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Energetic gamma ray experiment telescope high-energy gamma ray observations of the Moon and quiet Sun

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Abstract. High-energy gamma radiation has been seen from the Moon as it passed through the large field of view of the energetic gamma ray experiment telescope (EGRET) on the Compton Gamma Ray Observatory a number of times between mid-1991 and the end of 1994. The average lunar flux is $(4.7 \pm 0.7) \times 10^{-7}$ photons ($E > 100$ MeV) $\text{cm}^{-2}\ \text{s}^{-1}$. The observed energy spectrum is consistent with a model of gamma ray production by cosmic ray interactions with the lunar surface, and the flux varies as expected with the solar cycle. Although the same types of cosmic ray interactions that produce the lunar gamma rays may occur on the Sun, EGRET has not detected the quiet Sun. The 95% confidence upper limit on the flux above 100 MeV, 2.0×10^{-7} photons $\text{cm}^{-2}\ \text{s}^{-1}$, lies well below the lunar gamma ray flux, as expected.

1. Introduction

The dominant feature in the high-energy gamma ray sky, the bright ridge of the Milky Way, is produced largely by cosmic ray particles interacting with interstellar matter [*Kraushaar et al.*, 1972; *Hartman et al.*, 1979; *Mayer-Hasselwander et al.*, 1980; *Bertsch et al.*, 1993; *Hunter et al.*, 1997]. On a more local scale, cosmic rays interacting with the earth's atmosphere are a strong source of gamma radiation [e.g., *Thompson*, 1974; *Ryan et al.*, 1979; *Kur'yan et al.*, 1979; *Lockwood et al.*, 1981; *Thompson et al.*, 1981]. The secondary gamma rays are produced by inelastic collisions of cosmic ray particles with atmospheric nuclei, through π^0 production and decay, and $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ production and decay followed by bremsstrahlung. Models of the atmospheric gamma ray production show fairly good agreement with observations [*Stecker*, 1973; *Daniel and Stephens*, 1974; *Ling*, 1975; *Morris*, 1984].

This same type of model was extended to cosmic ray interactions with the lunar surface [*Morris*, 1984]. The predicted flux fell below the upper limit obtained by the SAS-2 high-energy gamma ray telescope but was expected to be visible to the energetic gamma ray experiment telescope (EGRET) on the Compton Gamma Ray Observatory. Solar modulation is expected to affect the flux and spectrum of the secondary gamma radiation. Higher solar activity sweeps more of the galactic cosmic radiation from the inner solar system.

During the 1991 period of high solar activity, large solar flares were found to be a strong source of high-energy gamma rays [*Kanbach et al.*, 1993; *Akimov et al.*, 1993]. The quiet Sun could also be a gamma ray source from the same type of cosmic ray interaction processes which produce the lunar gamma radiation [*Morris*, 1984]. An additional effect not found with the Moon is the exclusion of cosmic rays by the solar magnetic field. Although there is some uncertainty in this effect, the predicted gamma ray flux above 100 MeV from the quiet Sun is approximately 1×10^{-7} photons $\text{cm}^{-2}\ \text{s}^{-1}$ [*Hudson*, 1989; *Seckel et al.*, 1991].

2. Data Analysis

The energetic gamma ray experiment telescope (EGRET) is the high-energy gamma ray telescope on the Compton Gamma Ray Observatory. Descriptions and capabilities of the instrument are given by *Thompson et al.* [1993] and references therein. The telescope covers the energy range from about 30 MeV to over 20 GeV. EGRET records gamma ray photons individually as electron-positron pair production events, which are processed automatically (with manual verification) to provide the arrival time, direction, and energy of each photon. The point spread function (PSF) of the arrival direction is energy-dependent, having a full width at half maximum (FWHM) of approximately 5° at 100 MeV and smaller values at higher energies. The field of view of EGRET extends to more than 30° from the instrument axis, although the sensitivity at 30° is less than 15% of the on-axis sensitivity. Because of the low flux level of the high-energy gamma rays, observing periods typically view a fixed direction in the sky for 2–3 weeks.

