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INVESTIGATION OF X-RADIATION OF THE MOON BY MEANS OF THE LUNAR SATELLITE "LUNA-10"

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In this paper are given the calculations of intensity of characteristic fluorescent lines of silicon, aluminum and magnesium in the content of the surface layer of lunar rock formations, stimulated by the X-radiation of the Sun. Instrumentation installed on the satellite of the Moon "Luna-10" and used for the experimental discovery of X-radiation of the Moon is described. This paper includes the results of measurements in course of which the level of the cosmic background in the vicinity of the Moon was determined and electrons of the "tail" of the Earth's magnetosphere with an energy of more than 40 kev. have been discovered. Preliminary data on the registration of X-radiation is given.

INTRODUCTION

Several papers dedicated to the X-radiation of the Moon have been published recently. The papers (Ref. 1-4) conduct a theoretical examination of this problem, the paper (Ref. 5) makes an attempt to discover experimentally radiation by means of instruments, installed on rockets, which yielded negative results.

X-radiation of the Moon might occur in result of the following basic processes: reradiation and dispersion by the lunar surface of X-rays from the Sun, bombardment of the lunar surface by fast particles which might be included in the content of "a solar wind," and also electrons contained in the tail of the Earth's magnetosphere. It is also possible to anticipate X-radiation of the lunar surface caused as a result of natural radioactive lunar formations and induced radioactivity from cosmic rays. The evaluation shows that, with an exclusion of cases of particularly sharp increases in

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the flux of fast electrons of terrestrial or solar origin, the largest contribution to the X-radiation of the Moon is apparently made by the X-radiation fluorescence of lunar formations in the characteristic lines of K_α - Si, Al and Mg, which occurs due to the influence of X-radiation of the Sun.

The atoms of Si, Al, Mg absorb solar X-radiation with a wavelength shorter than the K_α-edges of absorption, which compose respectively λ_{sh} = 6.7, 7.9 and 9.4 Å and re-emit it in the characteristic lines of Siλ = 7.11 Å, Alλ = 8.3 Å and Mgλ = 9.87 Å. The contribution of lines of heavier elements to the overall radiation is very low, since the intensity of solar X-radiation with a wavelength shorter than 5-6 Å is extremely small (in the absence of solar eruptions); the contribution by lighter elements is also very small due to the low contents of these elements in the lunar rock formations.

Figure 1 presents schematically the distribution of a number of photons in the solar spectrum within a region shorter than 10 Å in the case of a quiet Sun and a mean level of solar activity (Ref. 6), as well as the position of characteristic lines of Si, Al, and Mg and the respective regions of absorption.

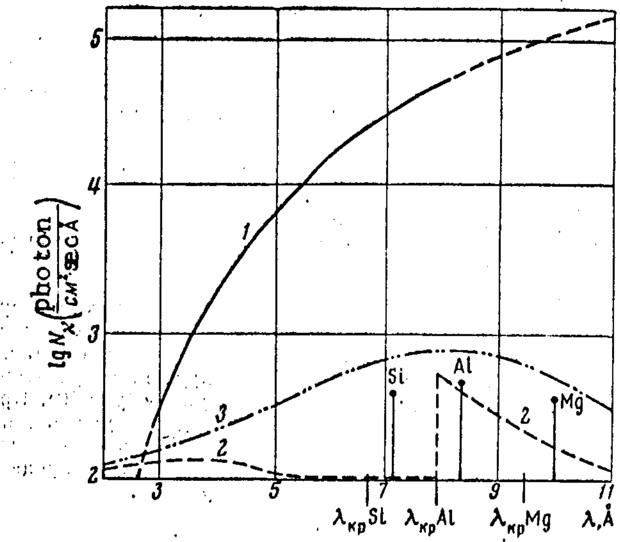

Figure 1. Experimental distribution of the number of photons in the X-ray spectrum of the Sun for July 21, 1959. (Ref. 6) (1); region of sensitivity of counters with aluminum (2) and organic (3) windows. The position of the characteristic lines and λ_{sh}-regions of absorption Si, Al and Mg is shown schematically.

