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SOVIET SATELLITE AND ROCKET INVESTIGATIONS OF THE NUCLEAR COMPONENT OF COSMIC RAYS

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INTRODUCTION

THE use of artificial earth satellites greatly increases the scope of research on the primary cosmic radiation, particularly the cosmic-ray nuclear component.

The Soviet satellites and rockets carried instruments which registered nuclei having different charges. These instruments yielded data on the fluxes of different groups of nuclei [1-6], their energy spectra [1,5], and the intensity variations of the cosmic-ray nuclear component [7-11].

In the course of the investigation of the cosmic-ray nuclear component, some data were also obtained on the earth's radiation belts (see [1,12-15]). We shall not concern ourselves here, however, with these results, since radiation belt studies made with Soviet satellites and space rockets are discussed in other papers [16-28]; this is a major problem and should be considered separately.

The purpose of the present article is to discuss the results of [1-5,7-11] and compare them with other data.

In addition to a report of the experimental material, we also discuss problems and some possibilities in the study of cosmic rays above the top of the atmosphere and outside the earth's magnetic field.

I. INVESTIGATION OF THE NUCLEAR COMPONENT OF COSMIC RAYS WITH SOVIET SATELLITES AND SPACE ROCKETS

Information on the structure of the universe can be obtained via three independent "channels." The first—optical—has been known from antiquity. The two other, connected with the reception of the emission from radioastronomy objects and registration of primary cosmic rays, have come into use relatively recently. Whereas radioastronomy methods can be used to investigate individual galaxies or galactic nebulas, the analysis of the properties of the primary cosmic rays does not yield direct information on the positions of their sources, since the tangled trajectories of the charged particles in interstellar space cause the cosmic ray distribution at the earth to be, in first approximation, isotropic. Nonetheless, from data on the chemical composition of the primary cosmic rays we can obtain very important information on their generation in the sources and on the conditions of their propagation in outer space [29-31].

It must also be emphasized that cosmic rays play a very important role in processes that occur in the universe. It is sufficient to state that the energy density of galactic cosmic rays is of the same order as the density of the kinetic energy of the interstellar gas and the energy density of the magnetic field in interstellar space. About one-half of the cosmic-ray energy [29-30] is due to multiply charged nuclei.

Thus, an investigation of the composition of the primary cosmic rays is not only of prime importance to the theory of their origin, but is also necessary for the understanding of the processes involved in the evolution of the galaxy. Investigations of the nuclear component of galactic cosmic rays are particularly important.

One of the advantages of investigations of the nuclear component with the aid of satellites and space rockets is the feasibility of prolonged measurements with very small thickness of matter over the apparatus. This is particularly important for heavy nuclei, which are strongly absorbed by the atmosphere (thus, for example, the ionization range of iron nuclei with kinetic energy 300 MeV/nucleon is merely about 5 g/cm^2 in air).

Instruments on the Soviet satellites and space rockets measured the composition of cosmic rays under not more than 1 g/cm^2 of matter (outside the earth's atmosphere). The space rockets also made possible measurements outside the earth's magnetic field. In this section we describe briefly the apparatus employed in Soviet space rockets and space probes for the investigation of the nuclear component of the cosmic rays. The results obtained are discussed and compared with data obtained by other means.

1. Procedure

The method employed predominantly on Soviet space rockets and satellites to investigate the nuclear component of the cosmic rays was that of Cerenkov counters. The pulse produced in a Cerenkov counter by a nucleus passing through it is proportional to Z^2 —the square of the nuclear charge. Unlike ionization chambers or luminescent (scintillation) counters, Cerenkov counters register only sufficiently rapid nuclei with minimum velocity $v_{min} = c/n$, where c is the velocity of light and n is the refractive index of the counter detector material (if dispersion is taken into account, n should be defined as a maximum value of n in the wavelength interval employed). A Cerenkov counter is therefore insensitive to slow particles and, in particular, does not register nuclear disintegrations whose products are nonrelativistic particles (for more details see [32]).

Both integral and differential Cerenkov counters were used during the measurements.

Cerenkov counters which register all nuclei with charges exceeding a specified value (for example, with $Z \geq 2$, $Z \geq 5$, $Z \geq 15$, etc.) are called integral. The nuclei were registered in counters of this type whenever the photomultiplier pulse (due to the passage of a nucleus through the detector) exceeded a certain specified magnitude. This recorded the passage of a nucleus with a charge exceeding a specified value, but the amplitude of the pulse was not measured, and consequently the charge of the individual nucleus was not measured. The counters employed gathered nuclei arriving from a broad solid angle, and had relatively large transmission ("geometrical factor"); consequently, these counters are convenient for the registration of nuclei with low flux. The integral counters can be used also to register time variations of the fluxes and their dependence on the position of the instrument in space (for example, to measure the latitudinal intensity variation of different groups of nuclei).

Counters of the integral type were installed on the third satellite, on the second and third space rockets, and also on the second and third space probes. The integral Cerenkov counter and the employed electronic circuitry are described in [32]. The exterior view of one of the integral-type counters employed is shown in Fig. 1.

The counters used to measure the differential charge spectrum of the nuclei registered the amplitude of the pulse produced by the passage of each nucleus through the detector, and thus the charge of this nucleus. Such counters are called differential. An exterior view of a differential type Cerenkov counter is shown in Fig. 2, while Fig. 3 shows its schematic diagram. Since the magnitude of the pulse is proportional to the path of the nucleus in the detector, it is necessary to select in the differential counters the nuclei that pass in a narrow solid angle, so that their paths in the detector do not differ greatly from one another. Such a selection is carried out with the aid of two rows of gas-discharge counters connected for coincidence

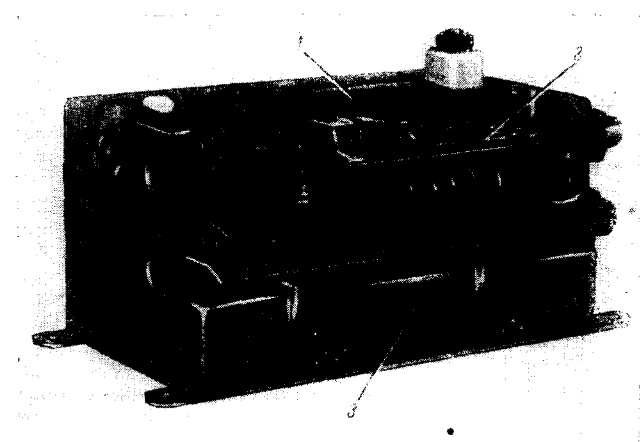

FIG. 1. Exterior view of one of the integral counters. 1—Detector with photomultiplier (in cover); 2—input stage of electronic circuit; 3—photomultiplier supply battery.

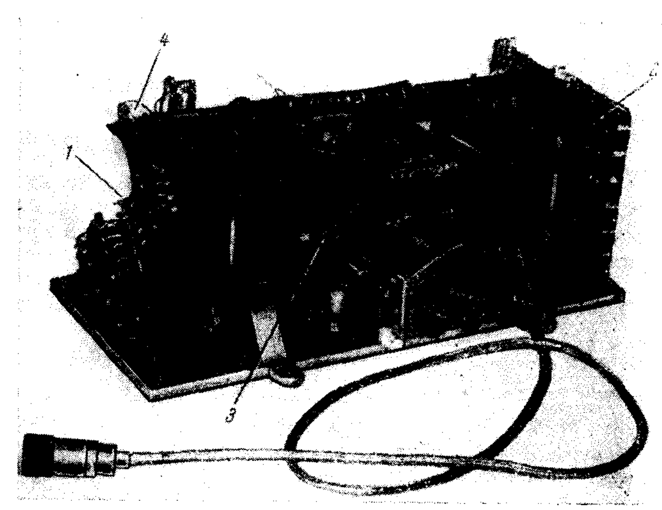

FIG. 2. Exterior view of differential Cerenkov counter. 1—Upper row of telescope counters; 2—lower row; 3—cover for Cerenkov detector and photomultiplier; 4—guard counters.

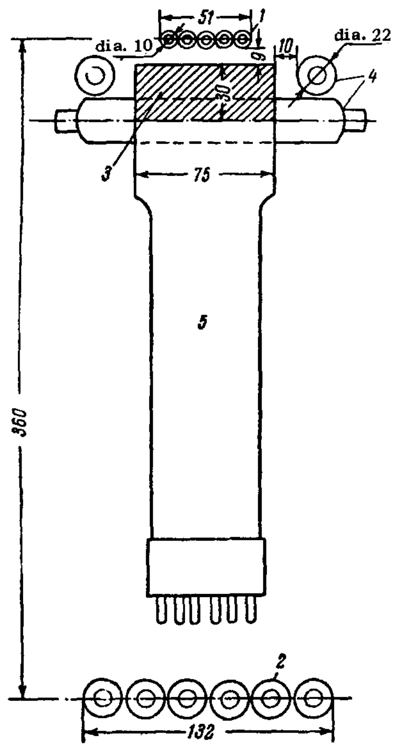

FIG. 3. Schematic diagram of a differential counter (the dimensions are in millimeters). 1—Upper row of telescope counters; 2—lower row; 3—Cerenkov detector; 4—guard counter; 5—photomultiplier.

("telescope" for the registration of cosmic rays). The pulse is measured in the Cerenkov counter only if the coincidence circuit goes into operation, that is, if the particle passes inside the solid angle of the telescope (the resolution time of the coincidence circuit is approximately 2×10^{-5} sec). To separate the cases when the registration of the nucleus was accompanied by a "shower" of particles, a system of "master pulses" is used. When more than one counter is discharged in the lower group of counters, a so-called "lower master pulse" appears, and if the discharge of more than one counter occurs in the upper row or in one of the "guard" counters, located around the detector outside the telescope solid angle, then an "upper master pulse" appears.

Differential counters were installed in the second and third space probes.

To determine the fluxes of each of the groups of nuclei registered by the counter from the counting rates in the corresponding channels, it is necessary to know the geometrical factor of the counter, with allowance for the conditions under which light is gathered in the detector.

Owing to the directivity of the Cerenkov radiation, the gathering of the light depends on the direction of arrival of the nucleus and, for a given threshold, the nuclei which produce radiation directed away from the photocathode of the multiplier will not be registered.

The geometrical factor can be calculated under certain assumptions concerning the gathering of the light in the detector; it is possible consequently to obtain the values of the fluxes of the registered groups of nuclei.

The upper end surfaces of the Cerenkov detectors used in differential counters are blackened, and the side surfaces are aluminized. Therefore the nuclei passing through a detector from the lower counter group of the telescope to the upper group are not registered, owing to the absorption of the light by the upper end surface. The geometrical factor Γ of the telescope was determined by the area of each of counter group (S_1 and S_2) and the distance R_{12} between them. If both counter groups are squares ($S_1 = a_1^2$, $S_2 = a_2^2$) with mutually parallel sides, the geometrical factors can be calculated from the formula*

$$\Gamma = 4R_{12}^2 \int_{\xi_1}^{\frac{\pi}{4}} d\xi \int_{\frac{a_1 - a_2}{R_{12}\sin\xi}}^{\frac{a_1}{R_{12}\cos\xi}} \Phi(\eta, \xi)\,\eta\, d\eta,$$

where

$$\xi_1 = \operatorname{arctg} \frac{a_1 - a_2}{a_1},$$

$$\Phi(\eta, \xi) = \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4,$$

$$\Phi_1 = \frac{\eta\cos\xi}{\sqrt{1+\eta^2\cos^2\xi}} \operatorname{arctg} \frac{k\sqrt{1+\eta^2\cos^2\xi}}{1+\eta^2 - k\eta\sin\xi},$$

$$\Phi_2 = \frac{k - \eta\sin\xi}{\sqrt{1+(k-\eta\sin\xi)^2}} \operatorname{arctg} \frac{k\sqrt{1+(k-\eta\sin\xi)^2}}{1+k^2+\eta^2 - k\eta(\cos\xi + 2\sin\xi)},$$

$$\Phi_3 = \frac{k - \eta\cos\xi}{\sqrt{1+(k-\eta\cos\xi)^2}} \operatorname{arctg} \frac{k\sqrt{1+(k-\eta\cos\xi)^2}}{1+k^2+\eta^2 - k\eta(2\cos\xi + \sin\xi)},$$

$$\Phi_4 = \frac{\eta\sin\xi}{\sqrt{1+\eta^2\sin^2\xi}} \operatorname{arctg} \frac{k\sqrt{1+\eta^2\sin^2\xi}}{1+\eta^2 - k\eta\cos\xi}$$

(here $k = a_1/R_{12}$).

If $S_1 \ll R_{12}^2$ and $S_2 \ll R_{12}^2$, then in first approximation, for any form of S_1 and S_2, the geometrical factor can be calculated from the formula

$$\Gamma \approx \frac{S_1 S_2}{R_{12}^2}.$$

The geometrical factor of the differential counters used in the second and third space probes was $\Gamma \approx 2.5$ cm^2 sr.

The geometrical factor of the integral counter was calculated under the assumption that all the light was received by the photocathode of the multiplier, for all nuclei arriving from the "upper hemisphere" (that is, for those nuclei whose direction made an angle less than 90° with the normal to the surface of the photomultiplier window), and the nuclei arriving from the "lower hemisphere" were not sensed at all by the counter, since their Cerenkov glow was directed away from the photocathode, and the "upper" base of the detector was made nonreflecting. The analytic expression and the plot for the determination of the geo-

*arctg = $\tan^{-1}$.

metrical factor are given in [32]. By specifying a definite form of the energy spectrum of the nuclei, we obtain the value of the geometrical factor Γ for any group of nuclei registered by the channel with given threshold.

Table I lists the values of the geometrical factor Γ obtained for a specified value of the threshold Z_{thr}, if nuclei with different Z are registered (cylindrical Cerenkov detector with height and diameter 26 mm each). The calculation was carried out for two values of the exponent $n = \gamma - 1$ of the integral energy spectrum $N(>E) = AE^{-n}$ (γ — exponent for the differential spectrum).

Table I

Threshold charge Z_{thr}	Nuclei which make main contribution to number of counts		Calculated value of Γ (cm^2 sr) for the threshold Z_{thr} and for nuclei with charge Z		Value of Γ used for determination of flux of nuclei with $Z \geq Z_{thr}$
	Symbol	Charge Z	$n = 1.2$	$n = 1.6$	
2	He	2	26	24.5	26
5	C N O Ne	6 7 8 10	24 29 33.5 38	22.5 28 32 36.5	30
15	Ca Cr Fe Ni	20 24 26 27	26.5 33 33.5 35	26.5 32 32.5 34	33

The geometrical factor calculated in this manner depends little on the exponent of the energy spectrum n and on the charge Z of the nuclei which make the main contribution to the flux registered by the given channel (with specified value of Z_{thr}). Consequently, we can neglect this dependence and calculate the fluxes of the different groups of nuclei for some average values of n and Z.

The last column of Table I lists the values of the geometrical factor used for the determination of the fluxes of nuclei with $Z \geq 2$, $Z \geq 5$, and $Z \geq 15$. These values of Γ were chosen with allowance for the particular group of nuclei which can make an appreciable contribution to the flux. Thus, for example, the main contribution to the flux of nuclei with $Z \geq 2$ is made by α particles, while that to the flux of nuclei with $Z \geq 5$ by the nuclei C, N, and O.

The electronic circuitry of the instrument, in the case of integral counters, consisted of an input matching unit, an amplifier stage, a threshold unit, a scaler circuit, a summing unit, and an output matching unit. All pulses which exceeded a certain threshold were counted.

In the case of the differential counter, the electronic circuitry was much more complicated. The operation of the Cerenkov counter was triggered by a telescope of gas-discharge counters with the aid of coincidence circuits and gates. In the case when more than one counter operated (in each counter group of the telescope), a special marker was produced, formed by the selection circuit and coincident circuit. The pulse from the photomultiplier was amplified in a linear amplification channel. The pulse was delayed after "gating" and the duration of this delayed pulse was proportional to the amplitude of the initial pulse. The delayed pulse was reshaped into a packet of pulses with the number of pulses in each packet proportional to the duration of the delayed pulse, and consequently to the amplitude of the initial signal. These pulses were counted by a scaler and data on the number in each packet were transmitted with the aid of the summing units and output matching units to a radio telemetry system. This yielded information on the amplitude of each pulse in the Cerenkov counter.

An exterior view of the electronic equipment used for differential counters on Soviet space ships is shown in Fig. 4.

The differential Cerenkov counter, which yields information concerning each individual particle passing through the telescope, makes it possible to plot the charge distribution of the registered nuclei. In the case of sufficiently large transmission, such distributions can be constructed for each small time interval and for a limited latitude interval, and thereby yield the time and energy variations of the composition.

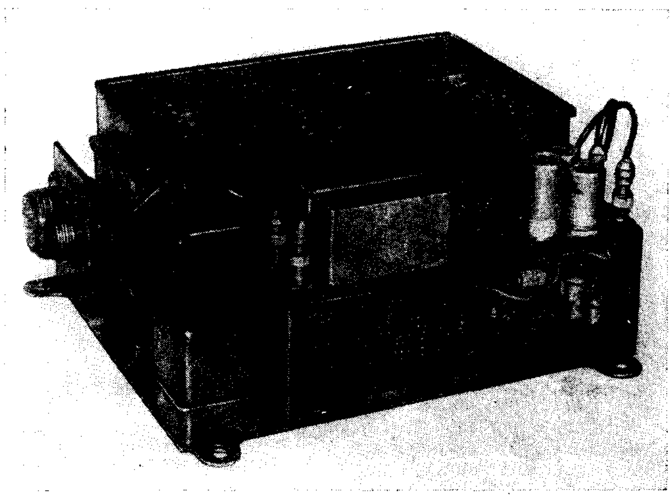

FIG. 4. Exterior view of electronic equipment for a differential counter.

In the case of a Cerenkov counter with $\Gamma \approx 2.5$ cm^2 sr, such an analysis cannot be made because of the insufficient statistics of the registered events. However, if no large changes in intensity are observed over the measurement period and allowance is made for the fact that the energy spectrum of different groups of nuclei are practically the same (see page 238 below), we can plot the summary distribution of the registered particles for the entire measurement time.

When a charge analysis is made of the spectrum obtained with the aid of Cerenkov counters, the effect of the difference in the velocities of the registered nuclei must be kept in mind. The point is that the number of photons produced in a Cerenkov counter when nuclei with charge Z pass through the detector depends on the velocity $\beta = v/c$:

$$I = A\left(1 - \frac{1}{n^2\beta^2}\right)Z^2,$$

where v —velocity of the nucleus, c —velocity of light, n —refractive index, and A —proportionality coefficient ($A \approx 450\,l$, where l —path of the particle in the detector). For very fast nuclei v is close to c ($\beta \approx 1$), and

$$I \approx I_0 = A\left(1 - \frac{1}{n^2}\right)Z^2.$$

This value of the amplitude is Z^2 times larger than the amplitude of the average pulse from a singly charged relativistic particle (for example, from a muon).

For monoenergetic relativistic nuclei one would obtain a peak with an average amplitude I_0 and a half-width proportional to Z. The half-width of the peak is determined in this case only by the properties of the photomultiplier (essentially by the efficiency of the photocathode), since the passage of each nucleus of given Z produces the same amount of light in the detector. If v differs from c appreciably the pulse is smaller than I_0.

It is possible to obtain theoretically the shape of the amplitude distribution for nuclei with a given charge, with allowance for the velocity spectrum of the nuclei. To this end it is necessary to specify a definite form of the energy spectrum of the nuclei and the photomultiplier cathode efficiency. It should be noted that the shape of the amplitude distribution curve depends little on the spectrum energy exponent. Figure 5 shows the theoretical amplitude distribution obtained for carbon nuclei under the assumption that the exponent of the integral energy distribution is equal to 1.5, and the photomultiplier cathode efficiency is 5%. Similar curves were obtained for other nuclear charges. By selecting some normalization factor for each of the curves, we can attempt to reconcile the over-all theoretical amplitude distribution curve with the experimental data.

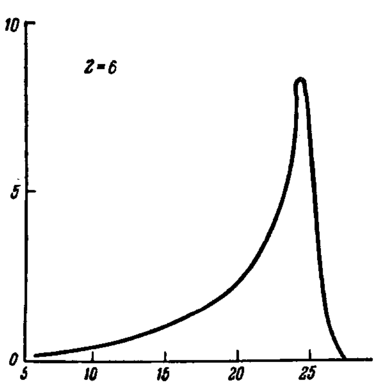

FIG. 5. Theoretical amplitude distribution obtained for carbon nuclei with allowance for the velocity spectrum of the nuclei. Abscissa–pulse amplitude in relative units, ordinates–number of pulses.

By comparing the values of the employed normalization factors we can obtain the relative values of the fluxes of nuclei with different charges.