EGRET has little internal background; the background against which sources are detected is the galactic and extragalactic cosmic diffuse gamma radiation, plus the effects of nearby sources. The diffuse galactic radiation within 10° of the plane is very intense and highly nonuniform [*Hunter et al.*, 1997]. Even with careful modeling of the galactic plane radiation the bright background reduces the EGRET sensitivity to

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Table 1. EGRET Viewing Periods for Observations of the Moon

Viewing Period	Start	End	l	b	Neutron Monitor, cts/(hr/100)
0110	Oct. 5, 1991 0925	Oct. 9, 1991 1330	294.25	63.67	2023
0190	Feb. 2, 1992 2109	Feb. 6, 1992 1514	58.15	−43.00	2068
0400	Sept. 22, 1992 0840	Sept. 25, 1992 1615	195.90	44.71	2246
3070	Nov. 9, 1993 1347	Nov. 12, 1993 0230	268.69	69.24	2336
3170	Feb. 17, 1994 1600	Feb. 19, 1994 1034	158.48	−45.38	2294
3200	March 9, 1994 2030	March 14, 1994 1345	83.09	−45.47	2244
4050	Nov. 29, 1994 1527	Dec. 1, 1994 0915	306.67	56.54	2319
4070	Dec. 25, 1994 0940	Dec. 29, 1994 0245	334.33	62.98	2340

Here, l is galactic longitude; b is galactic latitude.

point sources. At higher galactic latitudes the gamma radiation is weaker and more uniform (P. Sreekumar et al., Diffuse gamma radiation, submitted to *Astrophys. J.*, 1997). As can be seen in the second EGRET catalog [*Thompson et al.*, 1995], detection of weaker sources and setting of more stringent upper limits is possible in regions away from the galactic plane.

Because of the low photon detection rate and the extent of the PSF, statistical techniques are required to analyze EGRET data. Maximum likelihood [*Mattox et al.*, 1996] is used to estimate point source flux densities, source locations, and background model parameters. The likelihood ratio test is used to determine the significance of point sources. The likelihood ratio test statistic is $TS \equiv 2(\ln L_1 - \ln L_0)$, where $\ln L_1$ is the log of the likelihood of the data if a point source is included in the model and $\ln L_0$ is the log of the likelihood of the data without a point source. In the null hypothesis, TS is asymptotically distributed as χ_1^2 for a source at a specific position. *Mattox et al.* [1996] show that the corresponding significance, σ, is $\sqrt{TS}$. Monte Carlo simulation and experience with flight data indicate that these techniques provide reliable results. Source analysis requires not only an excess of gamma rays above that expected from the diffuse background and neighboring sources but also that the excess be distributed with the shape of the EGRET PSF. Analysis for the energy range $E > 100$ MeV in most cases gives an optimum balance between statistics (which decline with greater energy) and angular resolution (which improves with greater energy). For this energy range a region of 15° about the target position is used to model the background.

Although the Sun and Moon each subtend about a half degree from the Earth, this extent is considerably smaller than the EGRET point spread function at all but the highest energies; therefore the Moon and Sun can be treated as point sources for the analysis. Compared to the typical EGRET observing times, the Sun and Moon are "moving targets." In order to obtain adequate exposure to these sources we searched the EGRET data base for times when they passed through the EGRET field of view. The considerations for selecting observations were as follows.

1. The source should be within 25° of the EGRET axis for more than 1 day. The EGRET sensitivity at wide angles is limited, and shorter exposures at these wide angles produce too few photons to be useful.
2. The source should be more than 20° from the galactic plane. As discussed above, the highly structured, intense galactic radiation reduces the EGRET sensitivity to point sources.
3. The source should be well separated from bright gamma ray sources. Targets within 5° of a bright source are difficult to see because of the overlapping PSFs.

