Primary Cosmic Rays on the Lunar Surface

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With no atmosphere or magnetic field, the Moon is an ideal object for investigation of the temporal variations of cosmic rays in the region of the Earth's orbit. Results are reported for determination of the galactic cosmic ray flux during various time intervals in the 1965–1972 period, on the basis of data from the instruments of a spacecraft that made a soft landing on the lunar surface, and from the radioactivity of samples returned by the spacecraft. During minimum solar activity (the second half of 1965 and the beginning of 1966) I_0 ($E > 30$ | MeV/nucleon) was determined to be 0.43 (± 10 percent) particles • cm^{-2} • s^{-1} • $ster^{-1}$. the mean flux in the 1967-1970 period was I_{av} ($E > 100$ MeV/nucleon) = 0.31 (± 20 percent) particles • cm^{-2} • s^{-1} • $ster^{-1}$. These values, within the error limits of the determinations, agree with the corresponding values of galactic cosmic ray intensities determined by stratospheric measurements.

The mean flux of galactic cosmic rays over the past million years is equal to I ($E > 100$ MeV/nucleon) = 0.28 (± 20 percent) particles • cm^{-2} • s^{-1} • $ster^{-1}$; this value agrees with the mean flux of modulated cosmic rays during the period of the nineteenth solar cycle.

The mean flux of solar protons between 1965 and 1972 was I_p ($E_p > 20$ MeV) = 2.46 $\left(\begin{matrix}+0.44\\-0.74\end{matrix}\right)$ protons • cm^{-2} • s^{-1} • $ster^{-1}$.

With no atmosphere or magnetic field, the Moon is an ideal object for the study of temporal variations in the modulated galactic cosmic rays of solar cosmic rays at a distance of 1 AU from the Sun. In combination with the data from meteorites with orbits of various sizes which struck the Earth at the same time that samples of lunar soil were taken, studies of the radioactivity of the surface layers of the Moon yield the most precise information on spatial variations in the galactic cosmic rays and allow us to refine the position of the upper boundary of the area of modulation (refs. 1–5). The first estimate of radioactivity on the surface of the Moon was made by an instrument on the Luna 9 spacecraft, which was launched 30 January 1966 (ref. 6). Detailed analysis of the radioactivity of lunar rocks was performed on the speciments taken by the Apollo 11 astronauts on July 17, 1969. These data (ref. 7) allowed the first precise estimate of the mean flux of solar protons over the past million years, indicating that it equaled the average contemporary flux (refs. 8 and 9).

The present article reports some results from studies of the temporal variations of cosmic rays using data on the radioactivity of cosmogenic Na^{22} and Al^{26} in lunar soil samples returned by the Luna 16 and Luna 20 automatic spacecraft, as well as data from the instruments of Luna 9 (ref. 6).

Variations in Galactic Cosmic Rays

The most precise data for the intensity of cosmic rays on the surface of the Moon during various intervals of time can be produced by recording radiation in various energy intervals with instruments on automatic spacecraft soft-landed on the surface. Such an experiment was performed by the Luna 9 spacecraft (ref. 6). The landing was performed on 3 February 1966 at 21:45:30 Moscow time. The spacecraft carried an instrument with an SBM–10 gas discharge counter with the following working dimensions: diameter 6 mm, length 10 mm. The minimum shielding of the counter was $\cong 1$ g/cm^2 aluminum. The instrument was turned on immediately after the station went into orbit and remained on throughout the life of the station. Data on the intensity of radiation were averaged over 14 time intervals (fig. 1). The first 5 relate to the area traversed during the flight of the spacecraft from the Earth to the Moon. The sixth interval relates to the period of flight near the Moon (beginning at a distance of about 50,000 km from the Moon), the landing, and the first 5 minutes the spacecraft was on the Moon. The last 8 intervals relate to the period of operation of the spacecraft on the lunar surface. After making corrections for geometric shielding of the Moon, the flux of particles of cosmic rays with energies of over

