides a unique opportunity for energy calibration of γ-ray telescopes, such as the forthcoming *Gamma Ray Large Area Space Telescope* (GLAST). Since the albedo flux depends on the incident CR spectrum which changes over the solar cycle, it is possible to monitor the CR spectrum using the albedo γ-ray flux. Simultaneous measurements of CR proton and helium spectra by the *Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics* (PAMELA), and observations of the albedo γ-rays by the GLAST *Large Area Telescope* (LAT), can be used to test the model predictions and will enable the LAT to monitor the CR spectrum near the Earth beyond the lifetime of the PAMELA.

Background: Interactions of Galactic CR nuclei with the atmospheres of the Earth and the Sun produce albedo γ-rays due to the decay of secondary neutral pions and kaons [1,2]. Similarly, the Moon emits γ-rays due to CR interactions with its surface [3,4]. However, contrary to the CR interaction with the gaseous atmospheres of the Earth and the Sun, the Moon surface is solid, consisting of rock, making its albedo spectrum unique.

Due to the kinematics of the collision, the secondary particle cascade from CR particles hitting the Moon surface at small zenith angles develops deep into the rock making it difficult for γ-rays to get out. The spectrum of the albedo γ-rays is thus necessarily soft as it is produced by a small fraction of low-energy splash particles in the surface layer of the moon rock. The high energy γ-rays can be produced by CR particles hitting the Moon surface with a more tangential trajectory. However, since it is a solid target, only the very thin limb contributes to the high energy emission.

The γ-ray albedo of the Moon has been calculated in [3] using a Monte Carlo code for cascade development in the Earth's atmosphere that was modified for the Moon conditions. However, the CR spectra used as input in the calculation [3] differ considerably from recent measurements by AMS [5,6] and BESS [7] at both low and high energies. Additionally, due to the lack of accelerator data and models a number of approximations and ad-hoc assumptions were required to calculate the hadronic cascade development in the solid target of the Moon's surface.

The Moon has been detected by the EGRET as a point source with integral flux F(>100 MeV) = $(4.7\pm0.7)\cdot10^{-7}$ cm^{-2} s^{-1} [4], ~24% below the predictions by [3] although the spectral shape agrees with the data. The observed spectrum is steep and yields only the upper limit ~$5.7\cdot10^{-12}$ cm^{-2} s^{-1} above 1 GeV. At lower energies, γ-ray spectroscopy data acquired by the Lunar Prospector have been used to map the elemental composition of the Moon surface [8,9].

The γ-ray albedo from the Moon has been calculated using the GEANT4 software framework and discuss the consequences of its measurement by the upcoming GLAST mission [10,11]. Our calculations are detailed in [12].

Results: The GLAST LAT γ-ray telescope is scheduled for launch by NASA in early 2008. It will have superior angular resolution and effective area, and its field of view (FoV) will far exceed that of its predecessor, the EGRET [13]. The LAT will scan the sky continuously providing complete sky coverage every two orbits (approximately 3 hr). The on-axis effective area of the LAT increases from ~3000 cm^2 at 100 MeV to ~8500 – 9000 cm^2 at 1 GeV and higher (http://glast.stanford.edu). In this case, the point spread function (PSF) of the instrument has a 68% containment radius ~4.3º at 100 MeV reducing dramatically at higher energies: ~0.8º at 1 GeV, ~0.5º at 2 GeV, and ~0.2º at 10 GeV. Using only events from the front section of the LAT, the PSF improves to a 68% containment radius of ~3º at 100 MeV, ~0.5º at 1 GeV, ~0.25º at 2 GeV, and ~0.1º at 10 GeV, but the on-axis effective area is essentially halved. About 20% of the time the Moon will be in the FoV at different viewing angles.