3. Solar Activity During the Observations

As the cosmic ray spectrum and intensity change during the solar cycle, the resultant secondary gamma ray flux and intensity are also expected to change. Ground-based neutron monitors provide a record of the solar activity influence on the cosmic radiation both now and in the past. For the times of the EGRET observations the Mount Washington (J. Lockwood, private communication, 1996) and Climax (University of Chicago, National Science Foundation grant ATM-9420790) neutron monitor rates were compared and found to track each other well. The rates from the Mount Washington neutron monitor are shown in Table 1. The EGRET observations of the Moon are compared with the calculations of *Morris* [1984], which employed cosmic ray spectra measured near solar maximum in 1970 and near the following solar minimum in 1972 [*Rygg et al.*, 1974]. The Mount Washington rates at the times of those cosmic ray measurements were 2130 and 2385 cts/(hr/100), respectively.

4. Observations and Results

4.1. Moon

Between the beginning of the Compton Observatory mission (April 1991) and the end of the fourth observing cycle (October 1995) the Moon passed within 25° of the EGRET axis for at least 1 day on 34 occasions. The vast majority of these observations brought the Moon within 20° of the galactic plane or within a few degrees of bright gamma ray sources. As discussed above, under these conditions the EGRET sensitivity to sources is reduced; therefore we chose to focus analysis on those observations with the least background radiation. Results are based on eight observations, three in phase 1, three in phase 3, and two in phase 4 of the Compton Observatory viewing program. For the observations shown in Table 1 the EGRET pointing direction was far enough from the galactic plane that the background radiation, consisting of diffuse galactic and extragalactic radiation plus sources too weak to be resolved, could be approximated as smooth, showing no statistically significant fluctuations. This approximation must be verified in the analysis. The times shown in Table 1 are the portions of the full viewing period (VP) when the Moon was within 30° of the EGRET pointing direction, which is shown in columns 4 and 5 in galactic coordinates. The choice of observations is somewhat subjective. For example, VP0030 and VP0110 had both the Moon and the bright quasar 3C279 in the field of view, but we excluded VP0030 because the quasar was in a much brighter state than in VP0110 [*Kniffen et al.*, 1993].

In order to analyze the data for the Moon the EGRET field

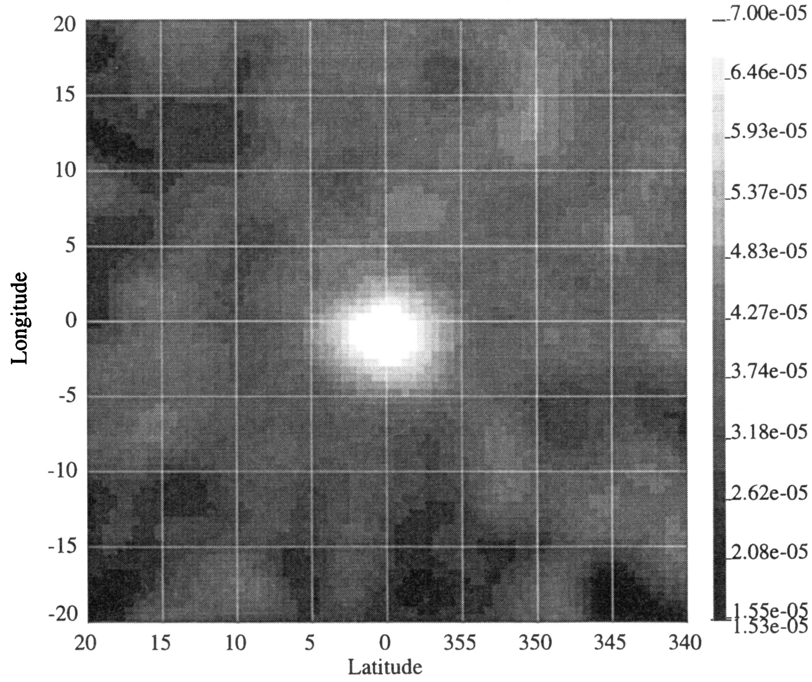

Figure 1. Combined intensity map of the energetic gamma ray experiment telescope (EGRET) observations of the Moon. The coordinate system is one which tracks the Moon, whose nominal position is (0,0). The offset of the excess from (0,0) is within the positional uncertainties of the EGRET measurement. The units are photons ($E > 100$ MeV) $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$, 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.