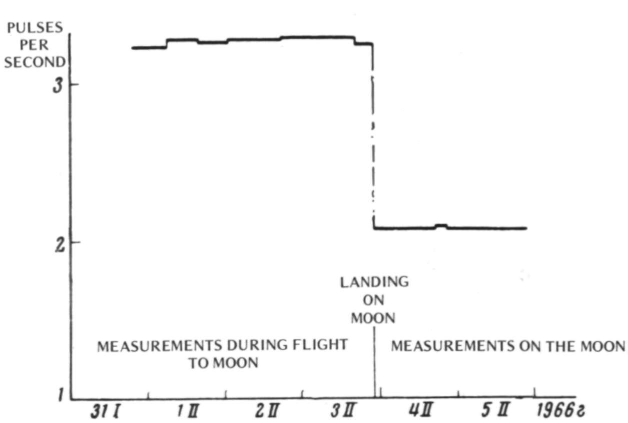

Figure 1.—*Mean counting rates of gas discharge counter of the Luna 9 spacecraft (ref. 8).*

30 MeV/nucleon was determined. Its value in space and on the lunar surface is $I(E > 30$ MeV/nucleon$) = 0.43$ particles · cm^{-2} · s^{-1} · ster^{-1} with an accuracy of 10 percent. This value corresponds to the flux of unmodulated galactic cosmic rays I_0 (E >100 MeV/nucleon) $= 0.41$ particles · cm^{-2} · s^{-1} · ster^{-1}, with an accuracy of $\pm$ 20 percent, determined from the Na^{22} activity in six chondrites which struck the earth during the nineteenth solar cycle (1959–1970) (ref. 1). Similar data (within the error limits) were produced by measurements in the region of the Moon's orbit by the Luna 7 and Luna 8 spacecraft on 4–8 October and 3–6 July 1965, respectively. Thus, the maximum intensity of cosmic rays in the region of the Earth occurred during the second half of 1965 and in January 1966, as measured on the lunar surface, in near Moon orbit, and also by stratospheric measurements (refs. 10 and 11). The intensity of galactic cosmic rays then decreased, in connection with the beginning of the twentieth cycle of solar activity. The delay of the activity maximum of galactic cosmic rays from the minimum of solar activity is about 1.5 years for protons with energies of over 30 MeV. This conclusion is also confirmed by data returned by the Zond 3, Venera 2, and Venera 3 interplanetary spacecraft (ref. 6).

The time which the Luna 7, 8, and 9 spacecraft spent on the surface of the Moon or in orbit near the Moon corresponded to the minimum of solar activity and, therefore, the instruments recorded only galactic cosmic radiation. In all other cases, the measurement corresponds to the integrated intensity of galactic and solar cosmic rays with their widely varying ratios. It is impossible to separate these components.

This possibility is provided by the lunar rocks taken from various depths below the surface, or from lunar regolith cores.

In order to detect the radioactive products of nuclear reactions caused by galactic components of the cosmic rays, we must study samples from a depth of over 10 cm below the lunar surface because theoretical calculations have shown (refs. 8 and 9) that at shallower depths the solar component is quite large.

Because of the small diameter of the drill used to take cores, the weight of the column of lunar soil causing the effect of decreasing radioisotope activity with depth is slight, 10–20 g (a few centimeters). A special apparatus was created to measure the activity of such small samples (ref. 12) and its effectiveness has been tested on meteorite specimens. Nondestructive testing of specimens was performed with a low-background γ scintillation spectrometer in the γ–γ coincidence mode, allowing simultaneous recording of Al^{26} and Na^{22}. The material to be studied, in cylindrical plexiglas cups, was placed between two low-background NaI(Tℓ) scintillators 120×100 mm in diameter. The background level was reduced by surrounding the NaI(Tℓ) crystals with an anticoincidence ring consisting of a plastic scintillator 500×600 mm in diameter and installing them in a massive shielding chamber with a wall thickness of 400–500 mm (300–400 mm steel + 100–150 mm of a mixture of paraffin with boric acid).

The measurement of activity of cosmogenic isotopes Al^{26} ($T_{1/2} = 7.4 \times 10^5$ years) and Na^{22} ($T_{1/2} = 2.6$ years) was performed in two specimens of regolith returned by the Luna 16 spacecraft; sample 1 weighed 18.87 g and was a mixture of soil from the surface layer to a depth of 13 cm; sample 2 weighed 10.396 g and was taken from a depth of 15–18 cm. A single 9.792-g specimen of regolith returned by Luna 20 was also tested and was a mixture of soils over the entire depth of the column (refs. 13 and 14). Measurements of the samples were alternated with measurements of the background in 5- to 11-hour cycles. Between cycles a Na^{22} control source in standard geometry was used to test the system, and amplifier drift was adjusted; the displacement of the photopeak at (511 + 1275) KeV did not exceed 1 percent over the duration of a full cycle. Background measurements were made with the use of specimens of powered dunite in the same quantities and packing as the lunar specimens. The spectrometer was calibrated by the use of moldings similar to the samples in size and weight but with known quantities of $Al^{26}Cl_3$ and $Na^{22}Cl$ distributed evenly through the volume (ref. 15). The characteristics of the method and results of measurements are presented in table 1.