Let us evaluate the anticipated number of photons within the radiation of the characteristic line of the element Z (See, for instance, Ref. 7). We will define by N_{sh} the flux of photons from the Sun with a wavelength of $\lambda < \lambda_{sh}$, which falls during one second on one square centimeter of the lunar surface. The number of photons reaching the depth ℓ will be

$$N = N_{sh} \cos\varphi e^{-\mu l/\cos\varphi},$$

where φ is the angle of incidence, μ is the linear coefficient of absorption. The number of photons absorbed by the layer $d\ell$ will be

$$dN = N_{sh}\tau e^{-\mu l/\cos\varphi} dl,$$

where τ is the coefficient of the true absorption. By defining the coefficient of fluorescence escape by w, the weight concentration of atoms of the given element Z in the rock formation by k_z and by P, the respective probability of transition for the given line, we will obtain the number of emitted photons with a wavelength λ

$$dN_\lambda = Pwk_Z N_{sh}\tau e^{-\mu l/\cos\varphi} dl.$$

The following number of photons will leave in a direction of Ψ, per unit of the solid angle

$$N_\lambda = N_{sh}\frac{Pwk_Z\tau}{4\pi}\int_0^\infty e^{-\mu l\left(\frac{1}{\cos\varphi}+\frac{1}{\cos\psi}\right)} dl.$$

Assuming, for instance, that in the case of Al: $N_{sh} \approx 1\cdot10^5$ photon/square centimeters • sec (high level of solar activity), $k_{Al} \approx 0.1$, $\tau \approx \mu$, $P \approx 1$, $w \approx 3\cdot10^{-2}$ and $\cos\varphi \approx \cos\psi \approx 1$, we obtain $N_\lambda \approx 10$ photon/square centimeters • sec • sterad. Such a number of photons might be reliably recorded by a lunar satellite with the help of, for instance, a photon counter.

The contents of elements of Si, Al and Mg in rock formation on Earth, an analogy of which might be anticipated on the Moon, changes very significantly (See table [Ref. 8], in which the content of elements in percent and the ratio of these contents is given).

Table

element	type of rock form.			
	rock meteor.	dunites	basalt	granit
Mg	14,0	26,0	4,5	2,2
Al	1,3	0,45	8,8	7,7
Si	18,0	19,0	24,0	32,3
Mg/Si	0,8	1,3	0,2	0,07
Al/Si	0,07	0,02	0,3	0,24
Mg/Al	11	55	0,51	0,22

Thus, by measuring the respective contents of the elements Mg, Al and Si, it is possible to get some idea about the character of lunar rock formations and in principle to prepare a map of the distribution of rock formations on the surface of the Moon.

In addition, the discovery of X-radiation of the Moon represents an interest independently, particularly on the part of the characteristic of the radiation background on the surface of the Moon.

These ideas formed the foundation for the experiment on the discovery of X-radiation of the Moon with the help of the first artificial satellite of the Moon "Luna-10". The purpose of this paper is to describe the instrumentation and the preliminary results of this experiment.

INSTRUMENTATION

In the capacity of radiation receivers served photon geiger counters with a neon-oxygen quenching mixture and two types of windows: aluminum foil with a mass of 2.7 mg/square centimeters and organic film with a mass of 1.1 mg/square centimeters. The area of the window was about 0.5 square centimeters; the field of vision was about 1 sterad.*

The areas of sensitivity of both types of counters are presented schematically in Figure 1; the counter with the organic window is sensitive to lines of Si, Al and Mg, the counter with the aluminum window is sensitive to the lines of Al and Mg. The counters were assembled in three units and

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*The counters were developed by L. S. Sorokin, V. G. Chaykovskiy, and A. B. Dmitriyev, to whom the authors of this paper extend their gratitude.

installed on the external surface of the satellite, as is shown schematically in Figure 2. Each unit included also a solar sensor (a silicon photoconverter). Pulses from the counters with aluminum windows were registered by three separate logarithmic integrals with a measurement range for the speed of count from 5 - 500 pulses per second; the time constant of the integrators was about 10 seconds.

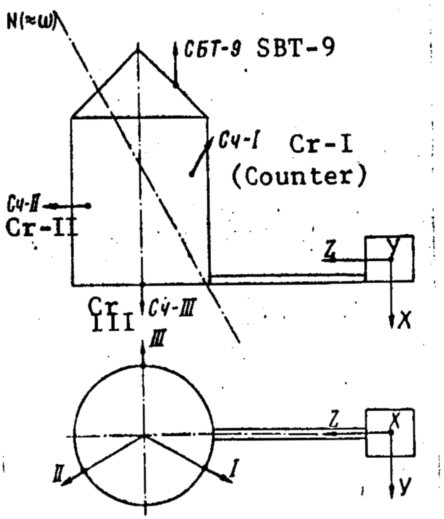


Figure 2. Direction of optical axis of the X-ray instrument indicators (Cr-I, Cr-II, Cr-III), the particles counter SBT-9 and the direction of the X, Y, Z axes of the ferrozondal indicators of the artificial satellite of the Moon "Luna-10".