of view was mapped onto a coordinate system which tracks the apparent position of the Moon. This mapping involves two transformations. The first is due to the motion of the Moon itself around the Earth; the second arises from the fact that the Moon is close enough to the Earth that the motion of the Compton Observatory around the Earth gives a parallax for the Moon of about a degree. For each of the viewing periods in Table 1 a set of maps was constructed in this moving coordinate system using various energy selections. Although each exposure was short, a maximum likelihood analysis of the $E > 100$ MeV map for each viewing period showed an excess positionally consistent with the Moon. Combining all eight $E > 100$ MeV maps gives the intensity map shown in Figure 1. The statistical significance of this excess determined by the likelihood analysis is 8.7 σ at the position of the Moon, with an average flux of $(4.7 \pm 0.7) \times 10^{-7}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. A box 10° on a side, centered on the position of the Moon, contains 500 photons, while the expectation from the surrounding region would be 330 photons. Analysis of this map also shows that the assumption of a background with no significant fluctuations is justified for these exposures. There is no strong gradient in the diffuse emission, at least within the 15° analysis radius used for modeling. Maximum likelihood analysis shows that the next largest source-like excess after the Moon has a statistical significance less than 3 σ. A similar analysis for the 30–100 MeV energy range also shows an excess positionally consistent with the Moon in each individual observation. The combined 30–100 MeV analysis gives an excess of $(18.4 \pm 3.5) \times 10^{-7}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and a significance of 6.1 σ.

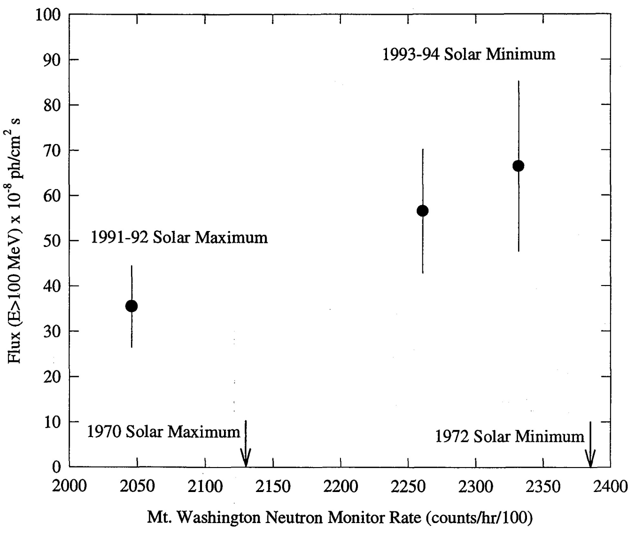

Figure 2. Gamma ray flux from the Moon as a function of the Mount Washington neutron monitor count rate. The arrows show the neutron monitor rates at times corresponding to the solar minimum and solar maximum calculations of *Morris* [1984].