Pulses produced in a Cerenkov detector by muons and cosmic-ray electrons are used to set the thresholds of the integral Cerenkov counters and to calibrate the differential counters. The amplitudes of these pulses have a considerable scatter, since the light flash produced in the detector by a singly charged particle is small, and consequently the number of photoelectrons knocked out from the photomultiplier cathode is small; this leads to noticeable statistical fluctuations in the registered amplitude. Therefore the amplitude distribution of the pulses from singly charged particles was plotted for each photomultiplier. The Cerenkov counter was placed at the same time between gas-discharge counters, forming a "telescope" and arranged to separate the particles that travel in a vertical direction. The telescope geometry was such that all particles passing through the two upper and two lower layers of telescope counters (connected for four-fold coincidence) had to pass through the detector, and their path in the detector was not shorter than the detector height. The master telescope used to calibrate the Cerenkov differential counters was made up of gas-discharge counters and constituted part of the instrument.

The adjustment of the integral thresholds of the counters and the calibration of the differential counters were against the mean value of the pulse amplitudes, obtained from the amplitude distribution curve for the muons.

2. Chemical Composition of Cosmic Rays. Fluxes of Nuclei of Different Groups and Their Energy Spectra

When dealing with nuclei and protons, the primary cosmic radiation is characterized by the flux, in a given direction, of particles having a charge Z, atomic weight A, and total energy per nucleon exceeding E. We denote this quantity by F(Z, A, E); it is expressed in the number of particles per square meter in sr-sec.* According to available data the flux F, within the attainable 1—3% accuracy, is independent of direction outside the region of influence of the earth's magnetic field (in other words, the cosmic-ray flux is isotropic).† Because of the isotropy of the cosmic rays,

*The particle flux in a given direction is frequently called the intensity and designated by the letter I (the letter F then usually denotes the quantity $\int I\,d\Omega$, where the integration is over the solid angle corresponding to one hemisphere).

†For galactic cosmic rays we can expect an anisotropy reaching several tenths of one per cent; we refer to the coefficient

it is usually unnecessary to consider the angle dependence of the function F (during measurements on earth F depends on the angles and on the place of observation, since the cosmic rays are influenced by the earth's magnetic field, but this influence can be calculated, in first approximation, on the basis of the theory of geomagnetic effects).

During the last two decades numerous measurements carried out in the stratosphere with the aid of various procedures have ascertained the basic properties of the primary component of cosmic radiation (see, for example, [29-37]). It has been established that the primary cosmic-ray particles are mostly protons and multiply charged nuclei. However, data on the fluxes of the nuclei of individual elements, other than protons and alpha particles, are still insufficient and in most papers fluxes are given only for groups of nuclei.

Nuclei with $Z \geq 3$ are usually divided into the following groups:

1. Light nuclei with $3 \leq Z \leq 5$ (group L).
2. Nuclei of the middle group with $6 \leq Z \leq 9$ (group M).
3. Heavy nuclei with $Z \geq 10$ (group H).

A symbol S is also used for the group of nuclei with $Z \geq 6$ ($S = M + H$). For a more detailed analysis, the H group is subdivided into a VH subgroup ($Z \geq 20$) and sometimes into the subgroups H_1 ($H = 20-28$), H_2 ($Z = 16-19$), and H_3 ($Z = 10-15$).

The accuracy with which the fluxes for the individual groups are known in likewise low, particularly when it comes to lithium, beryllium, and boron (L group), nuclei with $Z \approx 18-23$, "superheavy" nuclei with $Z \approx 28-30$, etc. There are many reasons for this uncertainty: the presence of a residual layer of atmosphere over the apparatus borne by pilot-balloons, the relatively low exposures, and various methodological difficulties. At the same time, details concerning the dependence of the flux of the nuclei on Z is exceedingly valuable from the point of view of the entire problem of the origin of cosmic rays [39-31]. We have already emphasized above the obvious advantages connected with the use for this purpose of outer-space apparatus, which makes it possible to observe the nucle.s without an atmospheric filter.

However, even measurements outside the atmosphere do not give complete information on the primary galactic cosmic rays, since the intensity and energy spectrum of the latter differ from those measured near the earth. This difference is due to the action of the earth's magnetic field and apparently also to the influence of interplanetary magnetic fields in the solar system.

The effect of the magnetic field on charged particles from the cosmic rays depends on the magnetic rigidity of the particles

$$R = \frac{Apc}{Ze},$$

where A — atomic weight of the nucleus, Z — its atomic number, p — momentum of each of the nucleons.

The earth's magnetic field allows a certain geomagnetic latitude to be reached from a definite direction only by those nuclei whose rigidity exceeds a definite value ("cutoff rigidity"). This is the cause of the latitudinal dependence of the intensity of cosmic rays. The value of the cutoff rigidity for each geomagnetic latitude is obtained from the theory of geomagnetic effects. As is well known from the theory of geomagnetic effects, the space over each point on earth can be divided into three regions: the principal cone, the Stormer cone, and the penumbra region. These regions are such that for particles of given rigidity all the directions inside the principal cone are allowed and all the directions outside the Stormer cone are forbidden, while in the penumbra region the allowed and forbidden directions alternate and form a rather entangled pattern. Depending on the latitude, the transparency of the penumbra region varies, and this influences the threshold cutoff rigidity. Figure 6 shows the latitude dependence of the cutoff rigidity for particles arriving from a vertical direction (curve 1). This dependence has been plotted with allowance for the different transparency of the penumbra region at different latitudes. Curves 2′ and 3′ represent the dependence of the cutoff energy (E, BeV/nucleon) on the

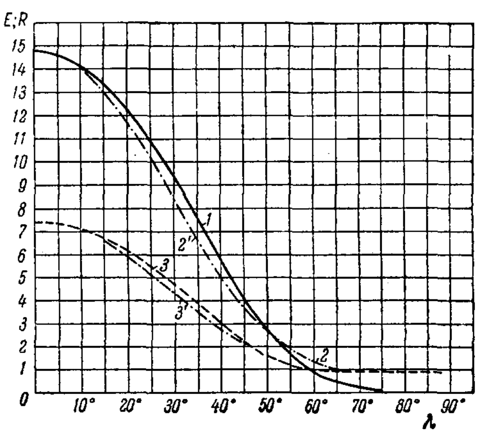

FIG. 6. Dependence of the minimum rigidity R and the total energy E on the geomagnetic latitude, for particles arriving in a vertical direction. 1–Rigidity R; 2–total proton energy; 3–total energy (per nucleon) of the nuclei; 2′ and 3′–corresponding curves constructed for the case of the Stormer cone.

$$\delta = (F_{max} - F_{min})/(F_{max} + F_{min}),$$

see [29,30]. There are indications that during the years of the solar minimum such an anisotropy is actually observed [33]; its measurement is of great interest. It is possible that satellites and rockets can be used advantageously for this purpose to eliminate atmospheric effects, and in the case of orbits with large apogees also to eliminate the effect of the earth's field and the influence of the radiation belts (we do not concern ourselves here with the anisotropy of cosmic rays at ultrahigh energies; the available data for this case are not fully conclusive [34-36]).

geomagnetic latitude for protons and multiply charged nuclei, respectively (in the region of medium and low latitudes curves 1 and 2 merge).

More detailed information on geomagnetic effects can be found in the review [38] and the literature cited there. It is much more difficult to account for the influence of the interplanetary magnetic fields in the solar system, on which little data is still available. It is known that the intensity of the galactic cosmic rays is modulated within the confines of the solar system, and that this modulation is connected with the solar activity (high-latitude cutoff of cosmic rays, 11-year variations, Forbush decrease in the cosmic ray intensity, etc.). This question is considered in detail in [39], but it must be noted that there is still no generally accepted opinion concerning the modulation mechanism. If the cosmic-ray modulation in the solar system is due, as is most likely, to the magnetic fields, then for a given rigidity (for particles with velocities $v \approx c$) the composition of the cosmic rays observed on earth should correspond to the composition of galactic cosmic rays. Therefore, when we deal with a comparison of the fluxes of different components of cosmic rays, we must carry out such comparisons for identical rigidity of the registered nuclei. For all the multiply charged nuclei $A/Z \approx 2$, and their rigidity is the same for a specified value of the momentum of each of the nucleons (and consequently, for a specified energy per nucleon of the nucleus). For protons $A/Z = 1$, and therefore the proton energy for a specified rigidity differs from the energy per nucleon of a multiply charged nucleus of the same rigidity.

Figure 7 shows the dependence of the total energy per nucleon on the rigidity R for protons, nuclei, and electrons.

The rigidity spectra of different nuclei, including protons, are similar, if not identical, over a rather wide range of R. Accordingly, the chemical composition of the cosmic rays remains constant over a large interval of rigidity values.

For multiply charged nuclei ($A/Z \approx 2$) this means also that the chemical composition is the same for different values of the energy per nucleon of the nucleus.

For protons ($A/Z = 1$) the comparison must be carried out for a corresponding value of the rigidity. Thus, according to the data of [40], the ratio of the fluxes of protons and alpha particles having the same rigidity remains constant at $F_p(R)/F_\alpha(R) = 7.0 \pm 0.2$ in the rigidity range from $R \approx 10^9$ V to $R \approx 5 \times 10^{12}$ V. At the same time, the ratio of the fluxes of the protons and alpha particles for a given energy per nucleon increases with increasing E, approaching a value $F_p(E)/F_\alpha(E) = 19.8 \pm 1.2$ (for $E \gg Mc^2$, when the rigidity ratio of the protons of alpha particles becomes independent of E). For nuclei with $Z \geq 2$, $Z \geq 5$, and $Z \geq 12$–14, an identity of the spectra for rigidities from 3 to 15 BV was observed, in particular, in measurements of the latitudinal effect during the flights of the Soviet space probes (see below).

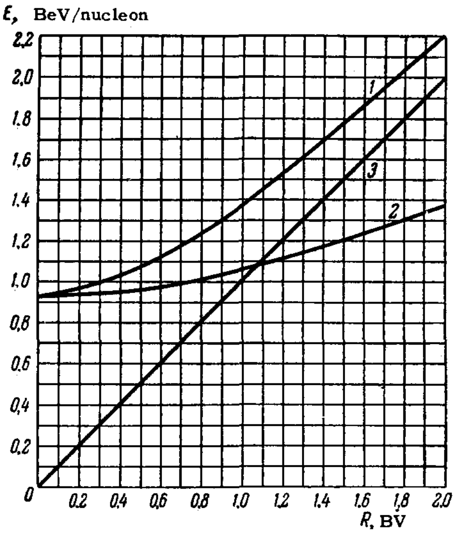

FIG. 7. Dependence of the energy of the particle E(BeV/nucleon) on its rigidity R (BV): 1—For protons; 2—for nuclei; 3—for electrons.

Until recently measurements of the latitudinal dependence of the intensity of the nuclei were made with apparatus lifted by pilot balloons from different points on earth. In addition to the shortcomings of this method due to the presence of a residual layer of atmosphere and the short observation time, the principal defect is that measurements at different points are carried out as a rule with different apparatus and during different times. This can lead to considerable errors, since readings of different instruments sometimes are difficult to reconcile, while measurements carried out during different times can pertain to different values of the flux because of its variations.

Satellite measurements eliminate these shortcomings: the measurements are carried out outside the atmosphere for a sufficiently long time and at the same time there are almost simultaneous different geomagnetic latitudes. Consequently, prolonged variations of the primary flux can be allowed for in such measurements, and the short-duration variations are eliminated by averaging the data obtained during multiple passages of the satellite through a given geomagnetic latitude.

a) Latitude dependence and energy spectra of nuclei of different groups from measurements on space probes. The second space ship carried three Cerenkov counters, one integral and two differential. The integral counter measured the relative intensity of nuclei with $Z \gtrsim 5$ and $Z \gtrsim 15$. The differential counters registered nuclei from alpha particles through oxygen. Similar apparatus was installed on the third Soviet space ship, but the thresholds of the integral counters were set to register nuclei with $Z \gtrsim 5$ and $Z \gtrsim 12$–14.

During the reduction of the measurement results, the numbers of the nuclei registered in the geomagnetic latitude intervals from zero to 10°, from 10 to 20°, etc., were summed, and the data of the southern and northern hemispheres were combined. The number of nuclei registered per unit time in each interval was then referred to the mean latitude of each interval, that is, to 5°, 15°, etc.*

An analysis of the events registered by the differential counter, accompanied by master pulses, gave grounds for assuming that the greater part of these events corresponds to the formation of showers by nuclei arriving at the detector from outside the telescope solid angle. The shower should then contain a large number of particles, that is, the showers should be produced by nuclei of sufficiently high energy (the latitudinal effect for such nuclei should be small, as is observed for the cases with the master pulses). In this connection, to compare the latitudinal dependence of the intensity of different groups of nuclei, only cases without master pulses were used, corresponding to the passage of nuclei in the allowed solid angle.

The geomagnetic latitudes were determined from maps given in [41]. Inasmuch as the averaging during the determination of the spectrum was over a relatively large interval of latitudes (10°), the use of more exact geomagnetic coordinates, which take into account the non-dipole terms (see, for example, [42]) should not influence in any appreciable manner the result. The dependence on the latitude of the intensity of nuclei with $Z \geq 2$ and $Z \geq 4$ (from data of the differential counter installed on the third space probe) is shown in Fig. 8. The values of the intensities of the nuclei with $Z \geq 4$ have been increased here by a factor 7.5.

As can be seen from Fig. 8, the latitude dependences of the intensity of nuclei with $Z \geq 2$ (these are essentially alpha particles) and nuclei with $Z \geq 4$ (for the most part from the M group) coincide, within the limits of statistical measurement error. Since the latitude dependence is determined by the form of the energy spectrum of the particles, the agreement of the latitudinal variation of the two groups of nuclei indicates that their energy spectra are identical in the energy region where the particles are subject to the action of geomagnetic effects.

It should be noted that the time variation of the orientation of the axis of the instrument relative to the direction of the force lines of the earth's magnetic field cannot influence the character of the latitudinal dependence and cause difficulties in determining the form of the energy spectrum from the measured latitudinal variation. However, this factor is eliminated by comparing the latitudinal variations of nuclei of two groups shown in Fig. 8, since measurements of the intensity of the nuclei of both groups were made by the same instrument simultaneously.

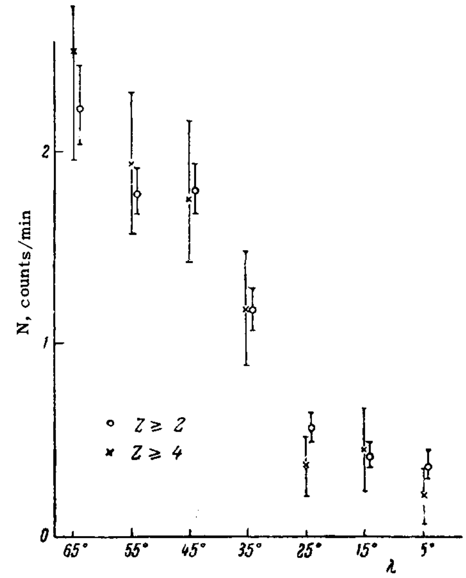

FIG. 8. Dependence of the intensity of nuclei with $Z \gtrsim 12$ and $Z \geq 4$ on the geomagnetic latitude as given by a differential counter (flight of the third space probe).

Figure 9 shows the latitude dependence of the intensity of nuclei with $Z \geq 5$ and $Z \gtrsim 12$—14 as given by an integral counter (on the third space probe). Both groups of data have been normalized by multiplying

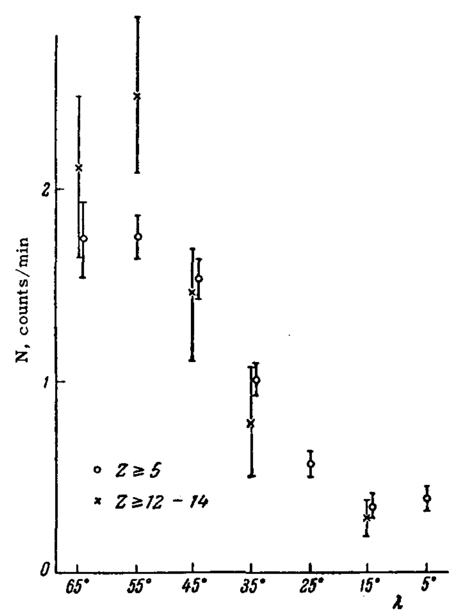

FIG. 9. Dependence of the intensity of nuclei with $Z \geq 5$ and $Z \gtrsim 12 - 14$ on the geomagnetic latitude as given by an integral type counter (flight of third space probe).

*At large telescope counting rates, cases were observed when a nucleus arriving from outside the solid angle subtended by the telescope was nevertheless registered, because it arrived at the instant when the pulse from the coincidence circuit "opened" the measuring channel (random coincidences). Consequently, the anomalous radiation intensity regions where the number of telescope counts was large, were eliminated when plotting the latitude dependence. (See [14].)

all the values of the intensity of nuclei with $Z \gtrsim 12-14$ by a constant factor (10). As can be seen from Fig. 9, the latitude dependences for these two groups of nuclei, obtained with the aid of the same instrument, agree within the limits of errors (some discrepancy in the latitudinal variation in the vicinity of 55—65° is apparently connected with the difference in the energy thresholds of the counting channels of the nuclei with $Z \geq 5$ and $Z \gtrsim 12-14$). From a comparison of the latitude dependences we can conclude that in the energy region under consideration the energy spectra of the nuclei with $Z \geq 2$, $Z \gtrsim 4-5$, and $Z \gtrsim 12-14$ are identical.

Knowing the latitude dependence of the intensity of the nuclei, we can plot on this basis the integral energy spectrum of the nuclei. Assuming that the spectrum obeys a power law, we obtain for the spectrum plotted in logarithmic coordinates of the cutoff energy and the intensity of the nuclei a straight line. We assume here that the average cutoff energy at a given latitude corresponds to the cutoff energy for nuclei arriving in a vertical direction. Since this assumption is to some degree arbitrary, the values obtained for the exponents of the energy spectra are also somewhat arbitrary in character. What is important is that the exponents obtained for different groups of nuclei with the same instrument agree, within the limits of error.

Figure 10 shows the energy spectrum for nuclei with $Z \geq 2$, obtained with the aid of two differential counters (from data of the third space ship). The abscissas represent the cutoff energy corresponding to minimum rigidity, for the arrival in a vertical direction at a given geomagnetic latitude λ, while the ordinates represent the counting rate N in a latitude strip $\lambda = \pm 5°$ (logarithmic scale on both axes).

It is seen from Fig. 10 that the curves exhibit a bend

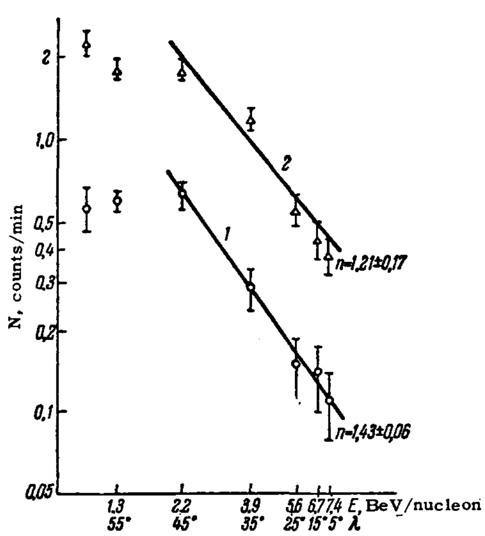

FIG. 10. Energy spectrum of nuclei with $Z \geq 2$, obtained with the aid of two differential counters (flight of the third satellite-ship).

in the region of high latitudes (low energies): in the region of total energy smaller than 1.5—2 BeV/nucleon, the counting rate becomes constant and independent of the latitude. At high latitudes, owing to the high-latitude cutoff, a bend should indeed be observed on the curve, similar to that shown in Fig. 10.

However, there is also another (methodological) reason for such a bend in the curve. It consists in the fact that the Cerenkov counter has an energy threshold lying near the energy $E_{thr} = 1.3$ BeV/nucleon or somewhat higher. For example, for the channel in which nuclei with $Z \geq 5$ are counted, the energy threshold in the integral counter is $E_{thr} = 1.6$ BeV/nucleon. The presence of an energy threshold in the counter can lead to cutoff of low-energy particles and "flattening" of the spectrum before the satellite enters the region of high-latitude cutoff (that is, at lower latitudes).

Since the momenta at the output of the photomultiplier, corresponding to the passage of a particle with specified Z and velocity v, have a certain scatter due to the properties of the photomultiplier, some "smearing" of the energy threshold can occur. An estimate shows that when this "smearing" is taken into account a fraction of the alpha particles will not be registered even at an energy on the order of 2 BeV/nucleon. Thus, the curve of the spectrum should have a change in slope in the latitude region 40—50° (cutoff energy 3—1.6 BeV/nucleon). Consequently the slope of the integral-spectrum curve is determined from points lying below 50°. In Fig. 10, straight lines are drawn through these points by the method of least squares. The slope of the line determines the exponent $n = \gamma - 1$ of the integral energy spectrum of the form $N(>E) = AE^{-n}$. For nuclei with $Z \geq 2$ the spectral exponent is $n_1 = 1.43 \pm 0.06$ (as given by counter 1) and $n_2 = 1.21 \pm 0.17$ (as given by counter 2).*

The counting rate in counter 1 is smaller at all latitudes than in counter 2. The reason for it is that there is a cutoff in the apparatus threshold for the small momenta corresponding to protons. In counter 1 this threshold is shifted towards larger amplitudes, so that partial discrimination of alpha particles takes place and this explains the reduced counting rate.

