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VARIATION OF GALACTIC COSMIC RAY FLUX DEDUCED FROM ^{22}Na—^{26}Al DATA IN SAMPLES BROUGHT TO THE EARTH BY THE SOVIET AUTOMATIC STATIONS LUNA[1])

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The aim of the research was to determine the content of cosmogenic and primordial radionuclides in lunar samples brought to the Earth by the Soviet automatic space probes of the Luna. The experimental concentrations of cosmogenic radionuclides ^{22}Na and ^{26}Al are compared with theoretical production rates in the lunar regolith as obtained by various methods of calculation.

ВАРИАЦИИ ПОТОКА ГАЛАКТИЧЕСКИХ КОСМИЧЕСКИХ ЛУЧЕЙ НА ОСНОВЕ ДАННЫХ О ^{22}Na—^{26}Al В ОБРАЗЦАХ, КОТОРЫЕ ДОСТАВЛЕНЫ НА ЗЕМЛЮ СОВЕТСКИМИ АВТОМАТИЧЕСКИМИ СТАНЦИЯМИ «ЛУНА»

Цель данного исследования состояла в определении содержания космогонических и древних радионуклидов в образцах лунного грунта, доставленных на Землю советскими автоматическими космическими зондами «Луна». Экспериментальные концентрации космогонических радионуклидов ^{22}Na и ^{26}Al сравнивались с теоретической скоростью образования частиц в лунном реголите, которые были получены при помощи различных методов вычисления.

I. INTRODUCTION

The start of the first Soviet automatic space probe in October 4, 1957 put the cosmic research on a new and qualitatively higher level. There arose new possibilities of the study of cosmic bodies. On the other hand, a great amount of information has been obtained by space probes, which studied the Moon from their own orbits or right from the Moon's surface after a successful landing [1]. However, the most interesting information about the Moon has been obtained from lunar samples returned to the Earth by the lunar expedition Apollo and the lunar unmanned Soviet probes Luna. These samples have been investigated in many laboratories and the obtained results have important implications on the Moon's history and on the exposure conditions of the Moon's surface [2].

It is common knowledge that radioactive elements play a prominent role in the history of a planetary body. The study of the distribution of radioactive elements in various cosmic bodies seems to be a possible way to establish new ideas about the history and the present stay of our Solar system.

It is possible to suppose that in an early age of our Solar system radioactive elements were homogeneously distributed in prestellar matter. At present K, Th, U are the dominant sources of radioactivity in cosmic bodies owing to their very long half-lives. However, primordial radionuclides from only part of the radioactivity of the lunar surface. The surface layers of cosmic bodies contain also radioactive nuclides, which are products of interactions of high energy cosmic ray particles with the elements present in the cosmic bodies. This group of radioactive nuclides is usually called cosmogenic radionuclides.

It is important that the Moon is the only planetary body whose surface is not screened by its own atmosphere. Therefore the lunar samples are targets containing a record of the primary cosmic-ray bombardment to which they have been subjected. Thus it should be possible to obtain from them information on the past intensity of cosmic radiation [7]. Among the most interesting samples taken during the lunar expeditions for the study of possible long term variations of galactic cosmic rays (GCR) are the deep drill core samples. Some of the drill cores penetrated the regolith to depths below 2 m and include the area where the secondary flux of GCR is fully developed. The deep core samples contain cosmogenic radionuclides which are produced entirely by the GCR particles with no solar flux contribution and thus permit the long term characteristics of intensity of the GCR flux to be determined over a time period of a few half-lives of the cosmogenic radionuclides which are being investigated.

The present paper deals with the investigation of the radioactivity of primordial and cosmogenic radionuclides in samples brought to the Earth by three unmanned Soviet lunar stations Luna 16, 20 and 24, which were kindly made available to our laboratory by the USSR Academy of Sciences.

All these samples are of special interest because they have given new information from three typical Moon's surface regions [3—5]. To make conclusions from the obtained content of cosmogenic radionuclides in lunar samples we performed many calculations of the depth dependence of the production rates of cosmogenic radionucledes.

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II. EXPERIMENTAL TECHNIQUES

A high sensitive beta-gamma-gamma coincidence spectrometer was used for measurement of the ^{22}Na and ^{26}Al content in lunar samples. The beta-gamma-gamma coincidence mode of operation has been found to be the most sensitive method. The detection limit of this spectrometer is more than a factor of 10 lower than for the gamma-gamma spectrometer and more than a factor of 100 lower than for the single gamma-ray spectrometer [12].

The gamma-spectrum was accumulated in a 4096 channel analyser ICA-70, measured and stored in 4 quarts. Simultaneously the coincidence as well as the single spectrum were taken. Radioactivity calculation was performed using the counting rates under the characteristic and the summation peaks of ^{22}Na and ^{26}Al.