In order to compare the results with the level of solar activity the eight viewings were separated into three combined maps based on the following neutron monitor readings: VP 0110 + 0190 ("low" rate, near solar maximum), VP 0400 + 3170 + 3200 ("high" rate, between solar maximum and minimum), and VP 3070 + 4050 + 4070 ("very high" rate, close to solar minimum). The results are shown in Figure 2 as a function of neutron monitor rate. Although the statistical error bars are large, the values are consistent with higher gamma ray fluxes

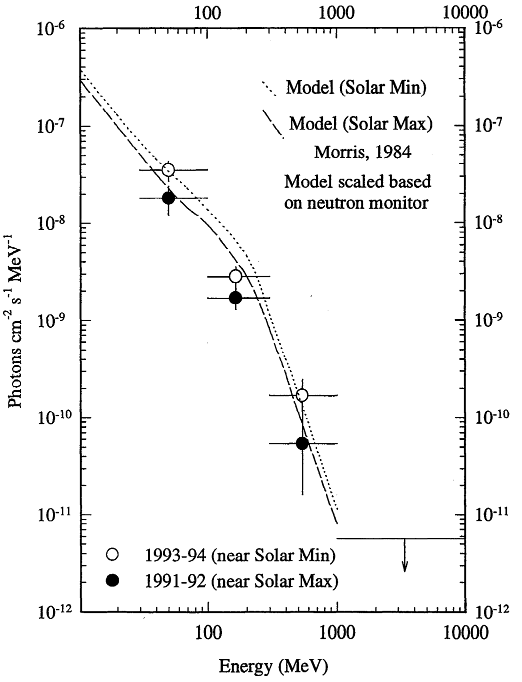

Figure 3. Energy spectrum of the lunar gamma radiation as measured by EGRET. The original calculations of *Morris* [1984] have been scaled down by 24% on the basis of the lower cosmic ray flux seen in the solar cycle of the 1990s compared to the 1970 solar cycle.

from the Moon when neutron monitor rates (i.e., cosmic ray fluxes) are higher.

In light of the limited statistics the energy spectrum was constructed for two subsets of the data: the 1991–1992 data near solar maximum and the 1993–1994 data closer to solar minimum. Fluxes were determined in four broad energy bands: 30–100 MeV, 100–300 MeV, 300–1000 MeV, and >1000 MeV. Only upper limits were obtained for the highest energy band. The resulting energy spectrum is shown in Figure 3. The flux near solar minimum is higher than the solar maximum flux for all three energy ranges.

The *Morris* [1984] model for secondary gamma ray production was a Monte Carlo calculation based on the cosmic ray spectra measured near the 1970 and 1972 solar maximum and minimum. As indicated in Figure 2, the solar cycle of the 1990s shows a lower cosmic ray flux at both extremes. The cosmic ray spectrum is not a simple function of the neutron monitor rate, but an approximate correction to the calculated spectrum can be made. In the Morris calculation the difference between the solar maximum and minimum gamma ray spectrum is about 60%, while the difference in the neutron monitor rates was about 10%. The current solar cycle neutron monitor rates are about 4% lower than the 1970–1972 cycle. To first order, then (and within the uncertainties of the calculation itself), the expected gamma ray spectrum from the Moon should be 24% lower than the original calculation. The *Morris* [1984] spectra, scaled by this factor, are shown in Figure 3. The measured points are close to the calculated curves at all energies. The principal discrepancy is that the data do not show as prominent a bump as expected because of π^0 decay between 100 and 300 MeV.

4.2. Sun

Between the beginning of the Compton Observatory mission (April 1991) and the end of the fourth observing cycle (October 1995) the Sun passed within 25° of the EGRET axis for at least 1 day on 8 occasions. Only one of these, VP 0190, met all the acceptance criteria for the Sun being well away from the galactic plane and bright sources. In order to increase the solar exposure we relaxed the criteria. Three additional viewings were included despite the presence of the bright Crab and Geminga pulsars and the galactic anticenter lying about 20° from the Sun. Three days of VP 0110 were included, selecting that time range when the bright 3C279 quasar was more than 3° from the Sun. Two and a half days of VP 3200 were included, selecting the times when the Sun was more than 3° from the unidentified EGRET source 2EGS J2322-0321 [*Thompson et al.*, 1996]. The solar observations are shown in Table 2.

