Reports

Alpha-Particle Emissivity of the Moon: An Observed Upper Limit

Abstract. *Measurements made by the moon-orbiting spacecraft Explorer 35 during 1967–1968 show that it is unlikely that the alpha-particle emissivity of the moon is greater than 0.064 per square centimeter per second per steradian and exceedingly unlikely that it is greater than 0.128, these values being respectively 0.1 and 0.2 of the provisional estimates made by Kraner* et al. *in 1966. This result implies that the abundance of uranium-238 in the outer crust (approximately a few meters thick) of the moon is much less than that typical of the earth's lithosphere, though it is consistent with the abundance of uranium-238 in terrestrial basalt or in chondritic meteorites.*

On the basis of several physical assumptions of a provisional nature, Kraner *et al.* (*1*) suggested in 1966 that easily detectable quantities of the radioactive noble gases radon ($_{86}Rn^{222}$) and thoron ($_{86}Rn^{220}$) might possibly be present in the atmosphere of the moon and on its outermost surface. They estimated the following equivalent surface activities (in disintegrations per square centimeter per second): radon, 4; thoron, 0.01. The portion of the $_{92}U^{238}$ radioactive series from $_{86}Rn^{222}$ to the stable end product $_{82}Pb^{206}$ yields four alpha particles per disintegration, ranging in energy from 5.3 to 7.7 Mev. If we neglect thoron and suppose that somewhat less than one-half of the daughter nuclei are lost (by virtue of surface roughness) at each step of the series, we adopt

$$\sigma = 8/4\pi = 0.64 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$

as Kraner's provisional estimate of the alpha-particle emissivity of the moon. The effect, if present, is a property of the moon as a total physical system, not of a disembodied sample as measured in the laboratory.

Among other detectors included by the University of Iowa on the moon-orbiting spacecraft Explorer 35 (NASA Goddard Space Flight Center) is one suitable for a direct determination of the alpha-particle emissivity of the moon. The spacecraft was injected into an eccentric lunar orbit on 22 July 1967 and has been operating in an essentially continuous manner since that time. The orbit has been a stable one with a mean radial distance to aposelene of 9386 km, a mean radial distance to periselene of 2576 km, and an orbital period of 11.53 hours (Fig. 1). The plane of the orbit is inclined 168° to the ecliptic.

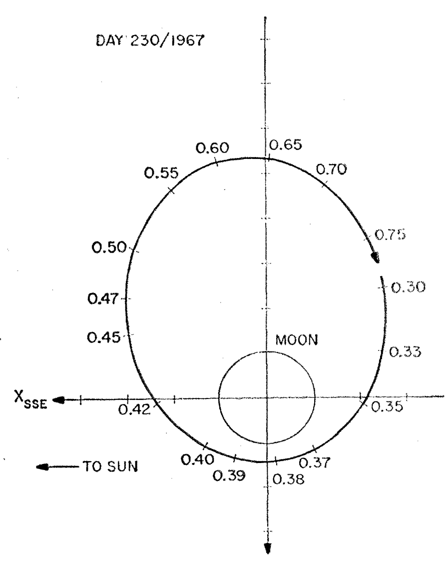


Fig. 1. A typical orbit of Explorer 35 about the moon, as projected on the ecliptic plane. The plane of the orbit is inclined at 168° to that plane (retrograde); X_{SSE}, Y_{SSE}, and Z_{SSE} are selenocentric solar ecliptic coordinates. The numbered tick marks along the orbit designate the time in decimal fractions of the day.