The photon flux expected from the Moon for the solar minimum conditions (modulation potential Φ = 500 MV) above 100 MeV, 1 GeV, and 4 GeV is

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~$5\cdot10^{-7}$, ~$2\cdot10^{-8}$, and <$1.6\cdot10^{-10}$ photons cm^{-2} s^{-1}, respectively (Fig.1). For the solar maximum conditions Φ = 1500 MV, the expected flux is reduced by a factor of 2 at 100 MeV only. With these fluxes and the above values for the effective area, and allowing for an additional factor 2 reduction to take into account time off-axis, instrumental deadtime, and South Atlantic Anomaly traversals, we estimate the LAT will collect ~5000, ~600, and <5 photons, respectively, in the above energy ranges in one year. These numbers are reduced by a factor of two if only events from the front section of the LAT are used. Interestingly, the albedo flux at low energies is high enough that the impact of the broader PSF is significantly reduced.

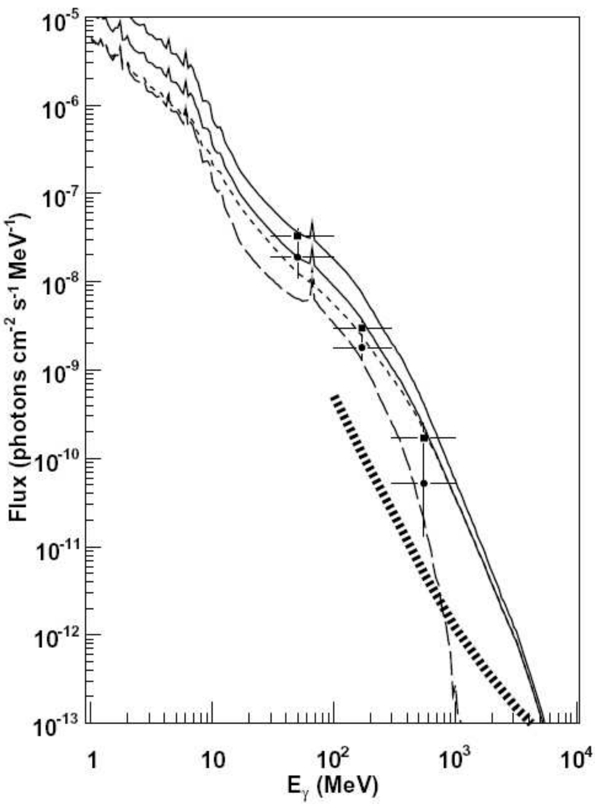

Fig.1. Calculated γ-ray albedo spectrum of the Moon. Line-styles: total – solid, limb (outer 5') – dotted, center (inner 20') – dashed. Upper solid line: Φ = 500 MV, lower solid line: Φ = 1500 MV. Limb and center components are only shown for Φ = 1500 MV. Data points from the EGRET [4] with upper and lower symbols corresponding to periods of lower and higher solar activity, respectively. The differential 1 yr sensitivity of the LAT is shown as the shaded region.

Measuring γ-rays from the Moon presents several interesting possibilities for the LAT. Apart from other astrophysical sources, the albedo spectrum of the Moon is well understood, including its absolute normalisation, while the Moon itself is a "moving target" passing through high Galactic latitudes and the Galactic centre region. This makes it a useful "standard candle" for the GLAST LAT at energies where the PSF is comparable to the Moon size 0.5º, i.e., at ~1 GeV and higher. At these energies the albedo flux is essentially independent of the solar modulation. At lower energies the γ-ray flux depends on the level of the solar modulation and thus can be used to infer the incident CR spectrum. A simultaneous presence of the PAMELA on-orbit capable of measuring protons and light nuclei with high precision [14] provides a necessary input for accurate prediction of the albedo flux and a possible independent calibration of the GLAST LAT. An additional bonus of such a calibration is the possibility to use the GLAST observations of the Moon to monitor the CR spectra near the Earth beyond the projected lifetime of the PAMELA (currently 3 years).

The line feature at 67.5 MeV from π^0-decay produced by CR particles in the solid rock target is interesting. There is no other astrophysical object predicted to produce such a narrow line and there is no other line expected except, perhaps, from dark matter annihilation. The lower energy limit of the LAT instrument is below 20 MeV while the energy resolution is ~15% at 100 MeV, and improves at higher energies. With a suitable event selection it may be possible to observe the line; if so, it will provide a possibility of in-orbit energy calibration. Another possibility for energy calibration at higher energy is provided by the steep albedo spectrum above 100 MeV: a small error in the energy determination will result in a large error in the intensity.

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