Each of the six observations was examined in the energy range $E > 100$ MeV using the maximum likelihood analysis and modeling the nearby sources as part of the background where necessary. Not one of the observations showed any evidence of an excess positionally consistent with the Sun. Using the best single observation, VP 0190, we obtain an upper limit above 100 MeV (95% confidence) of 3.0×10^{-7} photons cm^{-2} s^{-1}. Combining all six observations reduces the upper limit to 2.0×10^{-7} photons cm^{-2} s^{-1}.

Because the expected energy spectrum of the gamma radiation from the Sun is expected to have a flat spectrum [*Seckel et al.*, 1991], we made a further search of the EGRET data for the energy range $E > 500$ MeV. Combining the same six observation periods produces a small excess consistent in position with the Sun. The statistical significance is less than 3 σ, and the excess is only eight photons; therefore, no claim of a detection is warranted. The 95% confidence upper limit above 500 MeV is 5×10^{-8} photons cm^{-2} s^{-1}. The small excess may be taken as a suggestion that the solar gamma ray flux may lie just below the EGRET threshold.

Table 2. EGRET Viewing Periods for Observations of the Sun

Viewing Period	Start	End	l	b	Comments
0010	May 20, 1991 0630	May 30, 1991 1900	190.92	−4.74	galactic anticenter in view
0110	Oct. 14, 1991 1330	Oct. 17, 1991 1330	294.25	63.67	3C279 nearby
0190	Jan. 24, 1992 1900	Feb. 6, 1992 1514	58.15	−43.00	best observation
2210	May 16, 1993 1415	May 24, 1993 1530	187.52	−5.88	galactic anticenter in view
3200	March 13, 1994 0000	March 15, 1994 1415	83.09	−45.47	EGRET source nearby
4200	May 23, 1995 1555	June 6, 1995 1645	198.21	−18.26	galactic anticenter in view

Here, l is galactic longitude; b is galactic latitude.

5. Discussion

The *Morris* [1984] calculation of lunar gamma ray production was carried out in absolute terms, using the measured cosmic ray spectrum and interaction cross sections for the various processes involved in the cascade. In light of the fact that simplifying assumptions are needed for any such calculation the consistency of the observations with the calculation is good.

Why is the 100–300 MeV excess less prominent in the data than in the model for the Moon? As Figure 4 shows, modeling indicates that both the π^0 and charged pion channels should produce a "bump" in this energy band. One possibility, then, is that the modeled distribution of meson energies is too narrow. Another possibility is illustrated in Figure 5, which shows the model calculations for two ranges of lunar zenith angles. The 100–300 MeV excess is largely due to the photons coming from zenith angles 120°–180°, i.e., those originating at large angles to the incident directions of the parent cosmic rays. The cross section for pion production at large angles, relative to the small-angle pion production, may be overestimated. These large-angle cross sections are not extremely well measured and contribute the largest uncertainty to the calculation. Comparison of similar model calculations to the observed Earth albedo gamma radiation [*Morris*, 1984] also shows that the nadir radiation is overestimated by the calculation. Although the solid lunar surface is not an exact analogy to the Earth's gaseous atmosphere, the dominant physical processes remain the same.

The EGRET upper limit for gamma ray emission from the Sun is less than the flux seen from the Moon, as expected. The limited useful exposure of EGRET to the quiet Sun does not, however, allow a measurement at the level expected from calculations.