The pertinent detector (*2*) is a totally depleted gold-silicon surface barrier one of effective thickness 19.6×10^{-4} cm and of frontal area 0.10 cm². The detector is shielded from sunlight by a nickel foil with an air equivalent thickness for alpha particles of 0.18 mg cm^{-2} and is fitted with a conical collimator with a half-vertex angle of 30°. Thus, the unidirectional geometric factor of the detector g is 0.079 cm² sr. Among the four electronic discrimination levels, the one that is appropriate to the present discussion is designated channel *P4*. This channel is insensitive to protons and electrons of any energy and detects with unit efficiency alpha particles in the energy range $2.0 \leq E_\alpha \leq 10.2$ Mev, a range well suited to the alpha particles from the radioactive decays noted above. The spacecraft rotates about its axis of maximum moment of inertia with a period of about 2.3 seconds. The spin axis of the spacecraft is pointed stably at the south ecliptic pole to within 7°. The axis of the detector is inclined 90° to the spin axis of the spacecraft. Hence, the detector's field of view sweeps across the moon once per rotation. Pulses from the detector are accumulated in a storage register for a period of 25.57 seconds (about ten rotations) during each 81.81 seconds, and the sum is then transmitted.

Let $\bar{\omega}$ denote the spin-averaged value of the solid angle ω subtended at the detector by that portion of the moon within its field of view at any one instant. The search for lunar-emitted alpha particles exploits the variation of $\bar{\omega}$ as the spacecraft moves in its elliptical orbit. A typical plot of the calculated value of $\bar{\omega}$ as a function of time is shown in Fig. 2.

The counting rate of channel *P4* is the sum of the contributions from three sources: (i) alpha particles (5.48 Mev) from an $_{95}Am^{241}$ source that is permanently mounted on the detector to provide an in-flight calibration of the proper operability of the detector and its associated electronics; (ii) solar-emitted alpha particles in interplanetary space and in the earth's magnetospheric tail in the energy range $2.0 \leq E_\alpha \leq 10.2$ Mev; and (iii) lunar-emitted alpha particles in the same energy range.

The radius of curvature of the trajectory of an alpha particle moving orthogonal to a magnetic field (the most highly curved case) of typical strength, say,

7×10^{-5} gauss, is 30,000 km for $E_\alpha = 2$ Mev and 50,000 km for $E_\alpha = 6$ Mev. For approximate purposes it is assumed that both solar- and lunar-emitted alpha particles travel in straight lines over the distances from the moon that are involved in the present experiment.

If we designate the respective contributions to the total counting rate R of detector *P4* made by the sources (i), (ii), and (iii) by R_1, R_2, and R_3, one may expect

$$R_1 = a, \text{ independent of } \varpi \quad (1)$$

$$R_2 = bg\,(1 - \varpi/\omega_0) \quad (2)$$

$$R_3 = \sigma\, g\, \varpi/\omega_0 \quad (3)$$

In Eq. 3, limb-brightening has been estimated to be a minor effect and has been neglected. In Eqs. 1, 2, and 3, a is the rate attributable to the calibration source, b is the unidirectional intensity of solar-emitted alpha particles in the vicinity of the moon (assumed to be isotropic, as is usually the case to $\pm$ 10 percent), and ω_0 is the solid angle of the detector or 0.84 sr.

Preliminary examination of early data from Explorer 35 showed σ to be very much less than the estimate of Kraner *et al.* Subsequent work has been devoted to improving the quantitative sensitivity of the observations.

The principal difficulty, apart from low statistical accuracy, is in the selection of periods of time during which interplanetary space is relatively free of solar-emitted alpha particles. We first plotted values of the counting rate R of channel *P4* averaged over periods of 3 hours against time for a continuous period of 364 days of observations (decimal day 207/1967 to day 205/1968). Tentative blocks of time during which the intensities of solar-emitted alpha particles were a minimum were selected by inspection. Then smaller subblocks of time were selected such that no counting rate averaged over a 3-hour period departed by more than 3 standard deviations from the composite mean.

In this way, data were assembled in two separate epochs as follows: epoch I included days 232.1 to 252.9/1967, 270.2 to 277.9/1967, and 285.1 to 291.8/1967 for a total of 35.2 days; epoch II included days 57.9 to 68.7/1968, 93.0 to 100.5/1968, 138.1 to 143.7/1968, 169.8 to 180.1/1968, and 182.0 to 188.8/1968 for a total of 41.0 days.