III. METHODS OF CALCULATION

There are several ways of description of the interactions of cosmic ray particles with the Moon. The basic difference among various methods of the sampling of these processes is only in the range of simplifications which one uses to describe the transport of primary and secondary energy particles in the target material. The models used in our calculations are based on a semiempirical description of the cascade of nuclear active particles in the target material and they have one thing in common: contributions to the production rates of cosmogenic nuclides from galactic and solar cosmic rays are calculated separately. This is because the processes which originate due to the bombardment of GCR or SCR are different owing to different energy spectra of the incident particles.

The production rates of ^{22}Na and ^{26}Al are calculated by using the model of Reedy and Arnold [8]. The models of Lavrukhina and Ustinova [10] and Yokoyama et al. [9] are also used to compare the obtained values of the production rates.

IV. RESULTS AND DISCUSSION

The set of the obtained values of the content of primordial and cosmogenic radionuclides in lunar samples is presented in Tab. 1. Unfortunately there was no possibility to determine precise values of the abundance of primordial radionuclides in all available samples because of their small amount (~50 mg in weight). The obtained values of concentration of primordial radionuclides within the errors are in a good agreement with previous measured values for lunar samples from Luna and Apollo lunar missions [13].

The comparison of the measured concentrations of ^{22}Na and ^{26}Al in the lunar regolith from Luna 16 samples with calculated depth profiles of the production rates of these nuclides is shown in Fig. 1. The chemical composition of the investigated samples is taken from [3]. The theoretical values were obtained by using the model of Reedy and Arnold [8]. The values of cross-sections have been used from [8, 14].

Table 1

Counting results

Sample	^{22}Na	^{26}Al	U	Th	K
	$s^{-1}kg^{-1}$		ppm		%
Luna 16—1	0.67 ± 0.35	1.00 ± 0.42	<5	<20	0.08 ± 0.03
Luna 16—2*	0.80 ± 0.33	1.32 ± 0.33	0.6 ± 0.3	1.2 ± 0.7	0.10 ± 0.03
Luna 20	0.75 ± 0.38	1.20 ± 0.35	<1.7	<3.5	0.12 ± 0.05
24118.4—4	0.61 ± 0.38	0.85 ± 0.55	<5	<20	0.10 ± 0.08
24143.4—4	0.40 ± 0.27	0.45 ± 0.22	<5	<20	
24184.4—4	0.18 ± 0.11	0.42 ± 0.17	<5	<20	

Counting results
* — dry fraction

As we see the depth dependence of the production rates has a characteristic shape. In the depths below 10 gcm^{-2}, where the contribution from SCR is dominant, we see a sharp decrease of the production rate with depth. In these depths the cascade of nuclear active particles due to the bombardment by GCR particles is not fully developed. The flux of primary SCR which are the main cause of the production rate of cosmogenic radionuclides at these depths is rapidly decreasing owing to the ionization energy losses of solar protons. For deeper layers the contribution to the production rates from GCR becomes dominant and increases to the depth around 40 gcm^{-2} along with the increase of the number of nuclear active particles in the cascade. For greater depths the production rate decreases with the mean free attenuation path of particles present in the cascade (Fig. 3).

The best fit for the experimental values of the Luna 16 samples has been obtained by using the primary GCR flux of 1.7 protons cm^{-2}s^{-1} with the mean energy $E > 1$ GeV, and the 4π flux of primary solar protons $J =$ 80 protons.cm^{-2}s^{-1} with the energy $E > 10$ MeV and the mean rigidity $R_0 =$ 100 MV. In the depths of our experimental points the production of cosmogenic radionuclides becomes mainly due to GCR. A good agreement between the theoretical and the experimental values of the GCR production rates, within the errors, indicates that the GCR flux during the last 1—2 million years has been constant within ±30 % and it is practically the same as the average present day flux of GCR.

Fig. 2 shows concentrations of ^{22}Na and ^{26}Al in a sample from the Luna 20 regolith together with calculated values of the production rates. As reported by Vinogradov [4] the stratigraphy of this sample had been disturbed, therefore the experimental values are only average concentrations of ^{22}Na and ^{26}Al [15]. For the calculation of the production rates by means of the Reedy and Arnold model we used the same parameters of the incident cosmic ray flux as for the Luna 16 samples. The mean chemical composition of the Luna 20 regolith was taken from [4].

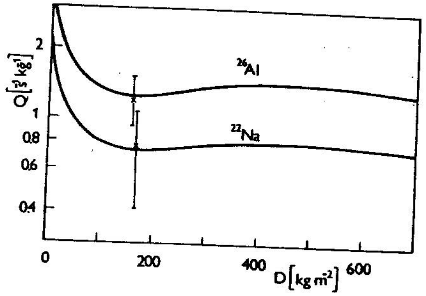

Fig. 1. ^{22}Na and ^{26}Al activities of Luna 16 fines together with theoretical profiles calculated with the Reedy and Arnold model.