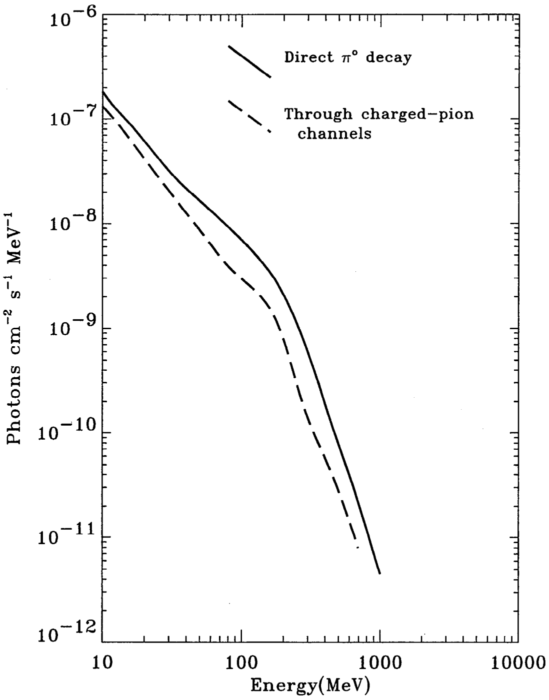

Figure 4. Calculated contributions of neutral and charged meson channels to the gamma ray emission from the Moon.

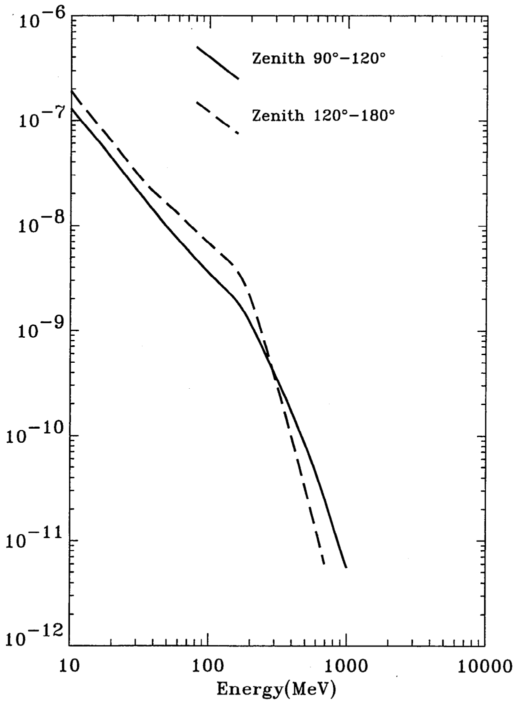

Figure 5. Calculated contributions of horizon and nadir channels to the gamma ray emission from the Moon.

6. Summary

Data from EGRET show that the Moon is a high-energy gamma ray source, as predicted by *Morris* [1984]. The flux values are consistent with the variation expected from solar modulation. Although the gamma ray flux and energy spectrum match the calculation in general, the energy spectrum does not show the enhancement in the 100–300 MeV range expected from the calculation.

Despite the possibility of seeing gamma rays from cosmic ray interactions on the Sun, the EGRET data offer no evidence of the quiet Sun as a gamma ray source. The upper limit above 100 MeV (95% confidence) of 2×10^{-7} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ lies well below the gamma ray flux seen from the Moon, as expected from calculations [*Hudson*, 1989; *Seckel et al.*, 1991]. The limit does not, however, constrain existing models. Detection of the quiet Sun in high-energy gamma rays will require a next generation gamma ray telescope.

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References

Akimov, V. V., et al., High-energy gamma rays at the late stage of the large solar flare of June 15, 1991 and accompanying phenomena, *Conf. Pap. Int. Cosmic Ray Conf. 23rd*, *3*, 111, 1993.

Bertsch, D. L., T. M. Dame, C. E. Fichtel, S. D. Hunter, P. Sreekumar, J. G. Stacy, and P. Thaddeus, Diffuse gamma ray emission in the galactic plane from cosmic ray, matter, and photon interactions, *Astrophys. J.*, *416*, 587, 1993.

Daniel, R. R., and S. A. Stephens, Cosmic ray produced electrons and gamma rays in the atmosphere, *Rev. Geophys.*, *12*, 233, 1974.

Hartman, R. C., et al., Galactic plane gamma radiation, *Astrophys. J.*, *230*, 597, 1979.