Another such integrator registered the readings of three counters with organic windows which were connected on a parallel to each other. Each of the four integrators was carried out to a telemetry channel. The signals of the three solar sensors, which were also connected parallel to each other, were fed, after amplification, to the output cascade with a time constant of about one second. The readings of this cascade were registered along two telemetry channels (in order to decrease the time between the subsequent interrogations). The output voltage of this cascade was inversely proportional to the luminescence of the photodetectors; the zero value U_{out} corresponded approximately to the direction toward the Sun of each of these photodetectors.

The telemetry system interrogated each of the outputs of the measurement channels of this instrument once every two minutes with a shift of twelve seconds.

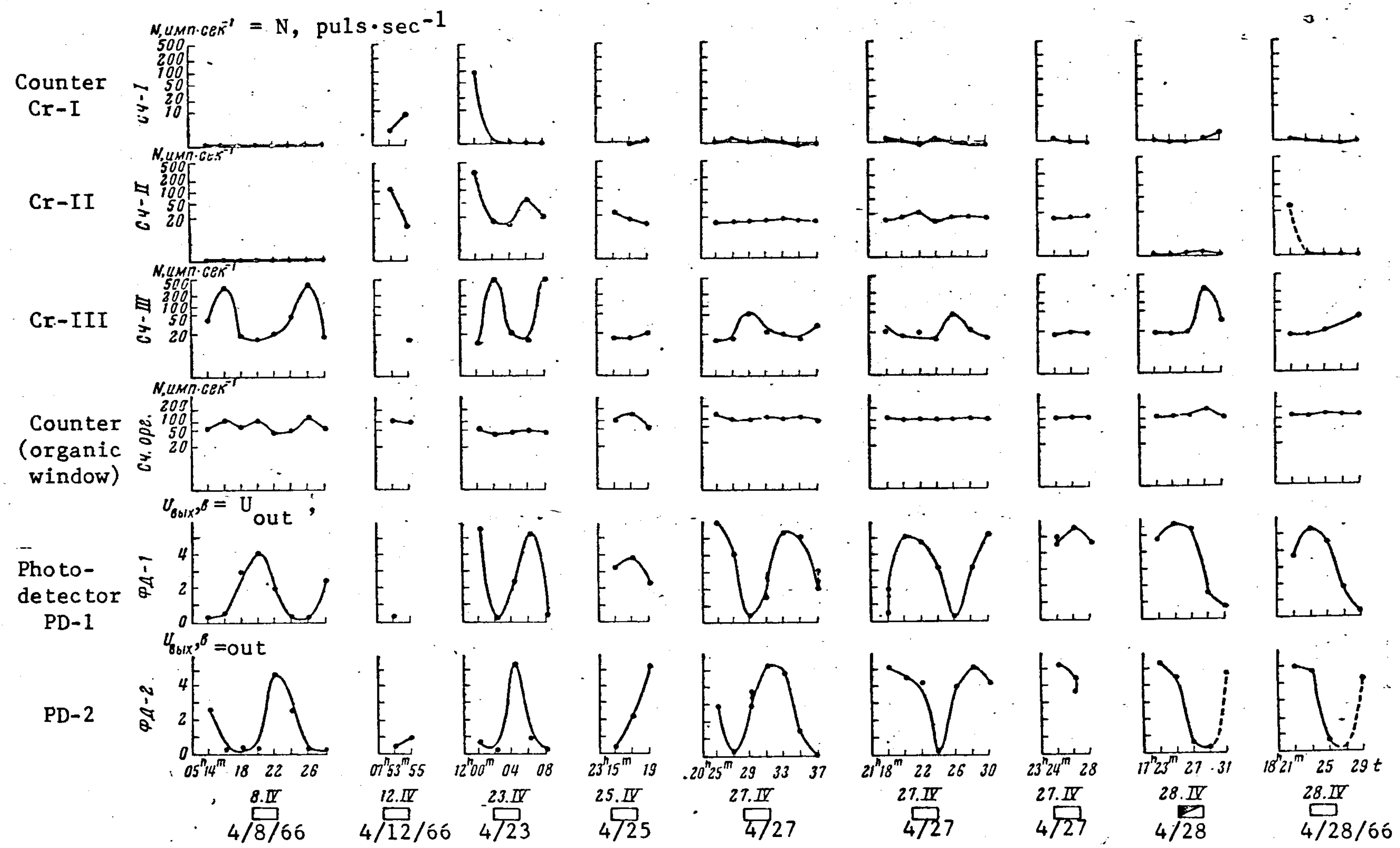
MEASUREMENT RESULTS

The instrumentation was activated by command from Earth during the period from April 8 - May 29, 1966. A total of more than 40 telemetry-measurement sessions has been conducted during that period of time. During the period between April 8 - May 23 - 29 of 1966, the level of solar activity was extremely high, and during the early part of May, the level of activity was considerably lower.