The power exponents n_1 and n_2 agree within the limits of errors. Since they have been obtained with the aid of identical instruments in the same flight, they can be averaged. The weighted average value is† n

---

*The integral energy spectra were plotted using the cutoff-energy values for the geomagnetic latitudes 45°, 35°, 25°, etc., in accordance with curve 3 of Fig. 6. This curve takes into account the different transparencies of the penumbra regions at different latitudes. However, almost the same energy-spectrum exponents are obtained if the Stormer values of the cutoff energy are used (curve 3′ on Fig. 6). In this case the values obtained for counters 1 and 2 are $n_1 = 1.40 \pm 0.08$ and $n_2 = 1.20 \pm 0.13$, respectively.

†The exponents n given here and below have been corrected and are weighted means, unlike [1,5], where arithmetic mean values are given.

= 1.41 ± 0.12. Let us compare this result with the data given in [43]. From emulsion measurements made during the maximum of solar activity (1957), the slope of the alpha-particle spectrum was found to be n = 1.17 ± 0.14; measurements carried out in July 1959 gave nearly the same value, 1.12 ± 0.12. During the period of the minimum of solar activity (1950—1954), the measured value of the spectral exponent was n = 1.48 ± 0.12.

The average value of n obtained by satellite measurements lies between the largest and smallest cited values.

From measurements made at different latitudes, of fluxes of nuclei with Z ≥ 4 on the third space probe, using the same counters, the energy spectrum exponents obtained for this group of nuclei are n_1 = 1.43 ± 0.54 and n_2 = 1.38 ± 0.34. Since the values of n_1 and n_2 are nearly equal, the error of the weighted mean is small. The weighted mean value of the spectral exponent of nuclei with Z ≥ 4 is in this case 1.40 ± 0.004.

Thus, within the limits of error, the exponents of the integral energy spectra for nuclei with Z ≥ 2 (for the most part alpha particles) and nuclei with Z ≥ 4 (for the most part from group M) agree with each other.

The energy spectra for the groups with Z ≥ 5 and Z ≳ 12—14, obtained with an integral Cerenkov counter in the same flight, are shown in Fig. 11. Straight lines are drawn through the points at latitudes 15°, 35°, and 45°, and their slopes yield the value of n. The spectral exponent is n = 1.06 ± 0.23 for nuclei with Z ≥ 5 and n = 1.35 ± 0.17 for nuclei with Z ≳ 12—14.

Data on the integral energy spectra were obtained also with the aid of instruments carried by the second space probe. A summary of the power exponents for

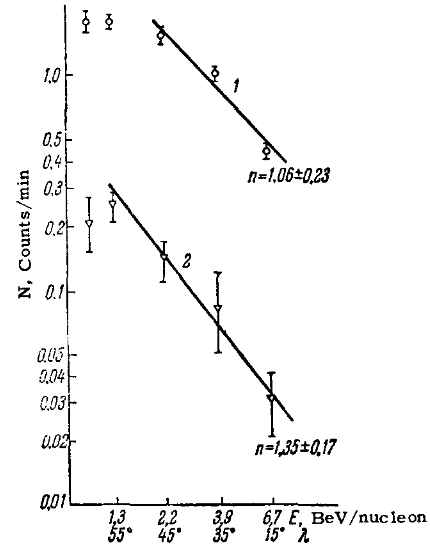

FIG. 11. Energy spectra of nuclei with Z ≳ 12(curve 1) and Z ≥ 12 – 14 (curve 2), obtained with the aid of an integral counter (flight of third space probe).

the energy spectra of different groups of nuclei as measured on the second and third space probes is listed in Table II. The values of n obtained by measurements on the second space probe for nuclei with Z ≥ 2 and Z ≥ 15 differ somewhat from the majority of values listed in Table II for the data of the third space probe (particularly for the case Z ≥ 2). In this connection we wish to point to the results of measurements of the energy spectrum of nuclei with Z ≥ 6, carried out with the aid of a pulsed ionization chamber on the satellite "Explorer VII"[44]. The reference cited indicates that a strong change occurred during a half year in the intensity and in the form of the spectrum of this group of nuclei. This result is

Table II

Name of satellite and recording instrument		Power exponent n for the integral energy spectrum of the nuclei: Z≥2	Z ≳ 4–5	Z ≳ 12–14	Z≥15
Third space probe	Differential counter 1	1.43±0.06	1.43±0.54	—	—
	Differential counter 2	1.21±0.17	1.38±0.34	—	—
	Weighted mean for counters 1 and 2	1.41±0.12	1.40±0.04	—	—
	Integral counter	—	1.06±0.23	1.35±0.17	—
Second space probe	Differential counter	0.83±0.24	1.18±0.43	—	—
	Integral counter	—	1.4±0.4	—	1.8 *

*This value of the spectral exponent has been obtained on the basis of scanty statistical material.

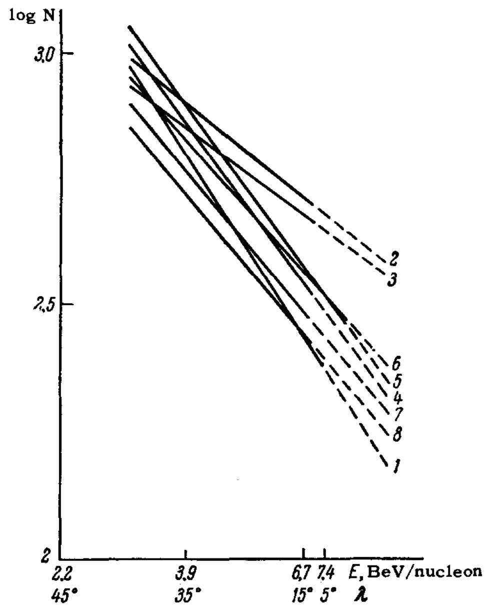

FIG. 12. Energy spectra of nuclei with Z ≥ 6 for different periods of time, plotted from the data of [44]. 1—End of October; 2 and 3—November (beginning and end); 4 and 5—December (beginning and end); 6 and 7—January (beginning and end); 8—beginning of February; the dashed lines denote extrapolation into the region of high energies.

shown in Fig. 12, where the energy spectra of nuclei with Z ≥ 6 have been plotted on the basis of data reported in [44] for different periods of the time from October 1959 through February 1960. The question of the nature of the observed changes is still unclear.

The values of n given in Table II for nuclei of different groups have been obtained under the assumption that at each latitude the cutoff energy corresponds to the arrival of nuclei in a vertical direction. In a rigorous analysis it would be necessary to take into account the time variation of the directivity of the instrument, and to calculate for each latitude the corresponding mean (effective) value of the cutoff energy. This, generally speaking, could change somewhat the obtained values of the exponents n. However, as already indicated, the deduction that the spectrum is identical for different groups of nuclei when registered with the same set of instruments is sufficiently well founded. We can therefore say that the spectral exponents are the same for nuclei with Z ≥ 2 and Z ≥ 4, which were registered by the same differential counter, and for the nuclei with Z ≥ 5 and Z ≳ 12—14, which were registered by the same integral counter.

According to some emulsion data (see the review [40]) the spectra remain the same for the nuclear groups M and H up to energies on the order of 100 BeV/nucleon.

The conclusion that the spectra of the nuclei of different groups are the same does not agree with the indications contained in [38] concerning a difference between the spectra, but agrees with the conclusions drawn in [37]. At the same time, it agrees with the notion that the composition which we observed in the "primary" cosmic rays is the result of fragmentation of very heavy nuclei accelerated in the source. Indeed, fragmentation results in particles which have approximately the same energy per nucleon as the "ancestor" nucleus. In this case the energy spectra of the "offspring" nuclei will more readily agree in practice with the spectrum of the nuclei accelerated in the cosmic-ray source.

b) Fluxes of nuclei of different groups and some information on the chemical composition of cosmic rays from measurements outside the earth's atmosphere. Investigations of the nuclear component of cosmic rays carried out with Soviet space vehicles were aimed at studying the chemical composition of the primary cosmic radiation. The instruments used were intended both to measure the fluxes of nuclei of different groups over a wide charge interval (and, in particular, to obtain an estimate of the relative fluxes of nuclei with very large Z) and to investigate the chemical composition of the cosmic rays in the region of light and medium nuclei.

Fluxes of nuclei with Z ≥ 2, Z ≥ 5, and Z ≥ 15. Let us discuss first the measurements carried out outside the earth's magnetic field with the aid of integral Cerenkov counters. The second space rocket [3] registered nuclei with Z ≥ 2, Z ≥ 5, and Z ≥ 15, while on the third space rocket [4] registered nuclei with Z ≥ 2, Z ≥ 15, and Z ≳ 28. The measurements were made on both rockets with identical counters, whose detectors had identical dimensions (the conditions under which the light was gathered in the detectors were also the same). We can therefore compare the counting rates in both counters without resorting to any recalculations.* For identical thresholds (Z ≥ 15) the counting rates of both counters agreed within the limits of statistical errors.

The ratios of the fluxes can be obtained directly with sufficient accuracy, without any assumptions, being equal to the ratios of the counting rates in the corresponding channels.

It must be emphasized that by measuring the relative fluxes of nuclei from different groups in a single flight, we eliminate to a considerable degree the influence of the time variations if we disregard variations of such a type that these fluxes vary in different fashions (see, in particular, Sec. 3).

Table III lists the values of the fluxes of different groups of nuclei, obtained on the basis of measure-

*The threshold Z ≥ 2 on the second space rocket corresponded to registration of two singly-charged relativistic particles, while the threshold Z ≥ 3 on the third space rocket corresponded to the registration of four singly-charged particles. Thus, a comparison of the measurement results at these two thresholds cannot be made directly, and calls for the introduction of suitable recalculations.

Table III

Registered group of nuclei	Counting rate of integral Cerenkov counter, pulses per minute	Flux, particles/m² sec-sr
$Z \geq 2$	23.5 ± 0.2	150
$Z \geq 5$	1.91 ± 0.06	10.6
$Z \geq 15$	0.08 ± 0.01	0.4—0.5

ments with integral Cerenkov counters during the flights of the second and third space rockets. The fluxes listed in Table III were obtained for the values of the geometrical factor indicated in the last column of Table I.

Measurements of the fluxes of the nuclei of different groups were made also with space probes, using integral and differential Cerenkov counters. The differential counter had a geometrical factor $\Gamma \approx 2.5$ cm²/sr and registered nuclei only in a narrow angle with aperture $\alpha \approx 27°$.

Table IV gives the flux of nuclei with $Z \geq 2$ (with differential counter) and with $Z \geq 5$ and $Z \gtrsim 12-14$ (integral counter) as measured on the third space probe. The errors indicated in the last three columns of Table IV characterize only the statistical accuracy of the measurements, and do not take into account such factors as the change in orientation; in the case of the integral counter no allowance is likewise made for the inaccuracy in determining the transmission of the instrument.

By a comparison with the nuclear fluxes measured in December 1960 at high latitudes with the flux in free space (Table III) we see that these quantities are close to each other.

Fluxes of nuclei with large Z. The measurement of the flux of nuclei with $Z \gtrsim 28$ (simultaneously with measurement of the flux of nuclei with $Z \geq 15$) was made during the flight of the third space rocket (AMS, 4—17 October 1959).

For the channel with $Z_{thr} \approx 28-30$, the factor Γ was calculated with less certainty, for in this case the nuclei with $Z \gg Z_{thr}$ are weakly represented in the cosmic rays, apparently, and Γ for nuclei with Z close to Z_{thr} changes noticeably for the neighboring nuclei.

Thus, we have $\Gamma \approx 21$ for $Z_{thr} = 28$ in the case of nuclei with $Z = 31$, $\Gamma \approx 18$ for $Z = 30$, and $\Gamma \approx 10$ for $Z = 28$.

If we assume that the counts in the channel with $Z_{thr} \approx 28-30$ are due to very heavy nuclei ($Z > 30$), then in this case $\Gamma \approx 20$ and the flux of such nuclei (called in [4] the flux of nuclei with $Z \geq 28-30$) amounts to approximately 0.1 particle/m² sec-sr.

Allowance must be made, however, for the fact that the threshold in this channel was established near the relatively abundant group of nuclei Fe, Co, and Ni. In this case, as indicated in [4], the Ni nuclei ($Z = 28$) and even the Fe nuclei ($Z = 26$) could contribute to the number of counts if they passed through the detector along the diagonal of the cross section. The geometrical factor for $Z = 28$ with $Z_{thr} = 28$ amounts to approximately 3, while for $Z = 27$ and $Z_{thr} = 28$ it is somewhat higher. Recognizing that the relations between the fluxes of Fe, Co, and Ni in cosmic rays are the same as for the average abundance in nature[45], and assuming that all the counts in the channel with $Z_{thr} \approx 28-30$ are due to the nuclei of this group, we obtain an upper limit of 0.5 particle/m² sec-sr for the flux of the Fe, Co, Ni group of nuclei. This is close to the flux given in Table III for the nuclei with $Z \geq 15$, which is most likely, for there are indications that the flux of nuclei from the group with $15 < Z < 20$ is

Table IV

Interval of geomagnetic latitudes	Rigidity cut-off interval for nuclei arriving vertically, BV	Rigidity and cutoff energy for nuclei arriving vertically at the average latitude		Nuclear fluxes*, particles/m² sec-sr		
		BV	BeV/nucleon	$Z \geq 2$	$Z \geq 5$	$Z \gtrsim 12-14$
0—10°	14.9—14.1	14.7	7.4	26.0 ± 4.7	2.3 ± 0.3	
10—20	14.1—12.2	13.2	6.7	29.3 ± 4.7	2.0 ± 0.3	0.15 ± 0.06
20—30	12.2—9.3	11.0	5.6	38.0 ± 5.3	3.2 ± 0.2	
30—40	9.3—5.7	7.6	3.9	80.0 ± 7.3	5.7 ± 0.5	0.40 ± 0.15
40—50	5.7—2.7	4.0	2.2	121.3 ± 8.7	8.5 ± 0.6	0.7 ± 0.2
50—60	2.7—0.9	1.6	1.2	120.6 ± 8.7	9.8 ± 0.7	1.3 ± 0.2
60—70	—	—	—	150.0 ± 14.7	9.7 ± 1.1	1.1 ± 0.3

*In determining the fluxes we eliminated from consideration regions of anomalies of the radiation intensity, where the number of discharges of the telescope was more than 50 per second (see [14]). At such a counting rate, the random coincidences of the telescope discharge and of the pulse from the alpha particle passing through the detector outside the solid angle subtended by the telescope, amounts to approximately 20% of the total true number of alpha particles passing through the telescope.

small[46] and the main contribution to the flux of the $Z \geq 15$ group is made by nuclei with $Z > 20$ (for the most part iron and the neighboring nuclei).

Thus, the data obtained determine the upper limit for the estimate of the flux of nuclei with $Z > 30$. This flux is at any rate smaller than 0.1 particle/m^2 sec-sr, since some of the counts of the Cerenkov counter are due to the passage of Fe, Co, and Ni nuclei through the counter.

Stratosphere measurements have made it possible to determine the flux of nuclei of the iron group under the residual layer of the atmosphere, but only scattered data are available on nuclei heavier than iron. One can expect their flux to be quite small compared with the flux of the iron nuclei, although indications of a different character have also been obtained[47].

To measure the flux of the heavy nuclei it is particularly important that there be no absorbing atmosphere layer, since the free path of the nuclei decreases with increasing atomic number.

An estimate of the flux of very heavy nuclei was made on the basis of measurements carried out during flights of the third satellite and the two space probes.

The first instrument for the registration of the nuclear component on a satellite (the third artificial earth satellite) was intended for the registration of the relative value of the fluxes of nuclei with $Z > 30-40$ and $Z \gtrsim 15$. It must be noted that the thresholds which determine the smallest charge of a registered nucleus were set in the first measurements quite crudely and possibly the nuclei registered in the experiments had a charge somewhat smaller than 15. A difficulty can arise also in the registration of nuclei with charge 30—40, because the large light pulses produced by such nuclei can saturate the photomultiplier. An important fact in this case is that the Cerenkov flash has a very short duration, and from the fact that the photomultiplier is linear for longer light pulses (for example, thyratron flashes) it still does not follow that the photomultiplier is linear when heavy nuclei are registered. It has been shown by plotting the characteristics of the employed photomultipliers with the aid of a spark source producing short pulses that the characteristic of the photomultiplier actually differs from linear, although saturation does not yet set in in the region of pulses corresponding to a charge of 30. A decrease in the slope of the characteristic in the region of large light flashes causes a threshold set at 30 to correspond actually to somewhat larger charges. For individual photomultipliers such a shift corresponds to moving the operation to the region of charges up to $Z \sim 40$.

Measurements of very heavy nuclei were made later with the aid of instruments mounted on the second and third space probes, but the signal was picked off in that case from one of the intermediate dynodes of the photomultiplier, thus ensuring absence of saturation.

The measurements carried out on the third artificial earth satellite and on the space probes* have shown that the flux of very heavy nuclei is quite small. It was possible to obtain only an upper estimate of the relative magnitude of the flux, since such nuclei were not registered in practice, owing to the smallness of the flux. The third earth sattelite registered only one nucleus with $Z > 30-40$ in nine days, and not a single nucleus was noted with $Z > 34$ during the days of the flight of either the second or the third space ship. Data from the third artificial earth satellite lead to an upper estimate of 0.01—0.03% for the ratio of the fluxes of nuclei with $Z > 30-40$ and $Z \gtrsim 15$.

The estimate presented takes into account the possibility of missing a certain number of nuclei (which pass through the detector) during the registration, as a result of the fact that the instrument readings were processed only for a definite time interval[2] (when a single nucleus is registered we have in practice a non-zero probability of passage of not more than 5 nuclei through the detector).

The upper estimates which can be obtained from the ratio of the fluxes of nuclei with $Z > 34$ and $Z \gtrsim 12-14$ on the basis of the measurements made on the third space ship, under the assumption that the flux of nuclei with $Z > 34$ corresponds to registration of one nucleus per day, is approximately 1%. Of course, this estimate is only an upper limit, and the true ratio of the fluxes is much smaller, since this value corresponds to registration of at least one nucleus, while actually not a single nucleus with $Z > 34$ was registered during the entire time of flight of the second and third space satellite-ships. Thus, the measurements carried out on the space ships do not contradict the estimate obtained from the data of the third artificial earth satellite.

The instrument installed on the third space probe had in addition to a channel for registration of nuclei with $Z > 34$, also a channel for counting the nuclei with $Z \gtrsim 31-34$, which registered only one nucleus per day, and there are grounds for assuming that this single event was due to arrival of nuclei of solar origin (the instant when the nucleus with $Z \gtrsim 31-34$ was registered coincided with a brief increase in the intensity of the other groups of nuclei, apparently connected with a solar chromospheric flare[9]; this case will be discussed later in Sec. 3). Thus, even for nuclei with $Z \gtrsim 31-34$ the ratio of their flux to the flux of nuclei with $Z \gtrsim 12-14$ does not exceed the given estimate, on the order of 1%, and if we recognize that the registered arrival of a nucleus with $Z \gtrsim 31-34$ may be due to nuclei from the sun, then the estimate of the intensity of very heavy nuclei of non-solar origin should be greatly reduced.

*The thresholds were set more accurately on the space probes than on the third artificial earth satellite. It must be borne in mind, however, that the threshold value of the charge could actually exceed the value indicated in the text by approximately 10%.

Nuclei of group L (Li, Be, B). Measurement of the flux of nuclei of group L calls for a sufficiently distinct separation by amplitude of the pulses produced in the Cerenkov detector by the nuclei with different charges. Such possibilities, as indicated above, are afforded in principle by a Cerenkov differential counter. The relatively low transmission of the instruments installed on the space probes did not make it possible to plot the amplitude distributions of the signals from the Cerenkov counters in narrow latitude intervals. However, since the energy spectra of the different groups of nuclei are practically the same during the period of one experiment (approximately 24 hours), no great changes were observed in the intensity of the most abundant groups of nuclei, and when plotting the distributions we were able to sum all the registrations of identical pulses and construct a summary distribution for the entire measurement time (Fig. 13).

The shaded area in Fig. 13 pertains to the case when nuclei were registered without accompaniment. The unshaded area pertains to the case when the passage of the nucleus through the detector was accompanied by a "master pulse" indicating operation of more than one counter in the lower row of the telescope.*

An examination of Fig. 13 shows that in the region $Z > 3$ there is satisfactory separation of the peaks. The peak of the Li nucleus is "washed out" by the pulses from the alpha particles. One could attempt to separate the Li nuclei by plotting the theoretical amplitude-distribution curve for the alpha particles, similar to that shown in Fig. 5. We shall use, however, the published data on the flux ratio of Li, Be, and B. According to [48], the fluxes of the nuclei Li, Be, and B are related as 1:2:3. According to our data the ratio of the numbers of Be and B nuclei is the same (2:3), and we therefore assume that the Li nuclei constitute approximately one-sixth of the flux of the group-L nuclei. It is seen from Fig. 13 that very few nuclei heavier than oxygen were registered. This is connected with the fact that pulses from nuclei with $Z \geq 8$ enter the region where saturation begins, and cannot be distinguished from one another. Some of these pulses contribute to the peak of the nitrogen nuclei; this is probably the cause of the large ratio of the flux of nitrogen nuclei to the flux of carbon nuclei, which is found in the literature.