Hudson, H. S., Solar gamma-ray astronomy in the 1990's and the Gamma-Ray Observatory, in *Gamma Ray Observatory Science Work-*

shop Proceedings, edited by W. N. Johnson, pp. 4-351–4-363, NASA Goddard Space Flight Cent., Greenbelt, Md., 1989.

Hunter, S. D., et al., EGRET Observations of the diffuse gamma-ray emission from the galactic plane, *Astrophys. J.*, in press, 1997.

Kanbach, G., et al., Detection of a long-duration solar gamma-ray flare on June 11, 1991, with EGRET on COMPTON-GRO, *Astron. Astrophys.*, *97*, suppl., 349, 1993.

Kniffen, D. A., et al., Time variability in the gamma-ray emission of 3C 279, *Astrophys. J.*, *411*, 133, 1993.

Kraushaar, W. L., G. W. Clark, G. P. Garmire, R. Borken, P. Higbie, C. Leong, and T. Thorsos, High-energy cosmic gamma ray observations from the OSO-3 satellite, *Astrophys. J.*, *177*, 341, 1972.

Kur'yan, Y. A., Y. P. Mazets, M. P. Proskura, and I. A. Sokolov, Atmospheric hard gamma-ray studies on Kosmos 461, *Geomagn. Aeron.*, *19*, 6, 1979.

Ling, J. C., A semiempirical model for atmospheric gamma rays from 0.3 to 10 MeV at $\lambda = 40°$, *J. Geophys. Res.*, *80*, 3241, 1975.

Lockwood, J. A., W. R. Webber, L. A. Friling, J. Macri, and L. Hsieh, Observations of gamma radiation between 0.4 MeV and 7 MeV at balloon altitudes using a Compton telescope, *Astrophys. J.*, *248*, 1194, 1981.

Mattox, J. R., et al., The likelihood analysis of EGRET data, *Astrophys. J.*, *461*, 396, 1996.

Mayer-Hasselwander, H., et al., COS B observations of the Milky Way in high-energy gamma rays, *Ann. N. Y. Acad. Sci.*, *336*, 211, 1980.

Morris, D. J., Production of high-energy gamma rays by cosmic ray interactions in the atmosphere and lunar surface, *J. Geophys. Res.*, *89*, 10,685, 1984.

Ryan, J. M., M. C. Jennings, M. D. Radwin, A. D. Zych, and R. S. White, Atmospheric gamma ray angle and energy distribution from sea level to 3.5 g/cm^2 and 2 to 25 MeV, *J. Geophys. Res.*, *84*, 5279, 1979.

Rygg, T. A., J. J. O'Gallagher, and J. A. Earl, Modulation of cosmic ray protons and helium nuclei near solar maximum, *J. Geophys. Res.*, *79*, 4127, 1974.

Seckel, D., T. Stanev, and T. K. Gaisser, Signatures of cosmic-ray interactions on the solar surface, *Astrophys. J.*, *382*, 652, 1991.

Stecker, F. W., Simple model for scanning-angle distribution of planetary albedo gamma-rays, *Nature Phys. Sci.*, *242*, 59, 1973.

Thompson, D. J., A three-dimensional study of 30- to 300-MeV atmospheric gamma rays, *J. Geophys. Res.*, *79*, 1309, 1974.

Thompson, D. J., G. A. Simpson, and M. E. Özel, SAS 2 observations of the earth albedo gamma radiation above 35 MeV, *J. Geophys. Res.*, *86*, 1265, 1981.

Thompson, D. J., et al., Calibration of the energetic gamma ray experiment telescope (EGRET) for the Compton Gamma Ray Observatory, *Astrophys. J.*, *86*, suppl., 629, 1993.

Thompson, D. J., et al., The second EGRET catalog of high-energy gamma-ray sources, *Astrophys. J.*, *101*, suppl., 259, 1995.

Thompson, D. J., et al., Supplement to the second EGRET catalog of high-energy gamma-ray sources, *Astrophys. J.*, *107*, suppl., 227, 1996.

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