The measurement results are presented in Figure 3. It is necessary to keep in mind the following during the examination of these results. According to the measurements of the intensity of radio signals from the satellite's transmitter, the magnetometer readings, and our indicators, the disoriented satellite rotated with a period of 30 - 40 seconds. The position of the momentum vector in respect to the axis of the satellite and in space has not yet been established. However, based on the results of magnetic measurements, it is possible to make the following assumption. During the period between April 8 and April 21, 1966, the component of the magnetic field on the X-axis remained positive during the entire period of time, the Z component remained negative, and the Y component was of an alternating character. From this it follows that the momentum vector (and the axis of rotation of the satellite close to it) was close to direction of the magnetic field and was located approximately within the plane of the drawing shown in Figure 2, passing through the second and fourth quadrants. If we assume that the registered magnetic field is basically of a solar origin, then the direction of the field should be close to the direction toward the Sun, whereby the vector of intensity of the field was directed toward the Sun. Thus, the Sun has been apparently located in the fourth quadrant (Figure 2). Taking into consideration the fact that the time interval between the two interrogations of the telemetry system comprised two minutes and the period of rotation of the satellite was 30 - 40 seconds, we find that the results of the registration of the counters, as given in Figure 3, contain a considerable stroboscopic effect, thanks to which the observed period is much larger than the actual period of rotation.

By taking into consideration these data during the analysis of the results of recordings, we arrive at the following conclusions. Modulated signals from the counter III during the period from April 8 - 28 are apparently of a solar origin; this fact is confirmed by the readings of the photodetectors. The minimal readings of the counters correspond to the cosmic background of $\sim$ 12 pulses per second.

The counters I and II could see the lunar surface. The counter I gave the speed of count below the level of the cosmic background, with the exception of several measurement sessions. This could be, if the counter was subjected to a very high load;--according to laboratory measurements at a temperature of about 20° - 30° C., this comprised $\sim 10^5$ pulses per second. If, however, we take into consideration the fact that the counter and the semiconductive elements of the input device were overloaded, then such a situation might occur at considerably lower speeds of count, for instance, at a temperature of about 70° - 80° C. at $\sim 10^3$ pulses per second. It is most probable, however, that as a result of the increased temperature of the counter and the semiconductive elements of the input device, the amplitude of the pulses was insufficient for a stable count. Incomprehensible remains so far the separate points in the readings of this counter, which correspond to a speed of count $\sim$ 500 pulses per square centimeter per second. In certain cases, the counters II and III registered during this period of time only the cosmic background, i.e., the agent which was registered by the counter I is of a directional character. Apparently all of this is not the X-radiation of the Moon: Against such an assumption testifies the circumstance that these readings of the counter I were taken when the satellite was located over the illuminated as well as dark sides of the Moon. We are unable at the present time to give an interpretation of the readings of this counter.


N, имп·сек⁻¹ = N, puls·sec⁻¹
Counter Cr-I
СЧ-I
Cr-II
СЧ-II
Cr-III
СЧ-III
Counter (organic window)
СЧ. орг.
500
200
100
50
20
10
U вых, в = U out
Photo-detector PD-1
ФД-1
U вых, в = out
PD-2
ФД-2
4
2
0
05h14m 18 22 26
8.IV
4/8/66
07h53m 55
12.IV
4/12/66
12h00m 04 08
23.IV
4/23
23h15m 19
25.IV
4/25
20h25m 29 33 37
27.IV
4/27
21h18m 22 26 30
27.IV
4/27
23h24m 28
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4/27
17h23m 27 31
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28.IV
4/28/66

Fig. 3.