During each of the two epochs the observed data were assembled into a

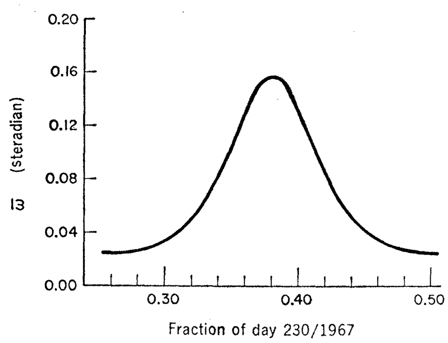


Fig. 2. A typical plot of the spin-averaged solid angle ϖ subtended at the detector by that portion of the moon within its field of view, as the spacecraft moves in its elliptical orbit. This case is referenced to the orbit of Fig. 1.

unified table in which mean counting rate R was plotted against ϖ in increments $\Delta\varpi$ equal to 0.0125 sr. These data were then represented by the weighted least-squares line:

$$R = A + B\varpi \quad (4)$$

According to Eqs. 1, 2, and 3

$$R = a + bg\,(1 - \varpi/\omega_0) + \sigma\, g\, \varpi/\omega_0 \quad (5)$$

Hence, the observational quantities A and B are related to the physical parameters as follows:

$$A = a + bg \quad (6)$$

$$B = (\sigma - b)\,(g/\omega_0) \quad (7)$$

and

$$A + B\,\omega_0 = a + \sigma\, g \quad (8)$$

The quantities g (0.079 cm^2 sr) and g/ω_0 (0.094 cm^2) are instrumental constants known to an accuracy of a few percent (*3*).

The best available preflight laboratory value of a is 0.0111 ± 0.0005 sec^{-1} (*3, 4*). The flight value of a is clearly less by at least 15 percent. The precise reason for this difference is not known. The $_{95}Am^{241}$ source was made intentionally a nonthin source in order to smear its alpha-particle spectrum and make the resulting rates of the several channels of the detector somewhat sensitive to effective discrimination levels. Despite considerable effort, the temperature compensation of the complete system was imperfect at the level of several percent over a temperature range of 30°C. Another possible reason for the disparity is inadvertent alpha-particle source contamination in the laboratory test chamber. Thus the precise value of a must be regarded as unknown. Hence, Eqs. 6, 7, and 8 provide only two independent relationships among three unknown quantities—the desired quantity σ and the two irrelevant quantities a and b.

Good estimates of a (or at least upper limits thereof) were obtained by finding the average value of R during several selected days within each of the two epochs such that the intensity of solar protons $0.48 \leq E_p \leq 3.0$ Mev (measured by a different channel of the same detector) divided by the typical ratio of protons to alpha particles as observed during high-intensity epochs suggested that b was probably less than 0.006 cm^{-2} sec^{-1} sr^{-1}. An overlapping check of simultaneous data from our similar equipment on earth-orbiting Explorer 33 (far from the moon) gave about the same result. The applicability of the ratio of protons to alpha particles during high-intensity epochs to low-intensity epochs is a reasonable but unproven physical assumption.

For epoch I a is less than or equal to 0.0093 ± 0.0003 sec^{-1}; for epoch II a is less than or equal to 0.0079 ± 0.0002 sec^{-1}.

The alpha-particle emissivity for epoch I was calculated as follows. The observed values of R as a function of ϖ are shown in Fig. 3.

$$A = 0.0106 \pm 0.0003 \text{ sec}^{-1} \quad (9a)$$

$$B = -0.0086 \pm 0.0035 \text{ sec}^{-1}\text{ sr}^{-1} \quad (9b)$$

If we use Eqs. 8 and 9 and $a = 0.0093 \pm 0.0003$ sec^{-1}, then

$$\sigma = (A + B\,\omega_0 - a)/g$$

$$\sigma = -0.0752 \pm 0.0377 \text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1} \quad (10)$$

If we use Eqs. 7 and 9b and $b = 0.0060$ cm^{-2} sec^{-1} sr^{-1}, then

$$\sigma = b + B\,\omega_0/g$$

$$\sigma = -0.0857 \pm 0.0374 \text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1} \quad (11)$$