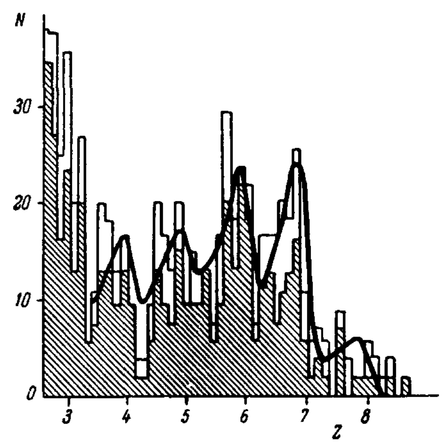

FIG. 13. Charge spectrum of nuclei in the region of values of Z from 4 to 7. Smooth curve–charge distribution calculated with allowance of the velocity spectrum of the nuclei and agreeing in best fashion with the measurement results.

*Cases accompanied by a lower master pulse were mostly due to passage of a nucleus through the telescope, with the lower counter array opperating as a result of production of a δ electron or a fragment in the detector. It can be noted that the cases accompanied by a lower master pulse, corresponding to nuclei with $Z \geq 4$, have a latitudinal dependence which is close to the latitudinal dependence of the cases without a "master pulse."

Since the available statistical material does not make it possible to separate data pertaining to the equatorial region and by the same token get rid of the influence of the velocities, it is necessary to allow in the analysis of the obtained summary distribution for the influence of the fact that the registered particles are not monoenergetic. To this end a theoretical curve is plotted, as indicated above (page 233). Figure 13 shows such a curve, obtained by summing the distributions for different Z, taken with normalization factors that make the theoretical curve pass closest to the experimental ones.

In constructing the theoretical curve for the amplitude distribution, no nuclei heavier than oxygen were taken into account, since the pulses produced by such nuclei entered the saturation region and were in fact included in the distribution in the form of a background, essentially in the region of the C, N, and O nuclei.

Without analyzing the chemical composition by individual elements, which can be distorted by saturation in the charge region 7–8, we can estimate the ratio of the flux of the light nuclei of group L to the flux of the nuclei of group $S = M + H$. The value obtained for this ratio is $31.0 \pm 9.6\%$. This quantity differs from the preliminary value $53 \pm 8\%$ given earlier [1] because allowance was made for the dependence of the amplitude distributions on the velocities of the nuclei.

c) Comparison with the published results. Let us compare the obtained values of the fluxes with the published data. In such a comparison it is necessary to bear in mind, however, that full agreement should not be demanded for the results obtained during different periods of time. Even if we disregard the noticeable changes in the spectrum and in the absolute intensity of the fluxes, which correlate with the 11-year cycle of solar activity, noticeable changes are observed also in the spectrum and in the flux over relatively small periods. Such a result was obtained, in particular, in [44] (see page 238).

Alpha-particle flux. The changes in the flux of alpha

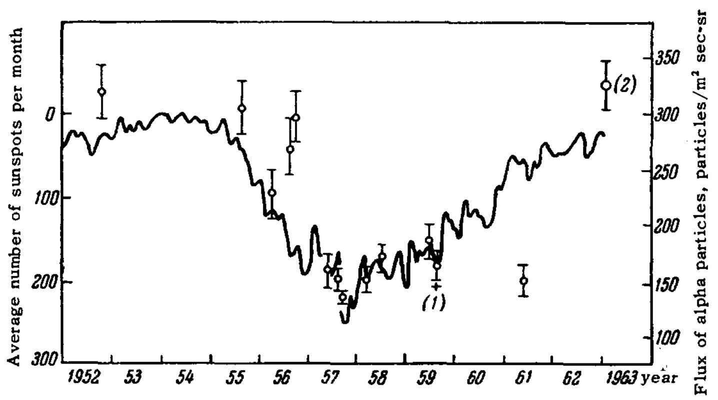

FIG. 14. Variation of the alpha-particle flux during the 11-year cycle of solar activity. Continuous line–number of sunspots characterizing the solar activity, points–alpha-particle flux. 1–Measurements on the second space rocket; 2–measurements on the rocket "Mars–I" (the point for 1961 was obtained in [57]).

particles as a function of the 11-year cycle of solar activity are illustrated in Fig. 14. The figure shows the values of the alpha particle flux with $E_{kin} \gtrsim 200$–500 MeV/nucleon, obtained during different years in different measurements, and shows the number of sun spots, which characterize the solar activity, observed in the corresponding years. The absolute values of the flux of alpha particles with $E_{kin} \gtrsim 200$ MeV/nucleon during the period from 1955 through 1961 are given in Table V (which list also the readings of a neutron monitor as reported in [43], characterizing the total cosmic-ray flux). From Fig. 14 and Table V it is seen that during the period of minimum solar activity (1951–1954) the largest values of the alpha-particle flux were registered, on the order of 300 particle/m^2 sec-sr, whereas during the period of maximum solar activity (1957–1958), the alpha-particle flux decreased to approximately 150 particles/m^2 sec-sr.

Measurements made at the end of 1962 on the rocket "Mars-I" (point 2 on Fig. 14) have shown that the alpha-particle flux during that period reached a value corresponding to the flux at the minimum solar activity (1954–1955).

Comparison of the presented data on the measurements made on space rockets and satellites with the results of other investigations is made difficult by the difference in the threshold energies of the registered particles and the difference in the time of measurements. Thus, the data of Table V cannot be used for such a comparison, since they were obtained at latitudes in which the cutoff energy lies below the threshold of the employed Cerenkov counter. The few published measurement data for 1959–1960, at sufficiently high cutoff-energy values, are gathered in Table VI.

Figure 15 shows the results of measurements of the flux of alpha particles for different values of the energy threshold (at different latitudes) during different periods of time. The straight line I was drawn through the points obtained during the flight of the third satellite-ship at geomagnetic latitudes below 50° by the method of least squares. As can be seen from Fig. 15, the values of the flux attained during the flight of the third satellite-ship in this region of latitudes are close to the values pertaining, in accordance with [37], to the period of minimum solar activity (and even exceed the latter somewhat).

This result agrees with the fact that by the end of

Table V

Measurement date	Cutoff energy, MeV/nucleon	Alpha particle flux, particles/m² sec-sr	Readings of neutron monitor	Procedure	No. of point on Fig. 15	Literature
7.VII.1955	280	305±25	3124	Cerenkov counter		49
13.III.1956	280	227±23	3012			49
17.V.1956	150	255±20	2959	Emulsions		50
17.VIII.1956	280	270±25	3104	Cerenkov counter		49
21.VIII.1956	200	298±25	3134			49
18.IX.1956	130	240±26	3133	Emulsion		51
17.V.1957	225	157±17	2837	The same		52
30.VII.1957	200	151±9	2829	"		53
1.IX.1957	200	136±9	2573	"	1	54
16.II.1958	225	150±12	2713	Cerenkov counter		55
14.VI.1958	200	171±11	2771	Emulsion		51
14.VI.1958	200	130±15	2771	"		43
2.VII.1958	160	149±12	2665	Cerenkov counter		55
16.V.1959	256	142±10	2728	The same	3	56
2.VI.1959	240	186±14	2838	"	4	56
29.VII.1959	200—300	167±12	2645	Emulsion	5	43
28.IV.1961	300	152±14	—	"	9	57

Table VI

Measurement date	Total cutoff energy, BeV/nucleon	Alpha particle flux, particles/m² sec-sr	Number of point on Fig. 15	Literature
23.VIII.1960	1.5	162±5	—	58
XI.1959	1.63	124±25	7	58
29.VII.1959	2	107±12	6	43
8.II.1959	2.9	76±4	2	59
12.III.1960	7.1	19.7±1.2	8	60

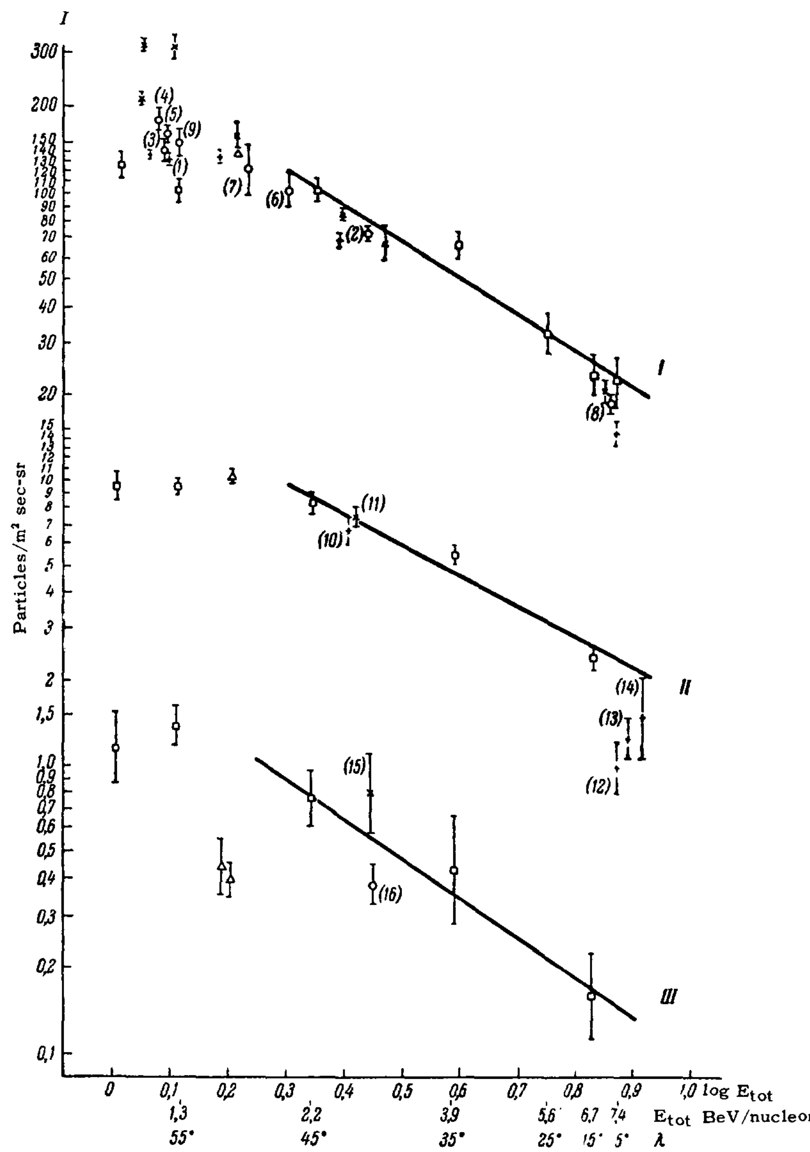

FIG. 15. Fluxes of alpha particles (I), nuclei with $Z \geq 5-6$ (II), and with $Z \gtrsim 12-15$ (III). □–measurements on the third space probe; △–measurements on the second and third space rockets (in cases □ and △ the alpha-particle fluxes were obtained as the difference of fluxes of nuclei with $Z \geq 2$ and $Z \geq 4$); circle with number–measurements during a period close to 1959; × and +–measurements during the period of minimum and maximum solar activity, respectively. The numbers of the points correspond to those in Tables V–VIII, and the points without numbers are taken from the review [37].

1960, when the flight of the third space probe took place, the solar activity was considerably lower than during the maximum (1957–1958), reaching almost the level of the end of 1955. It should be noted that the data of [37] do not pertain to the period of the deepest minimum of the solar activity, but include a broader time interval.

The results of measurements on the second space rocket, and also the measurement data of [43,58,60] (points 6, 7, and 8 on Fig. 15) were obtained in 1959 and at the beginning of 1960. Although at that time some decrease in the solar activity had already began, its level was still insignificantly below that of 1957–1958. Accordingly, the data of the second space rocket and the points 6, 7, and 8 occupy an intermediate position between the values characterizing in accordance with [37] the minimum and maximum solar activity.

Thus, the data of the third space probe, the second space rocket, and of [43,58,60] agree with the data of [37], indicating that the alpha-particle flux is dependent on the 11-year period of solar activity. At the same time, the value of the flux given in [59] (the point 2 on Fig. 15), which pertains to the beginning of 1959, is close to the results obtained during the period of minimum solar activity, although the beginning of 1959 was still characterized by a sufficiently high solar activity. In [57] is given the flux value obtained in the middle of 1961 which, to the contrary, is appreciably lower than the value expected during that period of time in accordance with the change in the solar activity (see Fig. 14). It is concluded in [57] on this basis that the variation of the alpha-particle flux lags the variation of the solar activity.

There is no doubt whatever that the flux of alpha particles is modulated by the 11-year period, but this modulation is more strongly pronounced for particles of lower energy. It is still necessary, however, to investigate the details of this process, particularly the depth of modulation at different energies, and its correlation with the directly observed solar activity, etc.

A comparison of the data on the fluxes of alpha particles with the readings of the neutron monitors pertaining to the same period of time shows good correlation of the measured values. Figure 16 shows the dependence of the alpha-particle flux on the readings of the neutron monitor as given by [61] (curves I and II), and also the points obtained in other investigations (this figure is borrowed from [61]). The values of the flux obtained during the flight of the second space rocket and the third space probe are designated by standing and lying crosses, respectively. Curve I pertains to a rigidity R > 1.5 BV, while curve II pertains to R > 4.5 BV. During the measurements made on the second space rocket, the threshold rigidity (defined by the threshold of the Cerenkov counter) was approximately 2.5 BV, but the measured flux turned out to be close to the value obtained in [61] for a threshold rigidity 1.5 BV. The expected difference between the flux of the alpha particles with R > 1.5 BV and the flux with R > 2.5 BV is approximately 20%. In the case of the space probe it was possible to employ the measured latitude dependence of the alpha-particle flux, and thereby select cases corresponding to R > 4.5 BV, so as to make a comparison between fluxes having the same threshold energy.

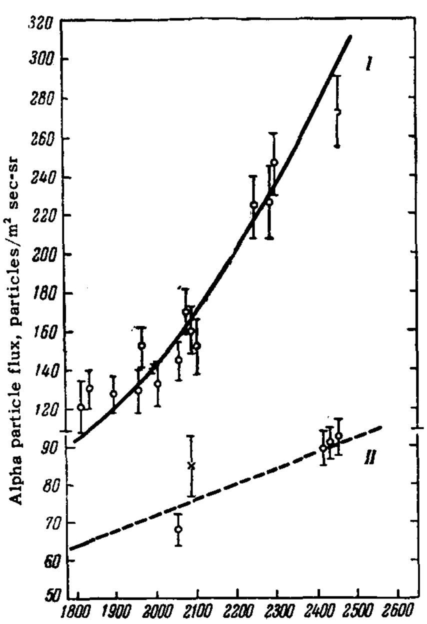

FIG. 16. Dependence of the alpha-particle flux on the readings of the neutron monitor as given by [61]. Curve I – R > 1.5 BV. Curve II – R > 4.5 BV. + –measurements on the second space rocket (E_{kin} > 500 MeV/nucleon). × – measurements on the third space probe (E_{kin} > 1.5 BeV/nucleon), O–data of [52,62-67,51] (taken from [61]).

Groups M and H. The values of the fluxes of nuclei with charge Z ≥ 5 as given by integral counters installed on the third space probe, for different latitudes [3,5], are shown in Fig. 15 (squares). A least-square line II was drawn through these points (measurements at latitudes smaller than 50° were used). Figure 15 shows also the flux of nuclei with Z ≥ 5 as obtained by the second space rocket (triangle).

For comparison, Table VII lists the fluxes of nuclei with charge Z ≥ 6 as obtained from different sources, and the corresponding points are plotted in Fig. 15. As in the case of alpha particles, the straight crosses pertain to the maximum period and the lying crosses to the minimum period of solar activity. The flux of nuclei with Z ≥ 5, obtained on the third space probe for cutoff energies (kinetic) on the order of 1.5 BeV/nucleon, lies between the maximum and minimum values of the flux of the group S nuclei, shown in Fig. 15. In the region of higher energies (equatorial latitudes), the flux exceeds the values obtained in other investigations. Also connected with this is the relatively low value of the exponent of the energy spectrum, n = 1.06 ± 0.23.

Figure 17 shows the flux of the group M nuclei as functions of the readings of the neutron monitor, as given by [61] and by other measurements (the figure is borrowed from [61]). Since the integral counters used on the second space rocket and in the third space

Table VII

Measurement date	Total cutoff energy, BeV/nucleon	Flux of nuclei with Z ≥ 6, particles/m² sec-sr	No. of point on Fig. 15	Literature
19.X.1957	2.6	6.8±0.8	10	68
Period of solar minimum	2.6	7.64±0.53	11	40
12.II.1957	7.3	1.03±0.19	12	69
I.1957	7.4	1.30±0.19	13	70
I.1957	7.4	1.54±0.43	14	71

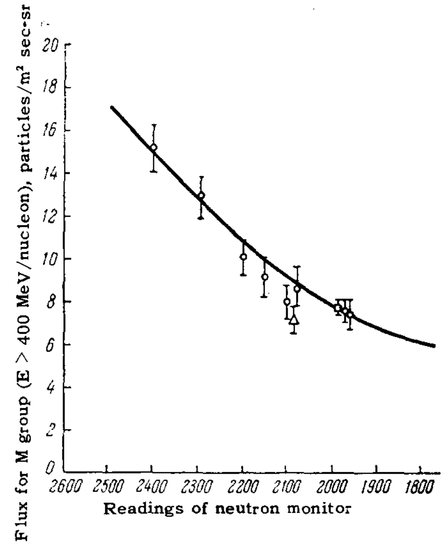

FIG. 17. Dependence of the flux of group M nuclei, with $E_{kin} > 400$ MeV/nucleon, on the readings of the nucleon monitor. ○ – data of [48,61,62,72] and others (from [61]); □ – measured on the second space rocket; △ – measured on the third space probe; —— – flux of alpha particles as given in [61] (reduced by a factor 12).

probe did not register separately the nuclei of group M, but measured the total flux of nuclei with $Z \geq 5$, in order to compare the results of these measurements with those given in 17 we used the ratio of the fluxes of nuclei of H and M known from different investigations (see below). It is equal to approximately $1/3$, that is, the flux of the group-M nuclei amounts to $3/4$ of the flux of nuclei M + H (nuclei with $Z \geq 6$). The values obtained in this manner for the flux of the M nuclei, equal to $3/4\, F\, (Z \geq 5)$, as obtained from the second space rocket and the third satellite-ship, are also shown in Fig. 17.

For nuclei with $Z \gtrsim 12-14$ it is difficult to make out definite comparisons, since there are very few results pertaining to the given region of charge values. Figure 15 shows the results of measurements made on the third space probe. The same figure shows points obtained during the flights of the second and third space rockets for nuclei with $Z \geq 15$. For comparison there are shown the results of measurements [46] and [73] (points 15 and 16, respectively; see Table VIII). Point 16, shown in Fig. 15, pertains to nuclei with $Z \geq 20$. Since the flux of primary nuclei is small in the region of charges from 15 to 20, the comparison of the fluxes of nuclei with $Z \geq 15$ and $Z \geq 20$ is perfectly permissible. As regards nuclei with charge $Z \geq 12$, their flux can be noticeably larger. Some uncertainty in the establishment of the threshold of the integral counter for nuclei of this group makes it difficult to make the comparisons. The data of the second and third space rockets give for the flux of nuclei with $Z \geq 15$ a somewhat smaller value than the results of [46,73].

Whereas for the alpha particles, and also apparently for the nuclei of group M, there is a noticeable dependence of the flux on the degree of solar activity, for the heavier nuclei the available data do not permit an unambiguous conclusion concerning the character of the dependence of the value of their flux on the solar activity. It is seen from Table VIII that the flux during the period of solar minimum is noticeably larger than the flux measured in 1957–1958. However, there are indications of a different character, too. Thus, for example, according to [75] no appreciable changes in the flux of nuclei of group H were observed over several years. It must be noted, however, that these data pertain essentially to the period of minimum solar activity, with the exception of the results of measurements made in 1956 and 1960.

Table VIII

Measurement date	Flux of nuclei with energy $E_{kin} \geq 1.55$ BeV/nucleon, particles/m² sec-sr		No. of point on Fig. 15	Literature
	Nuclei of group H	Nuclei of group VH		
4.II.1959	1.26±0.09	0.39±0.06	16	73
9.III.1958	1.11±0.11	—		74
19.X.1957	1.70±0.30	—		68
6.II.1956	2.07±0.28	0.71±0.23 ($Z \geq 20$)	—	46
		0.82±0.23 ($Z \geq 15$)	15	
Solar minimum	2.50±0.20	0.69±0.16		37

In order to establish reliably the character of the 11-year variations of the flux of heavy nuclei, further experiments are necessary, which would make it possible to determine the flux with sufficiently good statistical accuracy with the aid of identical apparatus during different years.