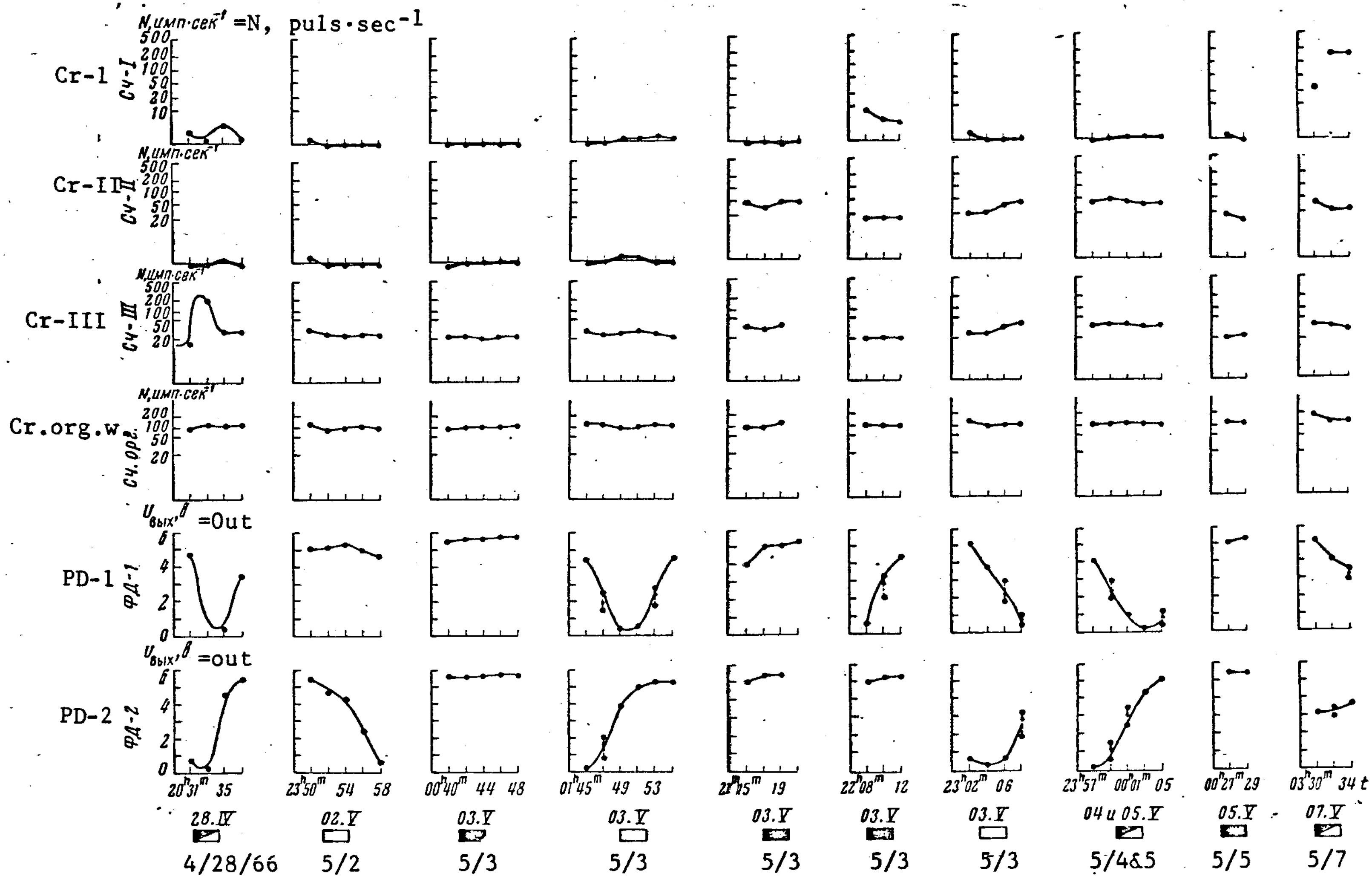

Fig. 3. (continuation)