The alpha-particle emissivity for epoch II was calculated as follows. The observed values of R as a function of ϖ are shown in Fig. 4.

$$A = 0.0089 \pm 0.0003 \text{ sec}^{-1} \quad (12a)$$

$$B = -0.0010 \pm 0.0034 \text{ sec}^{-1}\text{ sr}^{-1} \quad (12b)$$

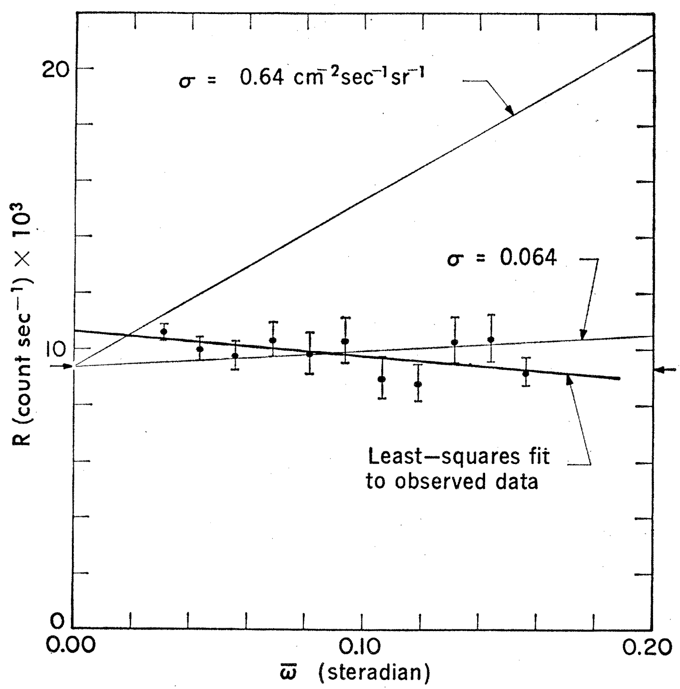
If we use Eqs. 8 and 12 and $a = 0.0079 \pm 0.0002$ sec^{-1}, then

$$\sigma = +0.0002 \pm 0.0366 \text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1} \quad (13)$$

If we use Eqs. 7 and 12b and $b = 0.0060$ cm^{-2} sec^{-1} sr^{-1}, then

$$\sigma = -0.0047 \pm 0.0363 \text{ cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1} \quad (14)$$

Physically, σ must be positive or zero. According to Eqs. 10 or 11, or both, for epoch I, the odds against σ