Measurements of the fluxes of group M and H nuclei would yield the ratio of these fluxes, something of great importance for comparison with a theoretical study of the origin of cosmic rays. Different investigators have obtained nearly equal values for this ratio. In [76] (emulsion method) a ratio H/M = 0.38 ± 0.04 was obtained; according to [61] (Cerenkov counter, flight in 1958 at a depth 6 g/cm²) H/M = 0.25 ± 0.07 (for nuclei with energy $E_{kin} > 0.55$ BeV/nucleon). Figure 18 shows the values H/M measured at different depths in the atmosphere by different investigators. The dashed line shows extrapolation of the data of [40], obtained at a depth 12 g/cm², to the top of the atmosphere. The solid line has been drawn by the method of least squares through all the points shown in Fig. 18. The best value is assumed in [40] to be H/N = 0.34 ± 0.04. This agrees with the value H/M = 0.30 ± 0.02 obtained in [46]. It must be noted that according to the data of this latest investigation, the ratio does not decrease but, conversely, increases somewhat with depth of the residual layer of matter above the apparatus.

Nuclei of group L. The ratio L/S = 0.31 ± 0.10 given above can be compared with the value L/S = 0.18 ± 0.04 obtained by extrapolating the measure-

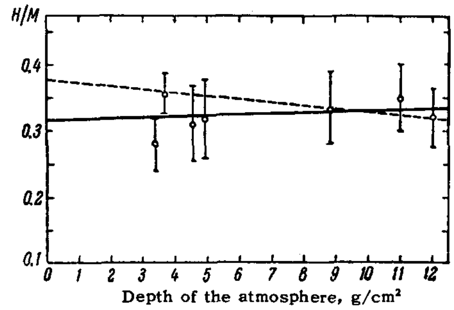

FIG. 18. Dependence of ratio A/M on the depth at which the measurements were carried out. The solid line [40] is drawn by least squares through points obtained in different investigations; the dashed line is an extrapolation of the data of [40], obtained at a depth 12 g/cm², to the top of the atmosphere.

ments of [76] to the top of the atmosphere. This quantity can vary somewhat, depending on the fragmentation parameters used in the extrapolation. For example, according to Waddington, the same experimental data (that is, L/S = 0.24) yield upon extrapolation a value L/S = 0.19 ± 0.02. Our value L/S = 0.31 ± 0.10 agrees somewhat better with the extrapolation of the data of [40], which yields a value L/S = 0.27 (Fig. 19), and also with the data [61] obtained in measurements with a Cerenkov counter at a depth of 6 g/cm². The measurements of [61] were made at the same threshold energy as our measurements ($E_{kin.thr} \approx 0.5$ BeV/nucleon), and yielded L/S = 0.31 ± 0.9 (for the 1958 flight). Our data are shown by a cross in Fig. 19. No corrections were made for the presence of a layer of matter, 1 g/cm² of aluminum, and for fragmentation of the primary nuclei in the detector itself. It must be noted, however, that these corrections are small, since the layer of matter is thin, and in addition the products of the breakup of the nuclei in this layer enter the detector without having a chance to fly asunder, so that they produce pulses which do not correspond to any definite value of the charge, but merely increase the total background. Some of these events are eliminated by the presence of master pulses indicating the operation of more than one counter in each of the counter groups of the telescope.

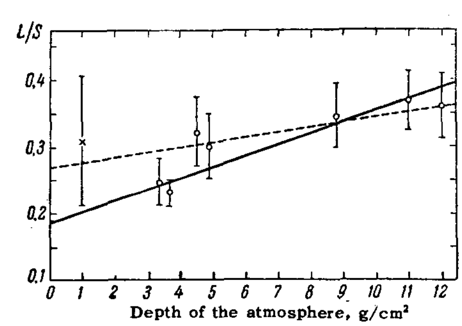

FIG. 19. Dependence of the ratio L/S on the depth at which the measurements were made. Notation is the same as in Fig. 18; for comparison, data obtained on the third space probe (cross) are indicated.

The value given for the ratio L/S pertains to cases which include pulses accompanied by a master pulse indicating the operation of more than one counter in the lower row. For cases which are not accompanied by master pulses, the value of L/S obtained does not differ within the limits of errors, from that given above (L/S = 0.25 ± 0.09).

The aggregate of experiments made at high altitudes indicates definitely that the primary flux of cosmic rays contains near the earth nuclei of lithium, beryllium, and boron, amounting to 20–30% of the heavier nuclei. The observed quantity of these nuclei corresponds to the passage of cosmic rays in interstellar space of a path of 5–10 g/cm² of matter [29–31], if it is assumed that the primary cosmic rays at the source, as on the average in nature, do not contain practically any nuclei of these elements. Some uncertainty in the estimate of the effective amount of matter traversed by the cosmic rays in space is connected with the insufficiently exact knowledge of the parameters of fragmentation of the heavy nuclei in the interstellar medium.

As was already indicated, there are still no sufficiently reliable data on the content of nuclei of individual elements in the cosmic rays. Some information on the fraction of nuclei with different charges in primary cosmic rays are given in Table IX.

As can be seen from Table IX, although the data relative to the abundance of nuclei of individual elements are not in agreement, there are some common features, for example, the predominance of carbon nuclei relative to oxygen nuclei (in a ratio on the order of 3:2), the lower content of nitrogen nuclei compared with nuclei of carbon and oxygen.

Table IX

Symbol of element	Percentage content of nuclei of different elements in the cosmic radiation (per cent of total flux of nuclei with Z ≥ 3)			
	as given in [40] (emulsions)*	as given in [60] (Cerenkov counter), $A_{kin} \gtrsim 0.5$, BeV/nucleon	as given in [76] (emulsions)	as given by measurements on the third space probe**
Li	3.9	—	5.3	4.0
Be	1.7	6.7	2.3	8.0
B	11.6	10.1	7.4	12.0
C	26.0	28.6	30.1	25.0
N	12.4	13.3	9.7	
O	17.9	17.9	19.4	
F	2.6	—	2.4	
Z⩾10	23.9	16.6	23.4	
Z>6	56.8	47.8	54.9	52.5

*The errors in the quantities presented are ±(20–30%).

**The content of Li nuclei is assumed to be 1/3 of the content of B nuclei; for nuclei with Z > 6 the total abundance of the entire group was obtained in these measurements.

d) Composition of cosmic rays and abundance of elements in nature. One of the general properties of the chemical composition of cosmic rays is the decrease (albeit nonmonotonic) of the flux of nuclei with increasing atomic number Z. In this respect, the composition of the cosmic rays is similar to the composition of astronomical objects. Were all the nuclei to be accelerated with equal efficiency during the production of the primary galactic cosmic rays in the sources, then it would be natural to expect the chemical composition of the cosmic rays on earth to reflect, in the main features, the composition at the sources. Actually, however, the chemical composition of the cosmic rays differs essentially from the average chemical composition possessed by the majority of observed astronomical bodies, that is, from the average abundance of the elements in the universe. The relative content of heavier nuclei is larger in cosmic rays than in nature on the average.

This singularity is quantitatively expressed by the Z-dependence of the ratio of the abundance of nuclei of different elements in the cosmic rays to their abundance in nature (this ratio will be designated K).

Figure 20 shows a plot of K(Z) based on the data gathered by Zuss and Urey[77] on the average abundance of elements in nature and data on the content of nuclei of different groups in cosmic rays, given in [40] and in [46]; the results of measurements made on the Soviet space rockets and satellites are also given[2-5]. A value K = 1 was assumed for the protons, and when using the data obtained on the cosmic rockets and satellites, the value of K for alpha particles was normalized to 2. It is seen from Fig. 20 that, as indicated in [78], the value of K increases with the increasing atomic number in approximate proportion to Z. However, it must be stipulated that this rule is quite arbitrary. Thus, for example, for nuclei of the group $Z \geq 15$ the experimental point obtained in [3] corresponds more or less well to such a rule, whereas usually one cites approximately double the value for the flux of these nuclei, and in this case the corresponding point lies much higher. On the other hand, in the region of light nuclei of group L, there is a sharp deviation from the indicated rule. (The value of K for this region of Z is of the order of 10^5 and is not shown in Fig. 20). This is due to the fact that the nuclei of group L have a higher relative abundance in cosmic rays than the nuclei of group M. In other words, the curve showing the dependence of the natural abundance of the elements on Z has a sharp dip in the region of values $Z = 3-5$, and the corresponding nuclei appear in cosmic rays following interactions between the heavy nuclei and the atoms of interstellar hydrogen.

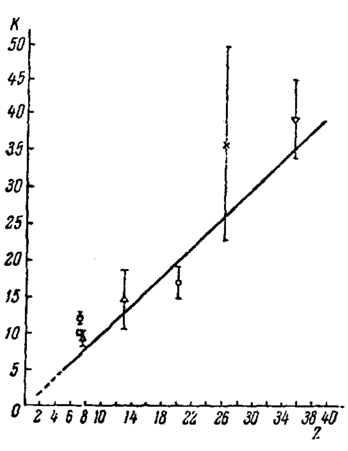

FIG. 20. Ratio of the content of nuclei in cosmic rays to their average abundance as a function of Z. □–data of [40]; ○–measurements on the second space rocket; △–measurement on the third satellite-ship; ×–data of [46]; ▽–measurement on the third artificial earth satellite. All the results were normalized to the straight line K = Z at the corresponding points: □–at Z = 1; ○ and △–at Z = 2; ×–at Z = 7; ▽–at Z = 15. The variation of K(Z) in the region of the L nuclei ($Z \approx 3-5$) is not shown.

Some uncertainty is produced also by the insufficient knowledge of the abundance of the elements in nature. Thus, for the relative abundances of helium and hydrogen, Cameron[45] gives values that are approximately double those used in the compilation of Fig. 20. This ratio of abundances of helium and hydrogen corresponds to their content in cosmic rays, and in this case K has the same value for Z = 1 and for Z = 2.

Since it becomes necessary to use the values of the fluxes not for individual nuclei but for groups, a certain uncertainty arises in the value of Z corresponding to a given K. This uncertainty is insignificant in the case of the M group (the corresponding value of K pertains to $\bar{Z} = 7$) and the group of nuclei $Z \gtrsim 12-14$ (K pertains to $\bar{Z} = 13$) but is apparently significant in the case of nuclei with $Z \geq 15$ ($\bar{Z} = 20$) and nuclei with $Z > 30-40$ ($\bar{Z} = 35$). The value of K obtained for nuclei with $Z > 30-40$ from measurements on the third Soviet artificial earth satellite[2] is only an upper estimate of this quantity.

The presented value of the ratio of the fluxes of nuclei with $Z > 30-40$ and $Z \gtrsim 15$, together with the data of the second space rocket for nuclei with $Z \geq 2$, $Z \geq 5$, and $Z \geq 15$ are in satisfactory agreement with the proportional dependence on Z of the ratio of the abundances of the nuclei of different elements in cosmic rays and in nature (see Fig. 20).

The regular increase in K with increasing Z apparently indicates that the acceleration of heavy nuclei in the cosmic-ray sources plays a major role. One of the possible mechanisms for the predominant acceleration of the nuclei is indicated in [29-31,79].

3. Variations of the Flux of the Nuclear Component of Cosmic Rays and Nuclei of Solar Origin.

The variations of cosmic rays connected with the solar activity can be broken up into two classes:

1) Variations due to the modulation of the primary cosmic rays of galactic origin (11-year variations and

shift of the threshold of the high-latitude cutoff, Forbush decreases in intensity, etc.).

2) Variations connected with the generation of cosmic rays on the sun.

It is well known that the intense generation of cosmic rays on the sun occurs during some chromospheric flares. However at the present time the nature of the chromospheric flares has not yet been investigated to an extent that would make it possible to explain fully all the phenomena which occur during the time of the flare, and in particular it is not clear what is the mechanism of generation of solar cosmic ray particles, observed during the flares.

We present some characteristic features of chromospheric flares and the parameters that characterize them. The development of chromospheric flares has an "explosive" character: after the appearance of the flare, its visible brightness increases very rapidly by a factor of several times ten, and reaches a maximum within several minutes (and sometimes within even less than a minute). The region covered by the flare extends over tens of thousands of kilometers. The decrease in the brightness of the flare is much slower.

Table X lists the average characteristics of flares of different intensity [80]. The greatest fraction of radiation of a chromospheric layer is emitted in the form of a line spectrum. The brightest in the visible region is the hydrogen H_α line (6563 Å). The last two colums of Table X give data on the intensity, measured at the center of the hydrogen H_α line and on the width of this line, characterizing the visible brightness of the flare during its maximum development. An intensity close to that of the H_α line is possessed by the lines of singly ionized calcium. Less intense are lines of helium, ionized iron, and atoms of other metals contained in the chromosphere [80].

Chromospheric flares are frequently accompanied by bursts of radio emission. The appearance of a burst of radio emission is sometimes delayed several minutes relative to the start of the optical flare. A more detailed description of the properties of chromospheric flares and the bursts of radio emission accompanying them can be found in [80–82].

Table X

Class * (intensity) of flare	Average duration, minutes	Area in millionths of the solar hemisphere**	Ratio of intensity at the center of the H_α line to the intensity of the continuous spectrum	Width of H_α line, Å
1	17	100—300	0.8—1.75	2—4
2	29	300—750	1.75—2.1	4—6
3	62	750—1200	2.1—2.4	6—8
3^+	~180	>1200	>2.4	>8

*The symbol 1^- is used for flares that are less bright than class 1; the symbol 1^+ is used for flares whose brightness is smaller than that of class 2, but larger than that of class 1; the symbol 2^+ denotes a flare intermediate between classes 2 and 3.

**One millionths of the solar hemisphere is equal to 3.04×10^6 km².

The increase in the intensity of the cosmic rays emitted during the time of the flare, according to available data, is quite sharp. This is particularly clearly seen in observations of large "bursts" of cosmic rays, when their intensity increases by hundreds of times and the start of the increase can be registered with high accuracy. Observations of this type show that the increase in the intensity of the cosmic rays to a maximum value occurs within several minutes. At the same time, the start of the steep increase in the intensity of the solar high-energy cosmic rays, observed on earth, lags the instant of maximum brightness of the visible chromospheric flare by merely 5—10 minutes, and in some cases even less. Particles of lower energy arrive later. This delay is possibly connected not only with the dispersion of the particle velocity, but also with the differences in the conditions under which particles of different energies are scattered in the vicinity of the sun [83–86].

The duration of the "burst" of intensity of cosmic rays exceeds by many times the duration of the visible chromospheric flare and reaches several hours. This can be attributed to different factors, and particularly to the diffusion of cosmic-ray particles in interplanetary magnetic fields [83–86].

Numerous observations of "bursts" of the intensity of cosmic rays at sea level and in the stratosphere leave no doubt that during the time of chromospheric solar flares there are generated protons with kinetic energy reaching several hundred MeV, and sometimes even several BeV. However, until recently the question of whether the nuclei of the different elements are also accelerated remained open.

Short-duration increases in the fluxes of nuclei, connected with the chromospheric solar flares, were first observed during the flight of the second space rocket [3,7,8]. The apparatus employed consisted of two independently acting integral Cerenkov counters, one of which registered nuclei with $Z \geq 2$, and the other nuclei with $Z \geq 5$ and $Z \geq 15$. During the entire time of flight of the rocket, 100 nuclei with charge $Z \geq 15$ were registered, more than 3,000 nuclei with $Z \geq 5$, and approximately 30,000 nuclei with $Z \geq 2$. The counting rates of the nuclei obtained by averaging over long time intervals, remained practically constant at large distances from the earth (farther than 45,000—50,000 km). However, at times the counting rate deviated considerably from its mean value.

The most noticeable case of short-duration increase in intensity was registered on 12 September at 11:27 world time, when an increase in the number of counts was observed in both instruments, lasting for approximately 17 minutes. This case is shown in Fig. 21, which shows also the dependence of the counting

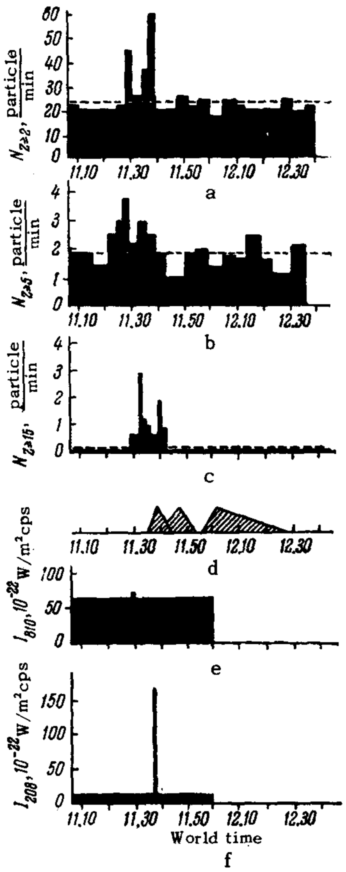

FIG. 21. Comparison of measurements of intensity of nuclei of different groups with the phenomena on the sun on 12 September 1959. a) Intensity of nuclei with $Z \geq 2$; b) intensity of nuclei with $Z \geq 5$; c) intensity of nuclei with $Z \geq 15$; d) chromospheric flares (dimension of base of triangle–duration of flash, position of vertex–instant of maximum brightness or middle of the interval); e) average intensity of radio emission from the sun and short-duration bursts at 810 Mc (schematic); f) the same at 208 Mc; abscissas–world time; the dashed lines in the first three figures denote the average intensities.

rate of different groups of nuclei on the time.

If the counting rate is determined using the time intervals during which the instrument registers the specified number of nuclei, then the counting rate is inversely proportional to the magnitude of the corresponding time intervals. In Fig. 21 the values of the counting rates (intensities) of the nuclei were obtained from the magnitude of the time intervals necessary to register 96 nuclei with $Z \geq 2$, 8 nuclei with $Z \geq 5$, and 2 nuclei with $Z \geq 5$. The dashed line denotes the average values of the counting rate (averaged over 12 hours).

During the 17 minutes following 11:27, a total of 512 nuclei with $Z \geq 2$ were registered, and their average over a similar time interval was 388. Recognizing that the instrument had a scaler circuit with a factor of 32, we can assume that the number of nuclei was not less than 480 in 17 minutes, and exceeded the average value by an amount equal to approximately four statistical deviations. The probability that the increase is the consequence of a statistical fluctuation is less than 10^{-5}.

At the same time, the number of counts from nuclei with $Z \geq 5$ and $Z \geq 15$ increased. The number of counts in the channels for the registration of nuclei with $Z \geq 2$, $Z \geq 5$, and $Z \geq 15$ increased by 1.3 ± 0.1, 1.5 ± 0.3, and 11.8 ± 3.7 times, respectively.* The probability of such an increase as a result of statistical fluctuations for the group of nuclei with $Z \geq 15$ is even several orders of magnitude lower than for the group for $Z \geq 2$.

The simultaneous increase in the counting rate in two independent counters indicates with certainty a variation of the nuclear component.

It must be noted that the increase in the number of counts in the channel for the registration of nuclei with $Z \geq 5$ is due to a considerable extent to the increase in the number of counts in the channel with $Z \geq 15$. After subtracting the counts due to the passage of nuclei with $Z \geq 15$, the number of counts in the channel for the registration of nuclei with $Z \geq 5$ differs from the average by an amount which exceeds only one statistical deviation.

Thus, an appreciable variation was observed in the heavy nuclei with $Z \geq 15$, and a less appreciable one was the variation of the flux of the α particles. According to [16], no variations in the proton flux were observed during the corresponding time interval.

In addition to the above case, other increases in the counting rate of the nuclear component were also observed, characterized by a smaller increase in the flux. Thus, for example, an increase lasting about 13 minutes was registered on 12 September at 12:57. During that time the counting rate of nuclei with $Z \geq 15$ increased by approximately six times, whereas the counting rate of nuclei with $Z \geq 2$ and $Z \geq 5$ did not increase.

In another case, registered on 12 September at 15:23 and lasting for 25 minutes, the counting rate of nuclei with $Z \geq 15$ and with $Z \geq 2$ increased by 4 and 1.2 times respectively, and the counting rate of nuclei with $Z \geq 5$ did not increase. An estimate shows that in both cases the probability of such an increase, due to statistical fluctuations, does not exceed 3×10^{-3}.

On 13 September at 7:07 world time there was registered an increase, by a factor of 1.5, in the flux of nuclei with $Z \geq 2$, lasting about 7 minutes (Fig. 22). In this case the increase can likewise not be interpreted as being a statistical fluctuation, since its probability is negligibly low.

*These include both the statistical errors and the errors connected with the registration system. The data used were obtained simultaneously from several land-based receiving points. This eliminated completely the possibility of errors due to intereference in the course of signal reception.

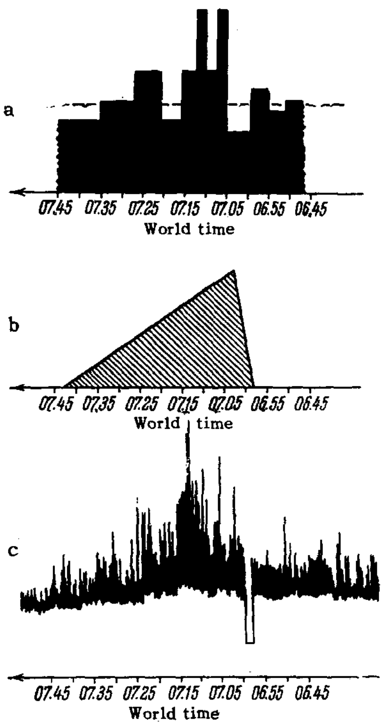

FIG. 22. Increase in flux of α particles and their accompanying phenomena on the sun, 13 September 1959. a) Counting rate of nuclei with $Z \geq 2$ (dashed line–average counting rate); b) schematic representation of chromospheric flare; 3) oscillogram of burst of radio emission at 208 Mc; abscissas–world time.