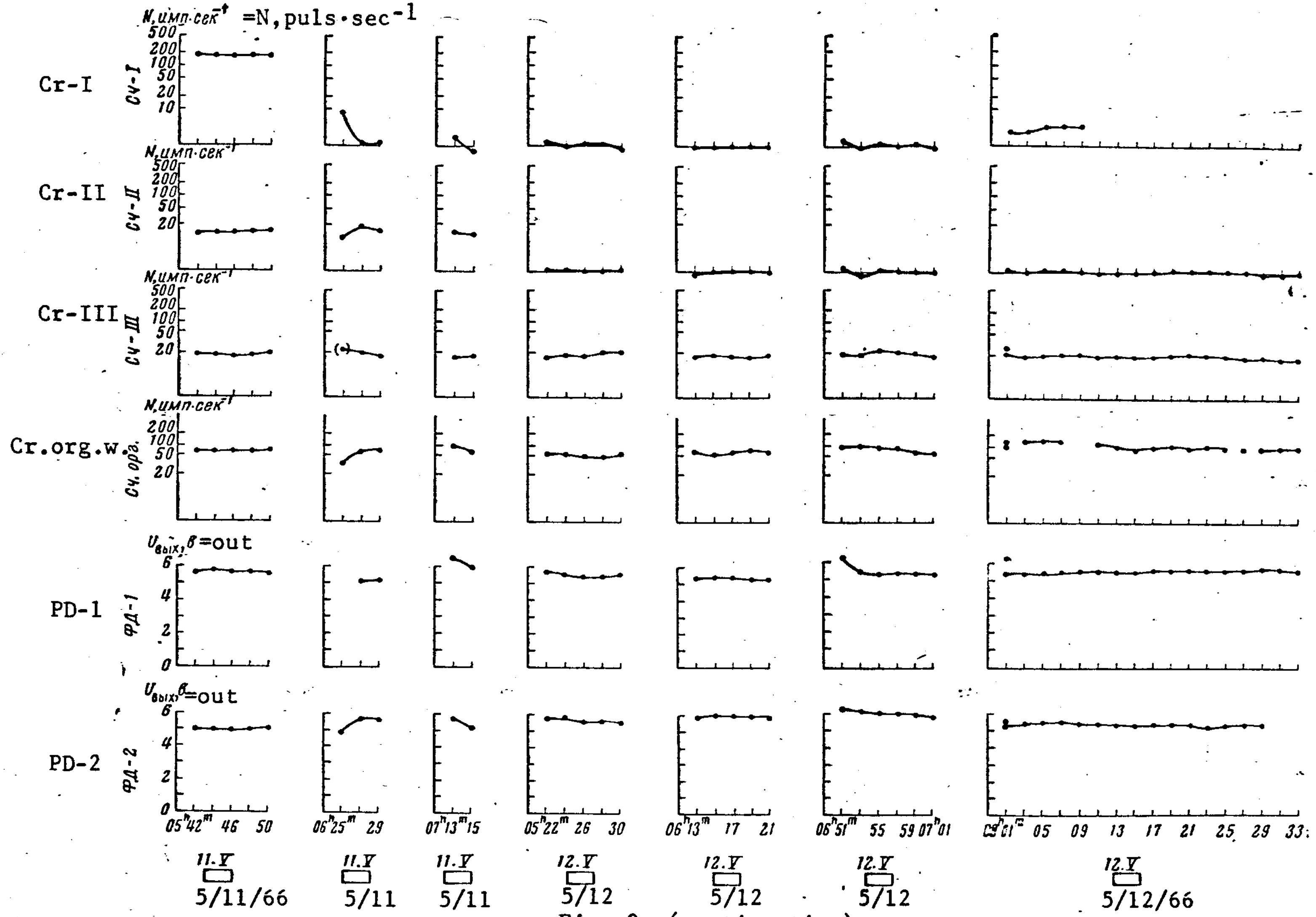

Fig. 3. (continuation)