In addition to the measured values of Al^{26} and Na^{22} activity in lunar specimens (solid crosses), figure 2 also shows the calculated curves for a depth distribution of these isotopes in the surface layers of cores of lunar soil returned by Luna 16 and Luna 20 down

Table 1.—*Characteristics and Results of Measurements of Radioactivity of Lunar Regolith Returned by Luna 16 and Luna 20 (refs. 15 and 16)*

Specimen	Luna 16 Specimen 1		Luna 16 Specimen 2		Luna 20	
Date of collection of soil from the lunar surface	20 Sept. 1970				22 Feb. 1972	
Weight of sample, g	18.87		10.396		9.792	
Distance from surface, cm	0–13		15–18		Mixed sample	
Measurement time, hours	200		250		500	
Isotope measured	Al^{26}	Na^{22}	Al^{26}	Na^{22}	Al^{26}	Na^{22}
Calculated photopeak, KeV	511+ 1830	511+ 1275	511+ 1830	511+ 1275	511+ 1830	511+ 1275
Background in photopeak, imp•hr^{-1}	0.35	0.84	0.38	0.95	0.31	0.63
Peak above background, imp•hr^{-1}	1.17	1.53	0.62	1.08	0.92	0.93
Effectiveness of recording, percent	1.4	2.3	1.6	2.85	2.21	2.95
Activity at moment of soil collection, events•min^{-1}•kg^{-1}	62 ± 8	42 ± 8	54 ± 9	48 ± 9	64 ± 5	43 ± 5

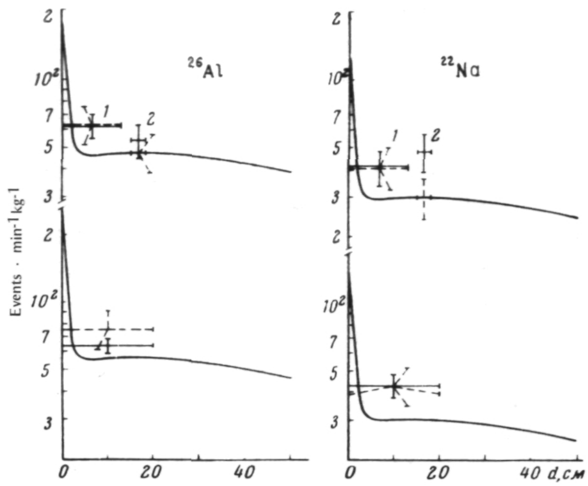

Figure 2.—*The depth distribution of Na^{22} and Al^{26} in the regolith cores returned by Luna 16 and Luna 20 (refs. 15, 16, and 17). Experimental values (solid crosses); theoretical values (dotted crosses). The curves produced considerable contribution of galactic and solar components of cosmic rays at various depths. Calculations were performed with data from stratospheric observations for the galactic component (refs. 21 and 22);* I_1 = *0.229 particles • cm^{-2} • s^{-1} • $ster^{-1}$ (mean value for 1967–1970) and* I_2 = *0.197 particles • cm^{-2} • s^{-1} • $ster^{-1}$ (mean value for 1968–1972) in agreement with the time of accumulation of Na^{22} in regolith samples returned by Luna 16 and Luna 20, respectively;* I_3 = *0.28 particles • cm^{-2} • s^{-1} • $ster^{-1}$ (mean value for nineteenth solar cycle) for Al^{26}. Figure shows value of the mean proton flux taken for the solar component* I_p = *2.46 protons • cm^{-2} • s^{-1} • $ster^{-1}$ (refs. 10 and 11).*

to a depth $d = 50$ cm, and the expected theoretical values of mean activity in the specimens analyzed (dotted-line crosses). The calculations were performed by the analytical method of Lavrukhina and Ustinova (ref. 16) and Lavrukhina et al. (ref. 17), whose effectiveness has been confirmed by many analyses of the radioactivity of meteorites (ref. 18), with consideration of differences in the chemical composition of the regolith (refs. 19 and 20). The elements from which cosmogenic Al^{22} and Na^{22} are primarily formed (Mg, Na, Al, Si, and Ca), are present in relatively large quantities in the Luna 20 regolith (for example, aluminum is 33 percent greater) in comparison with the Luna 16 regolith. This leads to differences in the weighted mean cross sections for the formation of these isotopes by various nuclear particles in the regoliths of both types (see fig. 2) and, consequently, two different levels of radioactivity when bombarded by identical fluxes of primary radiation. For example, at a depth of 50 cm the activity of Al^{26} in the Luna 20 regolith should be 1.2 times higher than in the Luna 16 regolith.