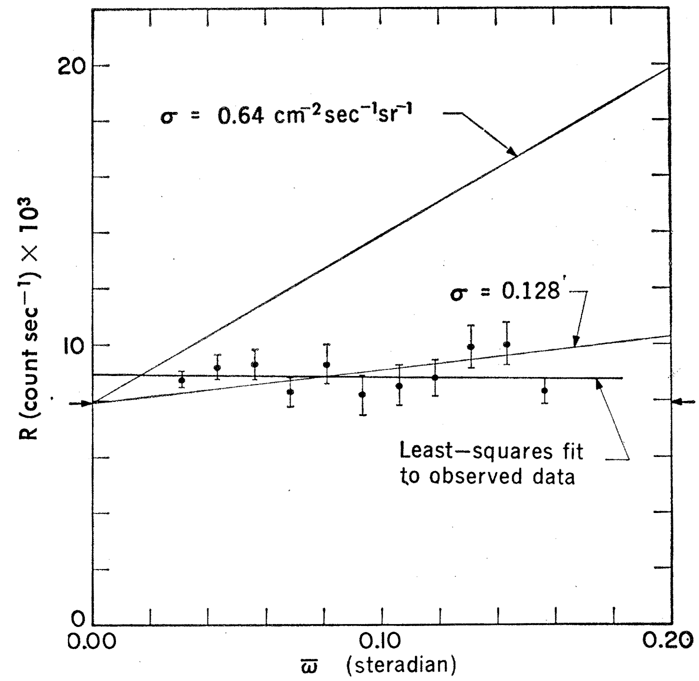


Fig. 3 (left). Observed values of the total counting rate R of detector *P4* (bar lengths indicate statistical standard deviations) as a function of ϖ for epoch I. Data are grouped in increments $\Delta\varpi$ equal to 0.0125 sr. The arrows on the vertical scale indicate the tentatively adopted value of a (0.0093 sec^{-1}). The dark line is the weighted least-squares fit to the data. Two auxiliary lines are shown. One represents the expected dependence of R on ϖ if $\sigma = 0.64$ cm^{-2} sec^{-1} sr^{-1} (Kraner's estimate), and the other, if $\sigma = 0.064$ (0.1 of Kraner's estimate); for both of these auxiliary lines, $a = 0.0093$ sec^{-1} and $b = 0$. Fig. 4 (right). Observed values of the total counting rate R of detector *P4* (bar lengths indicate statistical standard deviations) as a function of ϖ for epoch II. Data are grouped in increments $\Delta\varpi$ equal to 0.0125 sr. The arrows on the vertical scale indicate the tentatively adopted value of a (0.0079 sec^{-1}). The dark line is the weighted least-squares fit to the data. Two auxiliary lines are shown. One represents the expected dependence of R on ϖ if $\sigma = 0.64$ cm^{-2} sec^{-1} sr^{-1} (Kraner's estimate), and the other, if $\sigma = 0.128$ (0.2 of Kraner's estimate); for both of these auxiliary lines, $a = 0.0079$ sec^{-1} and $b = 0$.

being greater than zero are about 14 to 1. This is not an outrageous statistical possibility, but it does suggest that the adopted value of the solar-emitted alpha particle intensity b may have been too small and the corresponding value of a may have been too great. However, no combination of reasonably acceptable values for a and b raises σ above about -0.057 ± 0.036. Even this result corresponds to odds of 4 to 1 against σ being positive and 600 to 1 against σ being greater than 0.064 (0.1 of Kraner's estimate).

Equations 13 or 14, or both, are consistent with $\sigma = 0$ and provide odds of 6 to 1 against σ being greater than 0.064 (0.1 of Kraner's estimate) and 1500 to 1 against σ being greater than 0.128 (0.2 of Kraner's estimate).

Thus it is unlikely (Fig. 3 and 4) that σ is greater than 0.1 of Kraner's estimate and exceedingly unlikely that it is greater than 0.2 of Kraner's estimate.

Gold (*5*) has remarked that any gas in the lunar atmosphere, once ionized by solar ultraviolet radiation, by charge exchange, or by collisional ionization by the solar wind, will be immediately swept away by the moving magnetic field in the solar wind (that is, by the motional electric field). This process may very well be dominant in limiting the atmospheric density of stable gases. But for a radioactive gas ($_{86}Rn^{222}$) of half-life 3.8 days, our estimates for the lifetime against photo-ionization and Michel's estimates (*6*) for the lifetime against charge exchange and collisional ionization are both so great as to indicate that these processes are not important.

Hence, our result appears to require that the average abundance of $_{92}U^{238}$ (from which $_{86}Rn^{222}$ comes) in the outer crust of the moon is less than that in the accessible part of the earth's lithosphere (3 parts per million) (*7*) by a factor of the order of 10. It is, however, consistent with the abundance of $_{92}U^{238}$ in terrestrial basalt or in chondritic meteorites (0.6 ppm and 0.01 ppm, respectively) (*8*). The thickness of the lunar crust to which these inferences refer is that through which radon can diffuse during its lifetime, that is, a few meters (*9*). The result may or may not be applicable to the whole body of the moon.

Work on data from Explorer 35 is continuing with some prospect of improving the upper limit on σ reported here. An apparatus designed specifically for this purpose should have a much larger geometric factor, a weaker calibration source, and several different energy channels.

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References and Notes

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4. All numerical uncertainties given here are statistical standard deviations.
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10. The detector on which this work is based was developed and calibrated by Drs. T. P. Armstrong and S. M. Krimigis of this laboratory. Our work has been supported in part by NASA grant NGL 16-001-002 and by the U.S. Office of Naval Research contract Nonr 1509(06).

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