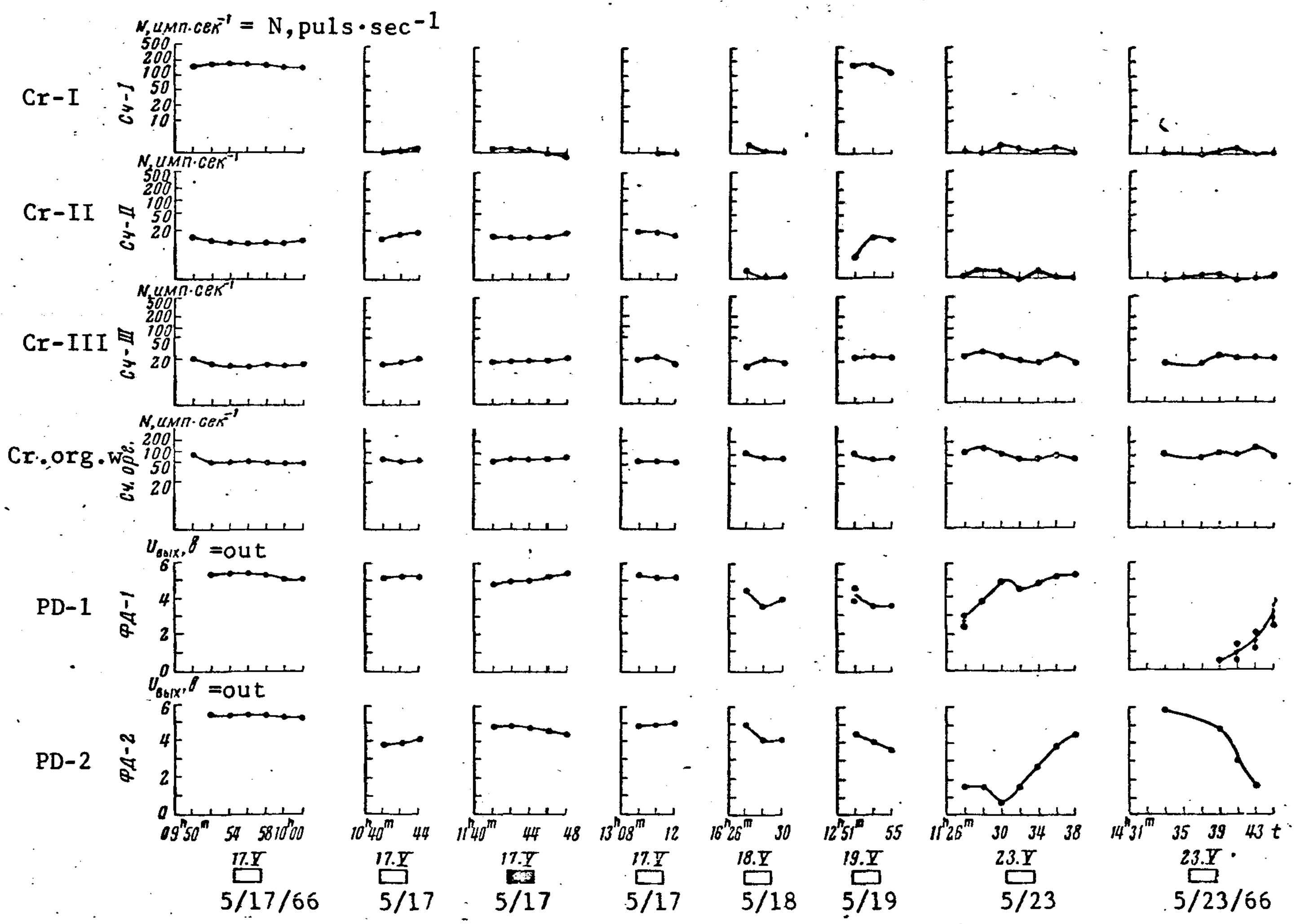

Fig. 3. (continuation)

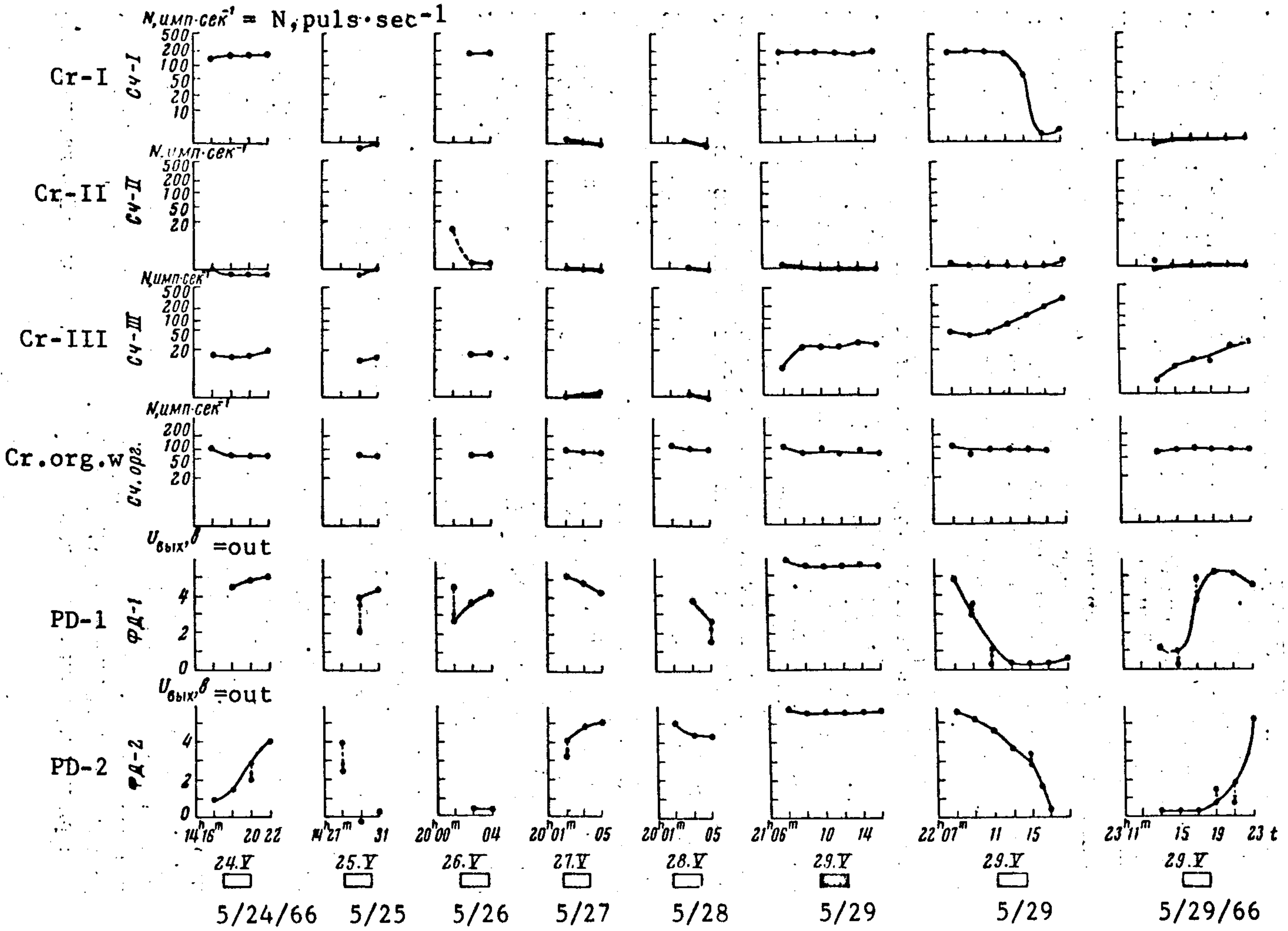

Fig. 3. (conclusion). Readings of X-ray counters and photodetectors during the period of 8 April through 29 May, 1966.