The activity of cosmogenic isotopes in the layer of the Luna 16 core between 15 and 18 cm from the surface can serve as an indicator of the intensity of galactic cosmic rays, because the depth effects and the activity induced by the solar component in this layer are negligible (less than 1 percent; see fig. 2). Considering the corrections for possible admixture of surface layers, the measured values of Al^{26} and Na^{22} activity in sample 2 of the Luna 16 core corresponds to the following values of mean intensity of galactic cosmic rays in the orbit of the Earth. The mean flux over the past million years (according to 1.5 $T_{1/2}$) for Al^{26} is $I_1(E > 100$ MeV/nucleon$) = 0.28$ particles · cm^{-2} · s^{-1} · $ster^{-1}$, which corresponds to the mean value for the flux of modulated galactic cosmic rays measured in the stratosphere of the Earth between 1958 and 1969 (refs. 10, 21 and 22), and proves the constancy of the mean intensity of galactic cosmic rays at least over the past million years. The mean flux during the period 1967–1970 (according to data for Na^{22}) was $I_2(E > 100$ MeV/nucleon$) = 0.31$ particles · cm^{-2} · s^{-1} · $ster^{-1}$. This last quantity is somewhat greater than the mean intensity of galactic cosmic rays for these years, according to the data from stratosphere measurements. This divergence apparently reflects an increase in the intensity of cosmic rays due to solar protons emitted during solar flares, since the maximum number of flares of the twentieth solar cycle occurred during this time. In this case, the fraction of Na^{22} activity formed in the surface layers of sample 2 should be significantly higher than that for Al^{26}, whose activity reflects the intensity of cosmic rays averaged over many solar cycles.

The Intensity of Solar Cosmic Rays

Low-energy solar cosmic rays cause radioactivity only in the near-surface layers of the lunar regolith, about 4 cm deep. The depth distribution of cosmogenic isotopes in this thin layer is characterized by a sharp drop in activity (by 4 to 5 times) in comparison with the surface activity (see fig. 2).

The mean flux of solar cosmic rays $I_p(E > 20 \text{ MeV}) = 2.46\left(\frac{+0.44}{-0.74}\right)$ protons $\cdot$ cm^{-2} $\cdot$ s^{-1} $\cdot$ ster^{-1}, a figure first obtained (refs. 10 and 11) on the basis of data from the analysis of the activity of Na^{22} in specimen 10017, which was removed from irradiation in July of 1969 by the Apollo 11 crew (ref. 7), and represents the mean flux between July 1965 and July 1969. The agreement of the values of Na^{22} activity in the samples returned by Luna 16 (sample 1) and Luna 20, calculated on the basis of this flux and the actual measured values (see fig. 2) indicates that the mean intensity of solar cosmic rays, within the limits of these errors, was identical from July 1965 through July 1969, from September 1966 through September 1970, and from February 1968 through February 1972. Consequently, the upper value of the integral intensity of solar protons apparently characterizes the "thickness" of the background of solar protons, whereas the measurement apparatus installed on the spacecraft records bursts of intensity above this background during flares (ref. 16).

Lunar samples provide a unique possibility for the study of long-term cosmic ray variations. Interest in this problem has recently increased in connection with the difficulties that have arisen in the neutron physics of the Sun. Several hypotheses have been suggested to eliminate these difficulties. One of the most common is the idea of the periodic convection of solar matter with a period of several hundreds of millions of years (ref. 23). The last minimum was about 3 million years ago. One result of this should be variations in solar activity and, apparently, the intensity of solar cosmic rays. Detailed investigation of the content of the radioactive isotopes with long half-life (Al^{26}, Mn^{53}, and K^{40}) in specimens taken at various depths from the lunar surface is of great interest in this aspect.

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