The non-statistical character of the noted deviations of the intensity from its mean values is clearly manifest if a comparison is made between the distribution of the number of nuclei registered in different intervals and the Poisson distribution.

Figure 23 shows the calculated and experimentally-obtained distributions for nuclei with $Z \geq 2$. The smooth curve describes the calculated distribution; it is given by a Poisson curve, which goes over for a large number of nuclei registered in each interval into a Gaussian distribution with a variance equal to the mean value. The stepped curve describes the experimentally obtained distribution for 8,480 nuclei with $Z \geq 2$, broken down into six-minute intervals.

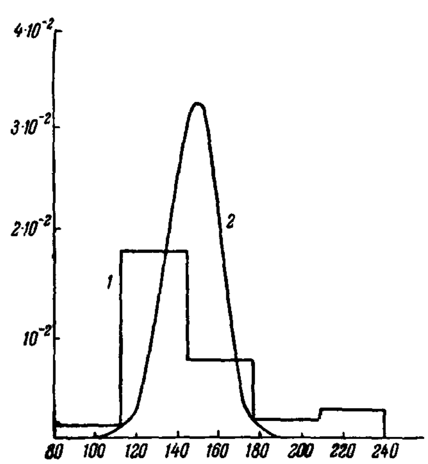

FIG. 23. Experimentally obtained (1) and calculated (2) distributions of nuclei with $Z \geq 2$. Abscissas–number of nuclei registered in a six-minute interval; ordinate–relative frequency of appearance of intervals with this number of nuclei and the corresponding value of the probability.

Figure 24 shows the distribution for 96 nuclei with $Z \geq 15$ broken down into intervals of 27.5 minutes (stepped curve). The same figure shows the Poisson curve for the corresponding average number of particles (the average number of particles for 27.5 minutes was 2). Figures 23 and 24 show that the increases in the number of counts were clearly of non-statistical character.

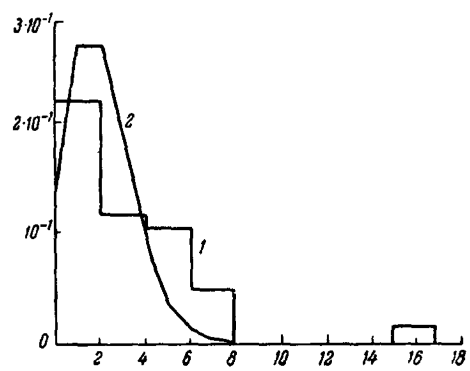

FIG. 24. Experimentally obtained (1) and calculated (2) distributions of nuclei with $Z \geq 15$. Abscissas – number of nuclei registered in a 27.5 – minute interval; ordinate – relative frequency of appearance of intervals with this number of nuclei and the corresponding value of the probability.

The short duration of the observed variations of the intensity of the nuclear component suggests that they are connected with rapidly occurring processes on the sun, for example with chromospheric flares. If the emission of nuclei from the surface of the sun is simultaneously accompanied by formation of a chromospheric flare, the increase in the nuclear flux can be observed almost simultaneously with the appearance of the flare, since the velocity of the nuclei registered by the Cerenkov counter is $v > 0.67c$.

The data of different observatories on chromospheric flares were reviewed in order to set in correspondence the registered short-duration increase in the intensity of the nuclear fluxes with the solar activity.

During the time interval corresponding to increasing activity of the nuclear component, on 12 September from 11:27 to 11:44, two observatories registered chromospheric flares of class 1^-, beginning at 11:36 and 11:39, with heliographic coordinates 21° N, 38° E and 19° N, 33° E, respectively. In the second case the flare was registered in the direct vicinity of a small sunspot (heliographic coordinates of the spot at the instant of appearance of the flare were 20° N, 22° E).

Other mentioned flux rises can also be set in correspondence with chromospheric flares. The increase registered on 12 September in the interval from 12:57 to 13:10 occurred during the time of a chromospheric flare of class 1^-, lasting from 12:45 to 13:40. The increase noted on 12 September at 15:23 was preceded by a chromospheric flare of class 1^-, lasting from 15:08 to 15:20. According to other data, a chromospheric flare was observed at a later time at a point having the same heliographic coordinates. The chromospheric flares set in correspondence with these two cases of short-duration increase in the flux of nuclear components occurred near large groups of sun spots. On 13 October at 7:05 there was observed a chromospheric flare of class 1, with a maximum brightness at 7:06, lasting up to 7:22. This flare corresponds in time to an increase in the flux of nuclei with $Z \geq 2$ at 7:07 (see Fig. 22).

Thus, the most noticeable increases in the fluxes of nuclei registered during the time of flight of the second space rocket were accompanied by weak chromospheric flares. Since, however, the number of weak chromospheric flares is large, the probability of random coincidence between the time of occurrence of the flare and the time of increase in the flux of nuclei is appreciable. The available data therefore still do not allow us to conclude finally that there is a complete correlation between these phenomena.

More characteristic is the agreement in time between the short-duration increases in the fluxes of nuclei and bursts of radio emission from the sun. For example, during the time of the short-duration increase in nuclear intensity on 12 September 1959, between 11:27 and 11:44, two bursts of radio emission were registered. Both bursts of radio emission are shown schematically in the lower part of Fig. 21. At 11:29, the Cracow Observatory [87] noted a short burst of intensity of radio emission of the sun at 810 Mc, lasting less than 0.3 minutes. It should be noted that such bursts are rare phenomena. Following daily observations of six hours each, the Cracow Observatory registered in one month, from the first through the 30th of September, only 5 additional bursts, of which 4 exceeded in magnitude the burst observed on 12 September. At such a frequency, the probability of random coincidence between the burst and short-duration increase in the flux of the nuclei, noted on 12 September at 11:27 does not exceed 10^{-2}.

During the same day, at 11:37, the observatory of IZMIRAN (Institute of Terrestrial Magnetism and Radio Wave Propagation of the USSR Academy of Sciences) near Moscow noted a burst of solar radio emission at 208 Mc [88]. The intensity of the burst amounted to 170×10^{-22} W/m^{2}cps, and on 13 September at 7:13 the same observatory observed a second burst of intensity 169×10^{-22} W/m^{2}cps at 208 Mc (see Fig. 22). Both bursts at this frequency were accompanied by a prolonged increase in intensity, of the type of a noise storm.

However, the bursts themselves, which were sharply pronounced against a general background, had a duration on the order of several seconds. During all the times of observation at the IZMIRAN Observatory on 12 and 13 September (i.e., over 12 hours), only 3 bursts were registered at 208 Mc with intensity exceeding 150×10^{-22} W/m^{2}cps. The two already mentioned above coincided in time with the short duration increase in the intensity of the nuclear component. The probability that this is a random coincidence is on the order of 10^{-2}.

In the most noticeable case of short-duration increase in the nuclear flux, on 12 September 1959 (at 11:27—11:44), there is no good correlation with the visible chromospheric flare: a weak chromospheric flare of class 1^- started only at 11:36, i.e., later than the start of the increase in the nuclear flux. It must be taken into account, however, that for weak flares different observers frequently indicate differences of several minutes in the start of time of the flare. It is therefore fully possible that the flare began not at 11:36, but somewhat earlier, and that its start indeed coincided with the burst of radio emission at 810 Mc, registered at 11:29. On the other hand, the sharpest increase in the flux of nuclei was registered not at 11:27 but approximately 3—5 minutes later, i.e., approximately 1—3 minutes after the burst of radio emission. Thus, it can be assumed that the start of the flare, the burst of radio emission at 810 Mc, and the instant of ejection of the nuclei all coincide. The small delay in the instant of the sharp increase in the flux of nuclei registered by the apparatus, relative to the burst of radio emission, indicates that the nuclei have considerable energy (on the order of 10 BeV).

Data on the short-duration increases in intensity of the nuclear component during the time of flight of the second space rocket and the accompanying manifestations of solar activity are gathered in Table XI.

In connection with the observed short-duration increases in the fluxes of the nuclei, mention can be made of the case [89] registered on 20 March 1958. The observations were carried out with the aid of an ionization chamber and a gas-discharge counter at a depth 10 g/cm^2. Within a very short time (18 seconds), the counting rate and the ionization in the chamber increased noticeably. This increase coincided with bursts of radio emission at 1500 and 10,000 Mc (Fig. 25). During that period the average ionization produced by the charged particles was 1.7 of the minimum ionization. The authors of [89], based on laboratory calibration measurements, interpreted this case as a flare of γ rays produced as a result of deceleration of the electrons in the sun's atmosphere.

It should be noted that, as indicated by the authors themselves, to explain the intensity of γ radiation as-

Table XI

Date	Increase of nuclear flux				Chromospheric flare			Class (intensity) of flare	Unusual phenomena in the radio emission from the sun					
	Time of start of increase	Duration	Charge of nucleus	Ratio of registered counting rate to the average over the measurement	Time of start of flare	Time of maximum of flare	Duration of flare		Time of start of phenomenon	Time of end of phenomenon	Time of maximum intensity	Frequency, megacycles	Intensity, 10^{-22} W/m^{2}cps	Characteristic of phenomenon
12.IX.59	11 h 27 m	17 m	$Z \geqslant 2$ $Z \geqslant 5$ $Z \geqslant 15$	1.3 1.5 11.8	11 h 36 m 11 h 39 m	11 h 39 m —	9 m ** 15 m **	1^- 1^-	11 h 29 m 06 h 00 m 06 h 40 m	11 h 29.5 m 12 h 00 m 13 h 17 m	11 h 29 m 11 h 37 m 06 h 50 m	810 208 231	74 170 65	Single burst of duration less than 0.3 minute Short burst (at 11:37) against a background of a prolonged noise storm Prolonged noise storm
12.IX.59	12 h 57 m	13. m	$Z \geqslant 2$ $Z \geqslant 5$ $Z \geqslant 15$	* * 6	12 h 45 m	—	55 m	1^-	06 h 40 m	13 h 17 m	06 h 50 m	231	65	Prolonged noise storm
12.IX.59	15 h 23 m	25 m	$Z \geqslant 2$ $Z \geqslant 15$ $Z \geqslant 5$	1.2 4 *	15 h 08 m	—	>12 m	1^-						
13.IX.59	07 h 07 m	7 m	$Z \geqslant 2$	1.6	07 h 04 m 06 h 58 m	07 h 06 m 07 h 03 m	18 m 44 m	1 1	06 h 00 m 06 h 05 m 07 h 00 m	12 h 00 m 15 h 10 m 11 h 30 m	07 h 13 m 13 h 20 m 10 h 06 m	208 231 178	169 70 136	Prolonged noise storm with maximum intensity at 06:13 at 208 Mc.

*The fluxes of these groups of nuclei exhibit no increases beyond the limits of statistical errors.

**The heliographic coordinates of these two flares, registered at different observatories, are close to each other (it is possible that this is the same flare).

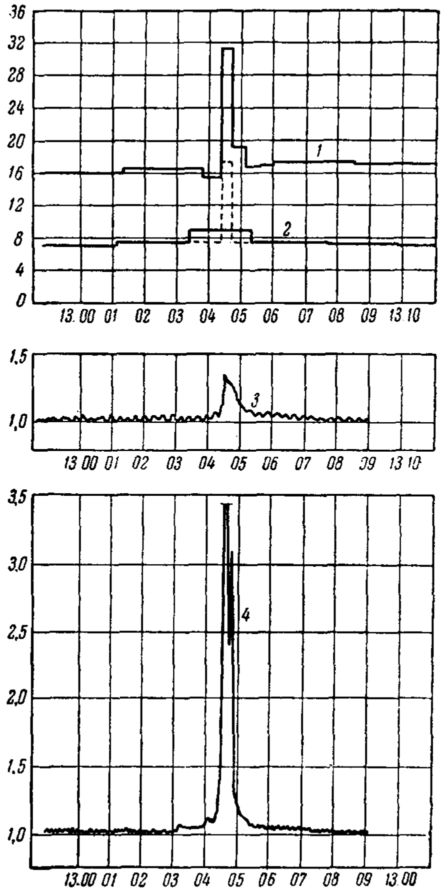

FIG. 25. Short-duration increase in intensity, registered by an ionization chamber and a gas-discharge counter, observed on 20 March 1958 [89]. 1—Counting rate of gas-discharge counter (counts/sec); 2—readings of ionization chamber (10^3 pulses/sec), averaged over 2 minutes (the dashed line indicates the increase in the chamber, which should be observed if the duration of the flare is assumed to be 18 seconds); 3 and 4—radio emission from the sun at 21 and 3 cm, respectively.

sumed in [89] it is necessary to employ an electron intensity which is approximately 10^4 times larger than that obtained in this case from the data on the bursts of radio emission. In [89] there are proposed possible qualitative explanations of this disagreement, but such a difficulty does not arise at all if the short-duration increase in ionization in the chamber is interpreted as being the result of registration of a burst of intensity of nuclei.

Whereas observations with the ionization chamber and the counter can be interpreted in two ways, the measurements carried out with the aid of a Cerenkov counter on the second space rocket cannot be attributed to registration of γ rays. Such an assumption would contradict the scintillation counter measurement data [16] and also the results of measurements with the aid of a radiation indicator (see [31]) mounted on the second space rocket. Taking into account the high efficiency of registration of γ radiation by a scintillation counter, we could expect an increase in the rate of this counter and an increase in the total ionization registered in the crystal. However, no noticeable effects of this type could be observed during the period of increased Cerenkov-counter rate. The increase in the flux of the nuclei should also lead to an increase in the ionization, as recorded by the light yield in the scintillator, but the registered increase may turn out to be small, for in this case the radiation in the crystal is released in relatively infrequent but large pulses, and it is possible that the photomultiplier is saturated.

In addition, if an attempt is made to explain the increase in the number of counts at a Cerenkov-counter threshold corresponding to $Z_{thr} \sim 15$ as being due to simultaneous formation in the detector of a large number of Compton electrons under the influence of γ rays, then it would be necessary to require a considerable amount of energy to be transformed into γ radiation (compared with the radiation in the visible region). Indeed, under such an assumption, approximately 225 Compton electrons should be produced in the detector within a time on the order of 30 microseconds (the resolution time of the electronic amplifier channel). Assuming that the probability of formation of one Compton electron is approximately 10^{-2}, we obtain for the intensity of the γ radiation a value 7.5×10^8 quanta/sec-cm^2. Even when the quantum energy is merely 1,000 keV, the γ-ray energy flux on the orbit of the earth would amount to approximately 80 erg/cm^2 sec.

This quantity can be compared with the estimate given in [89] for the energy flux of the γ rays (E_γ = 500 MeV) and with the energy flux in the H_α line in flares of class 2: the corresponding fluxes were 2×10^{-5} and 0.3 erg/cm^{2}sec. If we recognize that in our case no flare of class 2 was observed, we obtain an even greater disparity in the energy fluxes, if we assume that the increase is due to γ rays.

The conditions for the observation of short-duration variations of the nuclear fluxes are most favorable on space rockets, for then the influence of the earth's magnetic field is eliminated. On the other hand, satellites observe a nuclear component that varies all the time as a result of the latitudinal effect, and registration of the short-duration variations is difficult. Nonetheless, we can separate the variations of the flux of nuclei by comparing the flux at a given instant with the average value at the corresponding geomagnetic latitude. In the case of satellite measurements, the most effective from the point of view of registration of the variations are observations in the region of high latitudes, i.e., where the flux ceases to vary with increasing latitude, owing to the high-latitude cutoff (or owing to the presence of the energy threshold of the Cerenkov counter itself). A short-duration increase in the flux of the nuclei with $Z \geq 2$ and $Z \gtrsim 12-14$, registered during the flight of the third space probe, was described in [9]. As in the cases registered during the flight of the second space rocket, the short-duration increase in the flux of nuclei with $Z \geq 2$ and $Z \gtrsim 12-14$ was accompanied by a chromosphere flare (of intensity 1^{+}) and by a burst of radio emission from the sun (Fig. 26). It must be pointed out that there was no increase in the flux of nuclei with $Z \geq 5$ in this case.

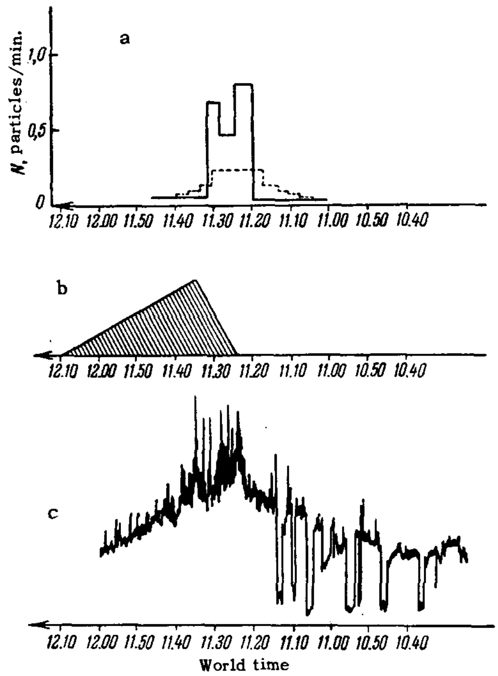

FIG. 26. Short-duration increase in the intensity of nuclei with $Z \gtrsim 12-14$, registered on 1 December 1960 (third space probe). a) Counting rate of nuclei with $Z \gtrsim 12-14$ (dashed line—average counting rate at the corresponding latitude); b) schematic representation of chromospheric flare; c) oscillogram of radio emission from the sun at 208 Mc (obtained at the IZMIRAN Laboratory).

It is interesting to note that the arrival of a nucleus with $Z \gtrsim 31-34$ was registered in the same time interval, when a sharp increase was observed in the flux of nuclei with $Z \geq 2$ and $Z \gtrsim 12-14$. During one day of observation, this was the only registered nucleus with so large a charge, and consequently the probability of random coincidence of the two events is low (less than 10^{-2}). It can be assumed that this agreement is not accidental and denotes that the flux of nuclei with $Z \gtrsim 31-34$ also increased appreciably, but only a single entry of the nucleus from this group into the detector of the Cerenkov counter was registered, owing to the small transmission of the apparatus. Counters with large transmission, i.e., with large detector dimensions, are necessary to register short-duration variations of nuclei with charges exceeding 30.

At the present time it is difficult to ascertain how the heavy nuclei are accelerated on the sun, how the nuclei are ejected from the sun's atmosphere, and how these processes are connected with radio emission. However, the low probability of random coincidence of the observed phenomena makes the assumption that they are connected quite likely. The existence of a short-duration increase in the flux of the nuclei of cosmic rays offers evidence that processes occur on the sun whereby nuclei are accelerated to kinetic energies, exceeding 0.5×10^{9} eV/nucleon, and this occurs also during the time of small chromospheric flares. The observed effect is easiest to explain if it is assumed that a preferred acceleration of the heavier nuclei occurs on the sun in definite cases. In other words, it can be assumed that at least two different mechanisms of cosmic-ray generation are effective on the sun. One (the more prevalent) leads predominantly to the acceleration of protons and leads perhaps to just as effective an acceleration of other nuclei (the latter denotes that the charge spectrum of the accelerated nuclei corresponds approximately to the relative abundance of the nuclei in the solar atmosphere). The second mechanism, to the contrary, leads to preferred acceleration not of protons but of nuclei and apparently only the heavier nuclei at that (the acceleration of the α particles can be connected in this case with the greater abundance of He^4, which compensates for the low acceleration efficiency). A mechanism of this type is known[29,79]. We note that the use of two or even more mechanisms to describe the acceleration of particles on the sun should not cause any surprise. It is sufficient to recall that to explain the sporadic radio emission from the sun it is also necessary to make use of several mechanisms of radiowave generation[90]. We note also that in the case of production of fast nuclei only, the pressure of these fast particles in the solar atmosphere may not be sufficiently strong to modify appreciably the solar and the near-solar magnetic fields. As a result, the emergence of the particles from the solar corona is inhibited and only nuclei with high energy, $E_{kin} \gtrsim 10^9$ eV/nucleon, would be observed in the solar system (and particularly on earth). Therefore the short-duration nuclear-intensity increases registered by the Cerenkov counter may not be accompanied by a subsequent increase in the intensity of the nuclei with lower energy.

Another interpretation of the observed increase in the flux of heavy nuclei is also conceivable. Assume that all the nuclei are accelerated on the sun with approximately equal efficiency, but the over-all pressure of the produced cosmic rays is low and consequently their emergence from the solar system is made difficult. Then the first to leave are the particles with the largest magnetic rigidity $R = Apc/Ze$. This means that the predominant particles in interplanetary space will be not only those with the largest momentum per nucleon p possible (see above), but also heavy nuclei which are "overgrown" with electrons (this possibility was pointed out to us by S. I. Syrovat-skiĭ). In the latter case the effective charge Z of the particle can be considerably smaller than the charge of the nucleus, and consequently, the rigidity R is A/Z times larger than that of the protons and A/2Z times larger than that of the α particles with the same values of p (if $A \sim 30$ and $Z \sim 1-2$, the rigidity increases by more than one order of magnitude).