Cr-I, Cr-II and Cr-III are the readings of the counters I, II and III equipped with aluminium windows. Cr.org.w. -- designates the readings of the counters I, II and III equipped with organic windows and turned-on in parallel. PD-1 and PD-2 are the readings of the photodetectors of the I, II and III units turned-on in parallel. The readings of PD-2 were obtained during each measurement cycle, 12 seconds after the readings of PD-1. (U_{out}=0 corresponds to the moment when the Sun comes into the center of field of vision of one of the photodetectors). The white rectangles at the bottom of the charts correspond to the satellites flight over the illuminated part of the lunar surface. The dark -- correspond to the flight over the dark side of the surface, and the partially shaded rectangles correspond to the flight near the lunar terminator.

The readings of the counter II contain also period when the speed of count is lower than the level of the cosmic background. In addition, we have also a number of measurements during which the speed of count was close to the level of the cosmic background. A comparison of these measurements when the satellite was located over the illuminated as well as dark parts of the lunar surface shows that if the counter II pointed toward the Moon at these moments, then the intensity of X-radiation of the Moon is lower than the measurement errors which comprise 3 - 5 pulses per square centimeter . sec. We must, however, underline the fact that due to the presence of a stroboscopic effect which we have mentioned earlier, and the short duration of the measurement sessions, it is not excluded that the counter II did not "see" the Moon during all of these moments of time.

An analysis of the readings taken by the counters with organic windows is hampered by the fact that all three counters are connected to one telemetry channel. The high level of count which is observed on this channel is possibly caused by the electrical leads on one of the counters. A slight modulation of the signals can probably be explained by the fact that the Sun came into the field of vision of the counter in the unit III.

Apparently the direction of the satellite's axis in respect to the momentum vector changes gradually in time; this circumstance does not permit the interpretation of readings obtained from the counters during the middle as well as the end parts of May.

Thus, due to the absence of accurate data on the orientation of the satellite in respect to the Sun and the Moon, we are unable at the present time to arrive at any definite conclusions about the registration of the Moon's X-radiation during this experiment. It is necessary to continue the experiments, possibly with the application of instruments of a much higher sensitivity.

An analysis of the recordings given in Figure 3 makes it possible to draw a conclusion about the registration of particles by our instrumentation, apparently electrons which are included in the content of the "tail" continuation of the Earth's magnetosphere (Ref. 9). The satellite intersected the limits of the proposed continuation of the Earth's magnetosphere four times around the dates of April 4, between April 8 and 9, between May 2 and 4, and on May 7. During all of these cases (with the exclusion of April 4, when the instrumentation was not turned on) an exceeding speed of count over the cosmic background was registered simultaneously by the counters II and III (the counter I remained "out of range"). This testifies to the comparatively isotropic character of the registered radiation. At the same time we observed an increase in the speed of count of the geiger counter SBT-9, of N. L. Grigorov's, et al, instrumentation (Ref. 10); intensive fluxes of slow electrons were discovered by the instrumentation prepared by K. I. Gringauz and others (Ref. 11). The counter used by Grigorov and others had a lower sensitivity to X-radiation as compared with out counters, and approximately the same sensitivity toward particles. It is natural to interpret the increased readings of the counters during these days as a registration of particles in the tail of the Earth's magnetosphere, which was earlier studied up to a distance of 31.5 Earth radii (Ref. 12).

When the satellite was located in a zone of radiation related to the tail of the magnetosphere, the speed of count (excluding the cosmic background) consisted of about 50 pulses per square centimeter • seconds • sterad. Assuming that electrons were registered, we find that the flux of electrons with an energy of $E \geq 40$ kev comprised ≈ 50 electron/square centimeters • sec • sterad.

It should be noted that such a flux of electrons is produced by a flux of X-bremsstrahlung of ~ 0.1 photon/square centimeter • seconds • sterad. (Accepting the fact that in the case of the lunar surface, this is $Z \sim 10$), i.e., considerably less than the anticipated flux of Roentgen fluorescence.

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