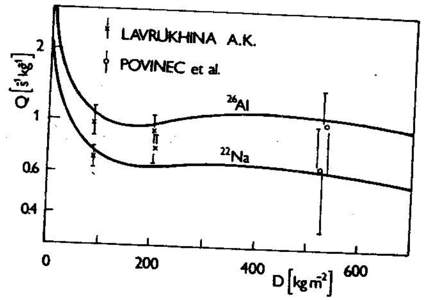

Fig. 2. ^{22}Na and ^{26}Al activities of Luna 20 fines as function of depth together with theoretical profiles calculated with the Reedy and Arnold model.

In Figs. 3 and 4 the activities of ^{22}Na and ^{26}Al in the Luna 24 samples are plotted together with theoretical values of production rates calculated by using all the three methods of calculation. The chemical composition used in calculations was taken from [16]. We used the same parameters of the Reedy and Arnold method for calculations of the production rates of ^{22}Na and ^{26}Al in Luna 24 samples as those used for the Luna 16 samples. The long term GCR flux of 0.24 particles . cm^{-2}s^{-1} with $R > 0.5$ GV was used in our calculation of the contribution to the production rate from the GCR bombardment using the Lavrukhina and Ustinova method for ^{26}Al and the average intensity of GCR during the last solar cycle was taken as 0.31 particles . cm^{-2}s^{-1}sr^{-1} with $R > 0.5$ GV for ^{22}Na. The average intensity of SCR was taken as 2.4 protons . cm^{-2}s^{-1}sr^{-1} with $E > 20$ MeV [10].

The mean value of the 2π isotropic primary GCR flux was taken 2.5 nucleons . cm^{-2}s^{-1} with the mean energy of 3 GeV in the third used model of calculation. In the calculation of the contribution to the production rate from the solar proton bombardment the incident flux of primary protons was normalized to the values reported in [8] as the average value of the solar proton flux during the last solar cycle.

For the comparison of the theoretical values of the production rates of ^{22}Na and ^{26}Al with the measured activities it is very important to know the actual depth of the investigated samples on the lunar surface. The sample numbers are correlated with the position of the sample in the core and are commonly composed of six digits [5]. The first two digits correspond to the number of the Luna 24 space probe and the next three digits indicate the depth of sampling along the core. In this case, the zero level is the place where the dust traces on the soil tube were observed. In this way, though, the depth designation is not quite correct. As presented in [17] we used in our calculation as the zero level the mark 64 cm, in agreement with a measurement of the depth profile distribution of ^{21}Ne [11]. In the paper presented by Surkov et al. [9] the mark of 73 cm below the conventional zero level was taken as the true zero level. In this work, however, as the true level that distance was considered below which the soil carrier was fully filled by lunar material. They did not take into account the part of the column which was only slightly dusted.

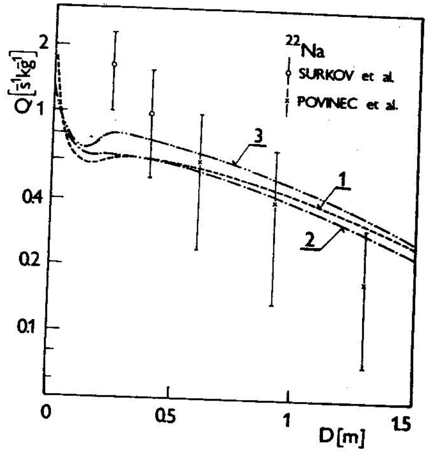

Fig. 3. ^{22}Na activities of Luna 24 core samples as function of depth together with theoretical profiles calculated with the Reedy and Arnold model (curve 1), the Lavrukhina and Ustinova model (curve 2) and with the YSRG model (curve 3).

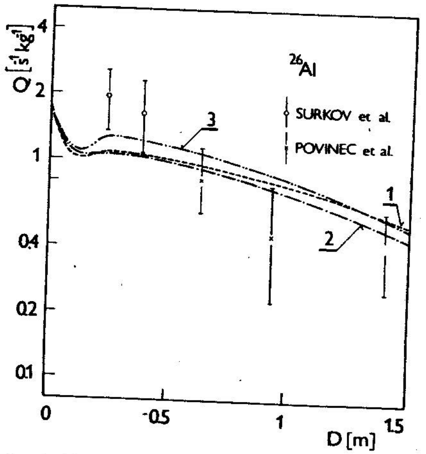

Fig. 4. ^{26}Al activities of Luna 24 core samples as function of depth together with theoretical profiles calculated with the Reedy and Arnold model (curve 1). The Lavrukhina and Ustinova model (curve 2) and with the YSRG model (curve 3).

It can be seen from Figs. 3 and 4 that a reasonable compromise has been obtained between the theoretical and the experimental values (if we take into account possible deviations of theoretical as well as experimental results).

From comparison of ^{26}Al in Fig. 4 we obtain that the average GCR of 0.24 particles . cm^{-2}s^{-1}sr^{-1} with $R > 0.5$ GV has been constant during the last million years within ±25 %.

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