Several recent papers [91,95] report observation of nuclei of solar origin which, unlike in [7-9,11], are in the main nonrelativistic particles.

Since the question of the generation of the nuclei during the time of chromospheric flares is of great interest, we report briefly the results obtained by the American investigators [91-94].

To register the protons and nucleons, thick-layer photoemulsions were used [91-93], raised by rockets shortly after a powerful chromospheric flare was registered. The measurements were made at a geomagnetic latitude 16.7° N, making it possible to register low-energy particles. The emulsions were raised to an altitude of 130 km and exposed for several minutes under less than 0.015 g/cm^2 of atmosphere. A layer of material (0.19 g/cm^2) heavier than aluminum was placed over the emulsions.

In the investigations described [91-93], an increased intensity of protons, α particles, group M nuclei, and heavier nuclei was observed in three cases. Table III lists the fluxes of the group M nuclei with kinetic energy $E_{kin} > 42.7$ MeV/nucleon obtained in these three flights [92].

Table XII

Date and time (world)		Flux of group M nuclei with $E_{kin} > 42.7$ MeV/nucleon particles/m^2 sec-sr
Start of flare	Start of flight	
3.IX.1960 00.40	3.IX.1960 14.08	19±4
12.XI.1960 13.22	12.XI.1960 18.40	1530±210
15.XI.1960 02.00	16.XI.1960 19.51	253±40

Control flights were also made during the time when the sun was in a quiet state, when only galactic cosmic rays were registered. Balloon-borne emulsions were also exposed during the flare of 3 September 1960. These registered protons and α particles of solar origin [95]. The results of observations of the same flare with the aid of balloon-borne counters and ionization chamber are given in [96].

Results on the increase in intensity of the protons and nuclei during a chromospheric flare of class 3$^+$, starting at 13:22 on 12 November 1960, are described in detail in [93]. This flare was accompanied by a strong increase in the intensity of the cosmic rays registered with neutron monitors, which started to show an increase in intensity 18 minutes after the occurrence of the chromospheric flare. The intensity increase registered by the neutron monitor in Deep River reached 200% of the normal level and continued for many hours. A characteristic of this flare was that it occurred soon after two powerful chromospheric flares, observed on 10 and 11 November 1960. It is therefore possible that the particles generated during the chromospheric flare of 12 November 1960 were enclosed in the magnetic trap connected with the corpuscular stream emitted during the flare of 11 November 1960 [93].

Following the registration of the flare of 12 November 1960, two rocket flights with emulsions were made at 18:40 on 12 November and 16:03 on 13 November 1960. A high intensity of protons, α particles, nuclei of group M, and heavier nuclei was registered in both flights. The energy intervals were 14.5—340 MeV in the first flight and 14.5—270 MeV in the second for protons, 37.5—180 and from 29—130 MeV/nucleon for α particles, and 42.5—135 MeV/nucleon in both flights for the M-group nuclei. The measurements made it possible to construct the differential energy spectra of the protons and nuclei, as shown in Fig. 27 for the measurements of 12 November. It is seen from this figure that the dependence of the flux on the total energy per nucleon is a power-law function. The exponent is approximately 21 for protons and 63 ± 7 for the α particles and the group-M nuclei, whose spectra coincide within the limit of error. The slope of the proton spectrum changes abruptly near 35 MeV/nucleon, becoming steeper at lower energies.

The low-energy particle flux registered during the second flight at 16:03 on 13 November 1960 increased, while the flux of the high-energy particles decreased.

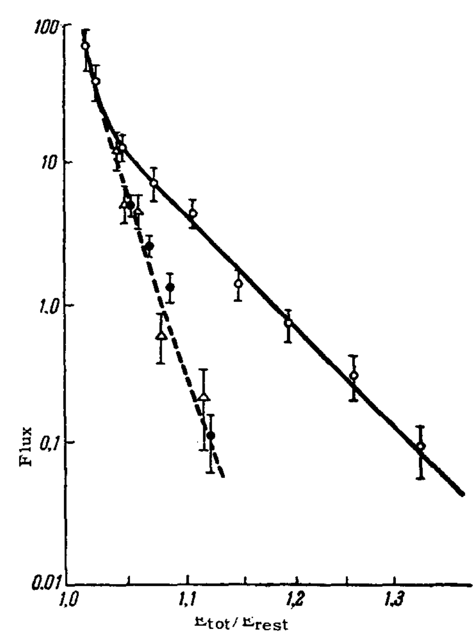

FIG. 27. Differential energy spectra of particles (particles/cm^2 sr-sec-MeV) registered [93] during the time of the flare of 12 November 1960. o — proton flux; △ — α-particle flux (increased 10 times): ● — group-M nuclei flux (increased 700 times).

The spectra obtained in this flight can be represented by a power function with exponent equal to approximately 37 for protons and 68 ± 7 for α particles and group-M nuclei.

Thus, the energy spectra are the same for multiply charged nuclei, but differ from the proton spectra. Figure 28 shows the rigidity spectra of protons, α particles, and group-M nuclei; we see that the rigidity spectra are the same for the protons and nuclei within the limits of error. It should be noted, however, that the rigidity interval in which the data were obtained is relatively small, both for the protons and for the multiply-charged nuclei, and it is therefore difficult to state that their rigidity spectra agree fully; this deduction is to some extent preliminary.

The relative abundance of the protons and nuclei in a definite energy interval turns out to be approximately the same as in the flights of 12 November and 13 November 1960, as well as in other flights. In Table XIII are listed the ratios of the fluxes of the protons and group-M nuclei, of protons and α particles, and of α particles and group-M nuclei, obtained in several flights for the kinetic-energy interval from 42.5 to 95 MeV/nucleon.

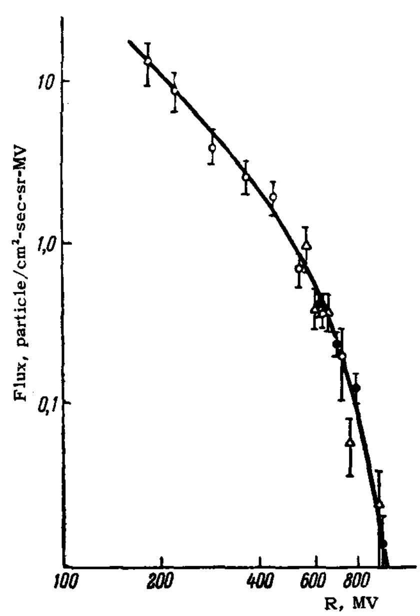

FIG. 28. Differential rigidity spectra (flare of 12 November 1960). o – proton flux; △ – α-particle flux (increased 5 times); ● – group-M nuclei flux (increased 350 times).

Table XIII

Date and time of flight (world)	Ratio of measured fluxes		
	protons/ M-nuclei	protons/ α particles	α particles/ M-nuclei
12.XI.1960 18.40	2000±400	32±6	63±14
13.XI.1960 16.03	2650±430	36±7	72±16
Average for the flight of 12 and 13 November	2330±290	34±5	68±11
3.IX.1960 14.08	2650±790	32±10	83±32
16.XI.1960 19.51	1870±360	26±7	77±20

Only the upper limit is given in [93] for the relative flux of light nuclei. The relative fluxes of the α particles, light nuclei of group L, nuclei of group M, and nuclei with $Z \geq 10$, registered on 12 November 1960, amounted to 680 ± 110, < 0.1, 10, and 1.0 ± 0.3 respectively (the flux of group-M nuclei was assumed equal to 10). Such a ratio is close to that obtained from spectroscopic data on the composition of the solar atmosphere (for the elements for which such data are available).

The composition of the solar cosmic rays (from the data of the flares of 3 September, 12 November, and 15 November 1960) in a specified rigidity interval, is compared in Table XIV with the abundance of the corresponding elements on the sun and with the composition of the galactic cosmic rays [92]. The authors of [92–93] conclude that the ratios they obtain between the fluxes of the different nuclei are reflections of the relative abundances of the corresponding elements on the sun. This point of view is corroborated by the fact that the ratios of the fluxes of He, C, O, Ne and heavier nuclei were the same in the case of three different chromospheric flares, two of which occurred in different regions of the sun. This hypothesis is confirmed also by the agreement between the obtained ratios of the fluxes and the spectroscopic data. In particular, the value obtained for the ratio of the fluxes of carbon and oxygen nuclei was $^3/_5$ (Fig. 29), in good agreement with the spectroscopic data for the sun.

Table XIV

	Protons	Be, B	C	N	O
Composition of particles registered during the time of the solar chromospheric flares*	$(2.6\text{—}50)\cdot 10^3$	$\leqslant 0.5$	10	6	19
Relative abundance of the elements on the sun	$20\cdot 10^3$	10^{-5}	10	2	18
Composition of galactic cosmic rays	$2.6\cdot 10^3$	5	10	$\leqslant 5$	6

*The fluxes of the nuclei and the abundances of the elements on the sun are referred to carbon.

Thus, there was apparently no predominant acceleration of the heavy particles in at least three large chromospheric flares, described in [91–93], and the composition of the flux of the nuclei generated on the sun reflected the abundances of the elements in the upper layers of the sun.

Table XV

Method of exposure	Date	Altitude, km	No. stopped nuclei with $Z \geq 6$ per cm^3 per day
Balloons	29.VII.1960 5.VIII.1960	42.5 42	7.78±1.15 8.60±1.02
Discoverer XVIII	XII.1960	636	8.65±0.93
Discoverer XVII	XI.1960	993	900±300

Thick-layer emulsions exposed on balloons and on satellites were also used in [94].

The average values of the intensity of the nuclei with $Z \geq 6$, obtained from emulsions exposed on balloons, turn out to be close to the values obtained with a retrieved emulsion stack exposed on the satellite "Discoverer XVIII." The average intensity obtained upon developing the stack retrieved from the "Discoverer XVII," the flight of which coincided with a powerful chromospheric flare (of class 3^+), turned out to be approximately 100 times larger. The data of [94] are given in Table XV.

Unlike the flares described in [91-93] (see, for example, Fig. 29), the flux of carbon nuclei measured on the "Discoverer XVII" turned out to be much larger than the flux of the oxygen nuclei. In this case, as in [91-93], no preferred increase in intensity of the heavy nuclei was observed.

In this connection we mention one case which we registered[11] during the time of flight of the second space probe and which can be interpreted as a short-duration increase in the intensity of the protons and nuclei with $Z > 5$. In this case a sharp increase was observed in the counting rate of a telescope made up of gas-discharge counters, accompanied by an increase in the intensity of the nuclei with $Z > 5$ registered by an integral Cerenkov counter. At the same time, no noticeable increase was observed in the intensity of the nuclei with $Z \geq 15$.

Figure 30 shows the change in the counting rate of a telescope along the trajectory of the satellite. A sharp increase is observed in the counting rate near 07:30 (world time) on 20 August 1960. On the neighboring loops of the trajectory, passing over the same geographical region, the intensity was considerably

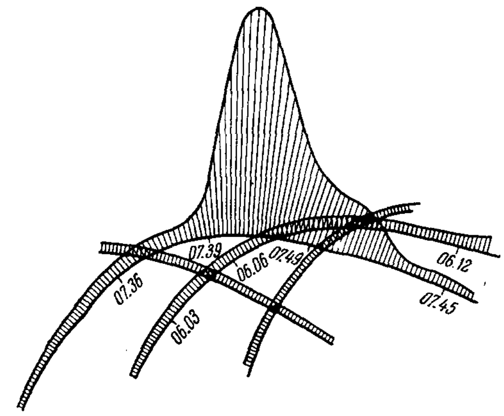

FIG. 30. Increase in telescope counting rate, registered on 20 August 1960 (second space probe). The projections of the individual sections of the trajectory of the second space probe on the earth's surface are shown together with the corresponding values of the counting rate of a telescope made up of gas-discharge counters (the height of the lines normal to the trajectory).

lower, thus confirming the short-duration character of the registered increase in intensity. Figure 31 shows the time dependences of the counting rate of the telescope and that of the integral Cerenkov counter registering nuclei with $Z > 5$. The class 2^+ chromospheric flare preceding the increase in intensity, is shown schematically. The same figure shows also that during the preceding passage of the satellite over the northern polar region (where a burst of intensity was registered), the telescope and Cerenkov-counter counting rates were noticeably lower. The large intensity peak registered by the telescope near 06:56 corresponds to the flight of the satellite in the region of a southern radiation anomaly (see [12-15]).

In all the cases just mentioned[91-95,11] the observed chromospheric flares were relatively large. Therefore the difference from the data discussed earlier[7-10], when only relativistic and essentially heavy nuclei were observed, may actually be due to one of the already noted two factors, either to the preferred acceleration of the heavy nuclei or to the more favorable conditions for the emergence of nuclei which are not completely ionized from the solar atmosphere.

For a more complete study of the mechanism whereby nuclei of different energy and different charge

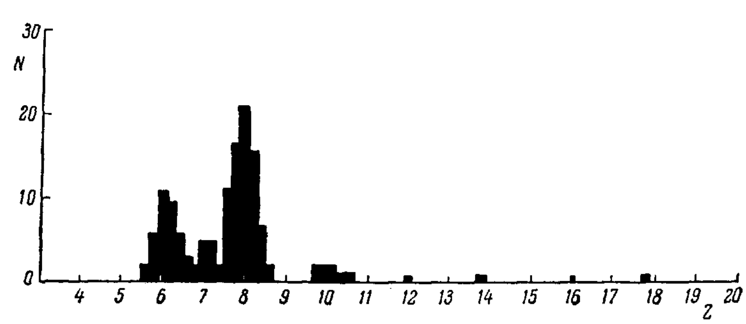

FIG. 29. Distribution of the nuclei, obtained with emulsions [93] during the time of the solar flare of 12 November 1960.

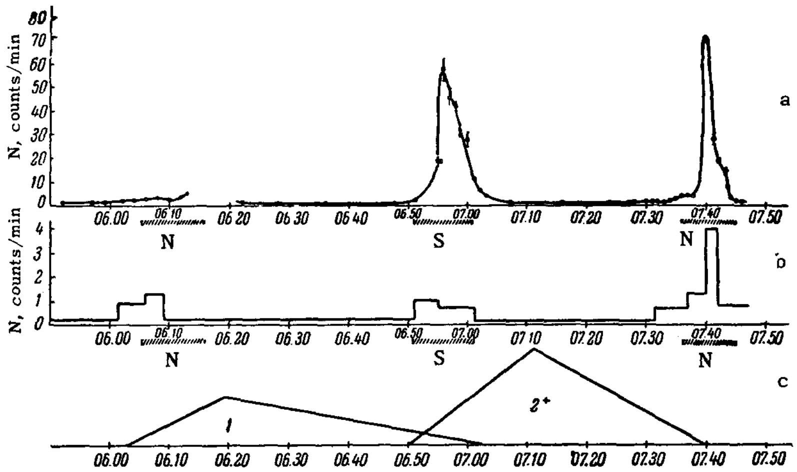

FIG. 31. Time dependence of the counting rate of a telescope (a) and of the counting rate of an integral Cerenkov counter which registered nuclei with $Z \geq 5$ (b). The lower curves (c) show schematically the chromospheric flares. The peak pertaining to the time interval 06:54 – 07:02 corresponds to the passage of the satellite through the region of the southern radiation anomaly. The shading indicates the northern (N) and southern (S) polar regions.

are generated on the sun, prolonged measurements are necessary outside the atmosphere and especially outside the earth's magnetic field.

In order to ascertain whether powerful chromospheric flares are always accompanied by the generation of low-energy nuclei and whether they are accompanied by nuclei with kinetic energy $E_{kin} \gtrsim 10^9$ eV/nucleon, it is necessary to obtain flux data for a few additional rare flares of this kind (we note by way of an example that in 1960 there were 9 flares of class 3 and only 1 flare of class 3^+).

It is necessary to investigate the charge composition and the energy spectrum of the nuclei generated by the sun, both in large flares and in flares of lower intensity, and it is most important that the observations be carried out during different phases of development of the flare, including the initial stage.

II. USE OF ARTIFICIAL SATELLITES AND ROCKETS TO INVESTIGATE THE PRIMARY COSMIC RADIATION

Numerous measurements made in the stratosphere by various means during the last two decades have clarified the main properties of the primary component of the cosmic radiation. It is now established that the most particles of the primary cosmic radiation are protons, and that the radiation includes also multiply-charged nuclei which carry approximately half of the total cosmic-ray energy.

Information has been obtained on the fluxes of protons, particles, and individual groups of heavier nuclei. However, many questions of great importance to the understanding of the physical processes in the universe and in the space around the sun still remain unclear. Thus, for example, we still do not know sufficiently well the chemical composition of the nuclear component of the cosmic rays, or the energy spectra of different groups of nuclei at high energies and large charges. We have practically no data on the primary electrons in the cosmic rays and no information whatever on positrons (see the note added in proof at the end of the article). Only recently (in 1961) were the first and still unreliable measurements made of the flux of cosmic γ rays. No complete investigation has been made so far of the so-called high-latitude cutoff in cosmic rays, which is apparently connected with the magnetic fields in the solar system.

This is a far from complete list of unsolved problems in the field of primary cosmic rays.

In the present section we dwell in somewhat greater detail on some of these problems and their solutions.

4. Nuclear Component of Galactic Cosmic Rays

The measurement of the percentage of nuclei of the elements and their isotopes in the flux of cosmic radiation over a wide range of charges would be very important for purposes of establishing a theory of the origin of cosmic rays and explaining their propagation in the interstellar medium[29-31]. In this sense the use of Cerenkov counters in pure form or in combination with gas-discharge and scintillation counters offers great possibilities. In particular, in investigations of the charge distribution in the region of large Z, it would be possible, by suitable choice of the photomultiplier and amplifier gains (so as not to saturate the signals), to obtain a system in which resolution of the peaks corresponding to two species of particles, whose charge differs by unity, would not depend on Z. Indeed, the difference between the average amplitude of the photomultiplier output pulses produced by nuclei with charges $(Z+1)$ and Z is proportional to $(2Z+1)$, and the half-widths of the pulse distributions are proportional to $(Z+1)$ and Z, respectively. Thus, the ratio of the difference between the average amplitudes of pulses from "neighboring nuclei" to the half-width of the distribution is approximately proportional to $(2Z+1)/(Z+1)$, and is practically independent of Z when $Z \gg 1$.

With the aid of apparatus similar to that used on the second and third space probes, we can investigate the composition of the cosmic rays over a wide interval of values of Z.

Since the electronic apparatus enables us to accumulate information on the registered nuclei of the type of interest to us without danger of being "contaminated" by the more numerous nuclei of the other group, it can also be used to measure very small fluxes, for example the fluxes of the superheavy nuclei ($Z > 30-40$).

The presently attained progress, and particularly the possibility of safely returning the apparatus from outer space, promises effective utilization of nuclear emulsions for the solution of some problems. This method seems very promising for studies of the isotopic composition of the primary nuclei in the region of small Z, particularly for detection of deuterons and tritium nuclei of solar origin.

The emulsion method can also be used to solve some other problems, but it must be borne in mind that the emulsions become strongly "contaminated" in prolonged flights. The emulsions cannot be processed in the presence of a large background, and this raises the problem of producing emulsions with a sensitivity that can be "regulated."

The first attempt at creating an installation with a limited exposure was made on the second space probe [97]. To monitor the operation of this instrument, an emulsion stack was also exposed and developed following the return of the probe to earth. The results obtained with the monitoring stack are reported in [6]. These experiments, however, were methodological in character, since the emulsions were covered with approximately 10 g/cm^2 of matter.

So far there is very little information on the dependence of the flux at a given Z on the atomic weight (more accurately, the mass number) A. The relative content of He^3 and He^4 in the primary cosmic rays was measured in [98-99]. According to [98], $[He^3]/[He^3 + He^4] = 0.41 \pm 0.09$ at 200—400 MeV/nucleon under a residual layer of atmosphere of approximately 9 g/cm^2.

As indicated in [99], corrections for the interaction of the He^3 and He^4 nuclei in the emulsion reduce this figure to 0.38 ± 0.09. In the same reference [99], a value $[He^3]/[He^3 + He^4] = 0.31 \pm 0.08$ was obtained for 160—355 MeV/nucleon at 3.8 g/cm^2 depth. The values obtained in [98] and [99] agree, within the limits of error, and in accordance with [99] the residual layer of the atmosphere should not influence greatly the measured ratio. The $[He^3]/[He^3 + He^4]$ ratio extrapolated from these data to the top of the atmosphere gives a lower estimate, equal to 0.25 [99]. At the same time, according to data in [48], the relative content of He^3 is much smaller (see the note added in proof at the end of the article). The value obtained in [99] for $[He^3]/[He^3 + He^4]$ corresponds to a range of approximately 12 g/cm^2 for the primary He^4 nuclei in interstellar matter, whereas measurements [48] lead to a much thinner layer.

The question of the isotopic composition is very interesting, particularly with respect to the admixture of the deuterons to the protons (in the case of solar cosmic rays, a search for the unstable tritium nuclei is also of interest). Whereas the average natural abundance of $D = H^2$ is approximately 0.01% of the number of protons, in cosmic rays we can expect up to 1—5% deuterons [100,101].

It is possible to distinguish between nuclei of a given isotope in cosmic rays only by measuring simultaneously the charge, energy, and velocity of each nucleus. Such measurements are possible in principle for nuclei with energy on the order of several BeV per nucleon, which are still present in cosmic rays.

We note that the procedure used to register nuclei can be adapted to antinuclei and antiprotons. In the emulsion method, for example, it is necessary to select for this purpose the particles stopped in the emulsion (the stopped antinuclei and antiprotons are annihilated with emission of a considerable number of pions). The detection of even a small amount of multiply-charged antinuclei is undoubtedly of great interest, although it is little likely that they are present in cosmic rays. At the same time it is clear that a certain number of antiprotons should be present in cosmic rays at least as a result of nuclear collisions in interstellar space, and in accordance with an estimate [102] their flux should not exceed 0.17% of the flux of the protons; taking into account the latest data on the antiproton annihilation cross sections, the fraction of the antiprotons should not exceed approximately 0.05%. According to [48,103] the number of antiprotons and antinuclei does not exceed 0.1% of the total number of stopped particles. From the data of [104], the fraction of the antinuclei is not more than 0.23% of the number of the corresponding nuclei. The attained measurement accuracy is low, and further study of this question would be of interest. In particular, a search should be made not only for stopped antinuclei, but also for fast antinuclei (a considerable fraction of such particles may annihilate "in flight" and not "survive" to the instant of stopping).

A vital problem in cosmic-ray physics is the determination of the chemical composition at different energies, in other words, the measurement of the energy spectra of nuclei of the different groups. In the region of energies that are sensitive to the "cutoff" by the earth's magnetic field ($E < 20 \times 10^9$ eV/nucleon for nuclei and $E < 40 \times 10^9$ eV for protons)*, the spectrum can be determined by measuring the latitude dependence of the fluxes of different groups of nuclei. Such measurements were carried out on the second and third Soviet space probes (see Sec. 2 of Part I). We can go to somewhat higher energies by using gas-

*Only nuclei ($A/Z \approx 2$) with $E > 7.5$ BeV/nucleon and protons with $E > 15$ BeV can arrive at the earth's equator in a vertical direction.

filled Cerenkov detectors with low refractive index, i.e., with high energy threshold. We can then raise the threshold to approximately 5×10^{11} eV/nucleon, corresponding in the case of iron nuclei to a total energy of 3×10^{13} eV.

One way of solving this problem at high energies with the aid of an array that measures simultaneously the charge of the particle (in a Cerenkov counter) and its total energy (by the ionization released under different thicknesses of matter)* has already been pointed out in [105]. Some possibilities of an analysis of the chemical composition of primary cosmic rays at superhigh energies from the data of extensive air showers are discussed in [107].

Another task of cosmic-rocket and long-range-satellite research is the measurement of the anisotropy coefficient δ (see Sec. 1 of Part I) and the determination of the preferred direction of cosmic rays arriving from the galaxy in the solar system. The importance of such measurements can hardly be overestimated. Here we can only emphasize that the value of δ should be larger for nuclei than for protons (see [29]). According to [33], during the minimum of solar activity the value of δ for all cosmic rays is 0.5%. There is no doubt of the advisability of measuring δ for nuclei, particularly during the solar minimum (even the establishment of an upper limit $\delta \leq 1\%$ would be of great significance).

5. Solar Cosmic Rays and High-Latitude Cutoff

Until recently there was practically no information on the variations of the nuclear component of cosmic rays. These variations are connected with solar activity and can be due either to the modulation of the galactic cosmic rays by magnetic fields in the solar system or to generation of cosmic rays on the sun.

In many recently observed cases protons with energies up to several BeV were generated on the sun during chromospheric flares. Whether fast nuclei can also be generated at the same time is still an open question. At the end of Part I we gave data on the variations of the nuclear component of cosmic rays, obtained with Soviet rockets and satellites, and also data obtained by American researchers.

The variations of the primary component of cosmic rays are best studied with satellites. A satellite with instruments can make prolonged measurements over practically the entire earth's sphere by passing periodically over each point, with the same instrument, making unnecessary comparison with readings of different apparatus. To be sure, there is a major shortcoming that the instrument moves continuously from one latitude to another, so that geomagnetic effects must be taken into account. To determine the time variation it is therefore necessary to break up the total data into individual intervals corresponding to the chosen spatial regions, and to make comparisons only within the limits of a chosen interval. It is consequently clear that reliable conclusions can be obtained only in the case when the recording element has sufficiently large effective area. To study the variations of the nuclear component it is thus necessary to employ a detector such as a Cerenkov counter or scintillation counter, or to use a combined array containing both types of detectors and having a large transmission. It is particularly convenient to observe the variations of the nuclear component with space rockets and long-range satellites, outside the earth's magnetic field. This yields actually the primary flux of the cosmic radiation in interplanetary space, undistorted by the influence of the earth's atmosphere or its magnetic field.

It would be most promising to organize a permanent station to record the nuclear intensity outside the atmosphere and outside the earth's field (on long-range satellites or on the moon). Such a station would permit not only the study of the regular variations, but to extend and continue measurements of fluxes of relativistic nuclei from the sun during the flights of space rockets.

One of the important problems in cosmic-ray research is the study of the "high latitude cutoff," the nature of which has not yet been finally ascertained. It is most probable that it is due to random "frozen in" magnetic fields in the interplanetary gas ejected from the sun[108,109]. It is possible, however, that some role is also played by the ordered magnetic field of the solar system[110,111]. At any rate it is important to establish the characteristic distance from the sun at which the cutoff takes place; strictly speaking, it is also necessary to demonstrate conclusively the magnetic nature of the high-latitude cutoff and its localization in the solar system.

At sufficiently large distances from the sun (and possibly also near the earth in the years of solar minimum)* one can hope to investigate primary cosmic rays of low energy. In this energy region cutoff (or an appreciable change) of the spectrum may be due already to the influence of cosmic-ray sources or ionization losses in the interstellar medium. The detection of spectral singularities connected with the nature of the source of cosmic rays and with the conditions of their propagation in the interstellar medium is very important for the understanding of the entire pattern of the origin and propagation of cosmic rays in the universe.

Measurement of the dependence of the flux of protons and nuclei on the distance to the sun can answer the raised questions. Of course, the study of the na-

*Such a method, as is well known, has been recently widely used for the measurement of cosmic-ray particle energies on earth ("calorimeter" for the measurement of particle energy [106]).

*As is well known, the next minimum of solar activity will occur in 1964–1965.

ture of the high-latitude cutoff with the aid of cosmic rockets is important not only for the physics of cosmic rays but also for the investigations of magnetic fields in the solar system.

One of the principal questions is whether cutoff occurs for different groups of nuclei (in particular, protons and more complicated nuclei) at equal or different values of the magnetic rigidity. At present there is no reliable and unambiguous answer. Yet it is the answer to just this question which will enable us to establish whether the cutoff is magnetic in character or whether it is connected with energy losses (for example, ionization).

Another question, still not investigated to a sufficient degree, is the connection between high-latitude cutoff and solar activity. There are indications [112] that the threshold cutoff energy decreases and the cutoff effect may disappear completely during the minimum of solar activity.

If cutoff is magnetic in nature, as is most probable, then at a sufficiently large distance from the earth's orbit (both towards the sun and especially away from the sun in the ecliptic plane) the intensity of the cosmic rays will vary because of the change in the magnetic conditions in different regions of interplanetary space.

It must be emphasized that in such measurements of the dependence of the flux on the position in the solar system it is necessary to record simultaneously both the total intensity of the cosmic rays (essentially protons) and the intensities of the α particles, the nuclei of group M, and possibly also heavier nuclei; it is also desirable to measure the local intensity of the magnetic field. It must be noted that no extensive changes in the intensity of the cosmic rays can apparently be expected except at very large distances from the sun or the ecliptic plane. However, even measurements at distances of several million kilometers from the earth's orbit can yield information of the gradient of the cosmic rays in the solar system and suitably revise our notions concerning interplanetary space.*

To investigate the high latitude cutoff one can use not only long-range space rockets, which give a "cross section" through space, but also short-range artificial earth satellites passing over the poles during the minimum of solar activity. In this case measurements of the total intensity and the intensity of the complex nuclei must also be carried out simultaneously. Such an experiment practically coincides with the experiment aimed at investigating the variations, and has the same advantages over balloon measurements.

*Measurements carried out on the "Pioneer V" rocket up to a distance of 0.1 astronomic units from the earth in the direction towards the sun have yielded for the cosmic-ray intensity gradient a value of (15–20)% per astronomic unit [113]. Measurements [114] on the "Mariner II" rocket, traveling towards Venus, did not give sufficient data on the presence of an intensity gradient, since large fluctuations in the counting rate were observed during the flight, owing to solar flares. In measurements [115] on the rocket "Mars I" 1.2 astronomic units from the earth in the direction of Mars, no changes in cosmic-ray intensity within the limits of measurement accuracy (2–3%), were observed compared with the intensity near the earth.

6. Electron-Positron Cosmic-Ray Component

We have listed above several questions concerning the nuclear component of the cosmic rays. It is also of great interest to investigate the electron component of both galactic and solar cosmic rays.

The electron-positron component of cosmic rays is responsible for the nonthermal cosmic radio emission [29,30,116,117], and thus plays an exceedingly important role in astrophysics. Radioastronomic data, together with some estimates, lead to the conclusion that the concentration of the electrons and positrons ($E_e > 10^9$ eV) in the region of the solar system should have a minimum of* $N_e(E_e > 10^9 \text{ eV}) \approx (3-5) \times 10^{-13}$ cm^{-3}. For energies $E > 10^8$ eV we have in the galaxy $N_e(E_e > 10^8 \text{ eV}) \approx 2 \times 10^{-11}$ cm^{-3}, but by virtue of the high-latitude cutoff only electrons and positrons with $E \gtrsim 10^9$ eV can reach the earth more or less freely (except during the deep minimum of solar activity).

The presence of electrons and positrons in the primary cosmic radiation was not observed until recently. According to measurements [118] the number of light nuclei with energy $E_e > 10^9$ eV is less than 0.6–1% of the total flux of cosmic rays (for more details see [110]). It follows therefore that the concentration of light particles (electrons and positrons) on earth is less than approximately 10^{-12} cm^{-3}.

Preliminary results of new measurements of the electron flux in the stratosphere at high latitudes (low geomagnetic threshold) are reported in [119-121]. The flux of electrons with $E_e > 0.5 \times 10^8$ eV amounts according to [119] to approximately 3% of the measured proton flux. However, the nature of the electrons registered in [119-120] remains insufficiently clear, for most of them may be of solar and not galactic origin.

Indeed, in the measurements of [119] galactic electrons with energy $E_e < 1.6$ BeV should not have reached the point of observation, by virtue of the high-latitude cutoff. Yet electrons with $E_e \gtrsim 0.7$ BeV were observed in the experiment, and in [120] electrons with even lower energy. If the high-latitude cutoff is sufficiently pronounced and has a magnetic character, then the result indicated offers evidence of the nongalactic origin of the observed electrons. On the other hand, the latest data [121], and to some extent also the data

*This estimate has been obtained under the assumption that the intensity of the interstellar magnetic field is $H \approx 10^{-5}$ Oe. If we assume that the average field intensity in the halo is somewhat lower ($\overline{H}_{halo} \approx 3 \times 10^{-6}$ Oe), then an estimate[30] of the electron concentration gives a value $N_e(E_e > 10^9 \text{ eV}) \approx 4.4 \times 10^{-12}$ cm^{-3}. Accordingly, the concentration of electrons with $E_e > 10^8$ eV increases.

of [119-120], do not allow us to assume that the observed *electrons are directly connected with solar activity.*

This induces us to review seriously the possibility of the existence of some kind of an electronic "radiation belt of the solar system." In other words, it can be assumed that, owing to processes occurring on the sun and possible also in the solar system, a certain number of relativistic electrons is produced and is retained in the solar system by magnetic fields (this point of view is particularly attractive if an ordered field exists[110,111]).

From the data of [122] we see that soft protons are also observed on earth, and these can have, from the indicated point of view, a solar origin (we are referring to protons which come not directly from the sun, but from the particles which get "tangled up" in the solar system).

To check on the existence of a "radiation belt of the solar system" it would be important, in particular, to determine the dependence of the electron flux on the distance to the sun (while moving toward the sun, away from the sun, and perpendicular to the plane of the earth's orbit).

We note also that from a broader point of view the hypothesis of the "radiation belt of the solar system" is one of the variants of the theory of solar origin of cosmic rays. However, unlike the hypotheses advanced in the previously discussed papers (see [116-117] and the literature cited there), we are now referring only to the softest particles that can still be regarded as belonging to the cosmic rays. With respect to the bulk of cosmic radiation ($E_{kin} \gtrsim 10^9$ eV/nucleon), it is presently undisputed that it cannot be of solar origin.

Another (more likely) way of explaining the appearance of relatively soft electrons and protons (with energies below the high-latitude cutoff "threshold") is to assume that the high-latitude cutoff is quite diffuse.

Thus, there are many still unclear and yet very interesting questions connected with the observation of protons and electrons with energies $E_{kin} \lesssim 1$ BeV.

As we go over to higher energies, we are dealing in practice only with galactic electrons. A study of these electrons (primarily the determination of their spectrum) is a most important problem, vital from the point of view of checking and refining the existing notions concerning the origin and distribution of cosmic rays in the galaxy.

This problem can be fully solved, especially if experiments are set up during the minimum of solar activity.

The lack of experimental data on galactic electrons with energies $E_e \approx 10^8$ eV near the earth is due to the fact that such electrons (as well as other particles with the same rigidity) apparently do not reach the vicinity of the earth because of the high-latitude cutoff. Thus, if the threshold at high latitude cutoff actually decreases sharply during the years of minimum solar activity, then experiments on the measurement of the flux of galactic electrons may turn out to be quite successful. Such an experiment can be carried out on a "polar" satellite (along with an investigation of the high-latitude cutoff).

It must be noted that although the increase in the electron flux will undoubtedly be accompanied by an increase of the total flux of cosmic rays, the conditions for the registration of electrons with $E_e \approx 10^8$ eV will be more favorable than the conditions for the registration of electrons with $E_e \approx 10^9$ eV. The point is that the increase in the flux of cosmic rays with decreasing high-latitude cutoff threshold will be due principally to nonrelativistic protons ($\beta < 0.74$), and the entire additional electron flux will consist of ultrarelativistic electrons ($1 - \beta < 10^{-3}$). Thus, by using a suitable detector (for example, a Cerenkov counter with $n = 1.25$, i.e., with a threshold velocity $\beta_{thr} \approx 0.80$), it is possible to detect the primary cosmic-ray electrons by registering the intensity rise in the polar regions, over and above the intensity in medium latitudes. Depending on the chosen refractive index n, the number of electrons with $E_e > 10^8$ eV will constitute more than one sixth of the flux registered by the same counter, as compared with several percent in the case of registration of electrons with $E_e > 1.3 \times 10^9$ eV[120] (it is assumed in this estimate that in the energy interval from 10^9 to 10^8 eV the integral energy spectrum of the electrons is of the form $E_e^{-1.5}$).

Similar measurements can be made also on long-range space rockets launched towards the periphery of our planetary system. In this case, however, in addition to measuring the dependence on the distance, which may turn out to be insignificant, it is necessary to analyze the nature of the particles, separating the electrons from the other particles (primarily from the protons). An estimate shows that we can separate the electrons from the background of the total particle flux in the region where the threshold momentum corresponding to high-latitude cutoff decreases to 10^8 eV/c, provided the electrons constitute more than 3% of the flux of the relativistic particles (the fraction of electrons expected in this case is several times larger).

Special mention should be made of the relativistic electrons coming directly from the sun, or the solar corpuscular streams captured by the magnetic field, which can possibly be observed with satellites and space rockets.*

At the present time there is no doubt concerning the assumption made long ago[123] that some components of the sporadic solar radio emission constitute

*During definite periods of time the number of relativistic electrons of solar origin may be much larger than the number in the primary cosmic rays. The solar electrons can therefore be investigated with much less sensitive instruments. In addition, in the case of solar origin, we are dealing primarily with electrons having energies $E_e \sim 10^6 - 10^8$ eV.

synchrotron radiation of relativistic electrons. The greatest interest from the point of view discussed here is apparently attached to the electrons responsible for type IV radio bursts [90]. A correlation was established between these bursts and the appearance of solar cosmic rays (protons with kinetic energies $E_{kin} \gtrsim 10^8$ eV). The effective temperature of type IV bursts offers evidence that the radiating electrons have energies $E_{kin} \gtrsim 10^6-10^8$ eV. During bursts of type IV, which last up to several hours, the concentration of such electrons in the solar corona should be sufficiently large ($N \sim 10^2-10^3$ cm^{-3}). Some fraction of these relativistic electrons should leave the corona and move together with the solar corpuscular streams in interplanetary space. Such an assumption is in complete agreement with the fact that the solar cosmic rays (for the most part protons with $E_{kin} \gtrsim 10^8$ eV) can leave the corona and reach the earth.

A certain difference between the behavior of the proton and electron components of solar cosmic rays can be due to different velocities with which the electrons and protons leave the corona [90]. Indeed, the velocity of escape from the corona due to drift in the inhomogeneous magnetic field is proportional to the radius of curvature of the particle trajectory. For protons with velocity $v \sim c$ and with energy on the order of Mc^2 the radius of curvature is approximately Mc^2/E_e times larger than for relativistic electrons with energy $E_e \ll Mc^2 \approx 10^9$ eV. Therefore electrons say with $E_e = 10^7$ eV will leave the corona, roughly speaking, 100 times more slowly than the protons with kinetic energy $E_{kin} \approx (1-3) \times 10^8$ eV. As a result we can expect the flux of the relativistic electrons from the sun, which is correlated with type IV bursts, to be smaller than the flux of the protons. In addition, the electrons may appear much later than the protons, but their escape may continue longer than is characteristic of the proton component of solar cosmic rays during the same period. It must also be kept in mind that by virtue of the synchrotron and Cerenkov losses the electrons will slow down and this in final analysis will hinder the emergence of the relativistic electrons from the corona. No theoretical estimate of the flux of such electrons has been made, and one can hardly expect such a calculation to be reliable. There is all the more reason for assuming that the observation of electrons with energies $E_e > 10^6-10^8$, which form the electron component of the solar cosmic rays, is one of the timely problems connected with satellite and rocket research.

Relatively recent measurements made following the appearance of a group of bursts [124] registered electrons of solar origin with $E_e > 10^8$ eV. It can be assumed that systematic observations of the electron emission from the sun will provide solar physics with a new very valuable research method. It goes without saying that such a method will be effective only if observations are made simultaneously of the sun with the aid of modern radio astronomic equipment (radio spectrographs etc.).

The registration of electrons of solar origin is a less difficult problem than the observation of galactic electrons, if allowance is made for the fact that the expected fluxes of the electrons with energy 10^6-10^8 eV can reach during the time of the flare values close to the average value of the total flux of cosmic rays in quiet days, and the increase in the cosmic ray flux, associated with the flare, is due to the appearance of protons of relatively low energies. Using a system of Cerenkov counters with filters of different thicknesses, we can separate electrons with energies 10^7-10^8 eV from the protons that appear during solar flares and the protons from the cosmic rays. Use is made here of the fact that the solar protons do not produce Cerenkov radiation, while the cosmic-ray protons capable of producing Cerenkov radiation have a much larger range than the electrons. The statements made with respect to the solar cosmic rays pertain also to electrons in the "radiation belt of the solar system," the possible existence of which has already been pointed out.

Let us dwell on the problem of separate measurements of the fluxes of electrons and positrons. If the light particles in the primary galactic cosmic rays were not to contain a considerable number of positrons (on the order of 50%), this would mean that these light particles are not of secondary origin. Yet until recently it seemed possible and even probable that the light particles in the cosmic rays are essentially products of $\mu^\pm \rightarrow e^\pm$ decay of $\pi^\pm$ mesons produced in nuclear collisions between cosmic protons and nuclei in the interstellar medium [29,30,116]. However, calculations made recently [125,126] have shown that the electron-positron component of cosmic rays in the galaxy is essentially primary in nature. Therefore it is necessary to expect it to contain a most insignificant number of positrons. However, this does make the problem of experimentally determining the relative numbers of positrons and electrons less urgent (see note added in proof at the end of the article).

No less important is the measurement of the flux of cosmic γ rays (γ-astronomy). There is no doubt that the development of γ astronomy is among the most urgent and promising trends in the field of outer space research (see in this connection [30,117,126-130]). However, we cannot touch on this problem in the present article.

The most direct way of separating the electrons from the positrons, by magnetic analysis of the electron component, entails many difficulties, for to separate electrons with energies exceeding $3 \times 10^8-10^9$ eV (and it is apparently only such galactic electrons which can arrive on earth in sufficient amounts in the presence of high-latitude cutoff) calls for very large magnetic fields of sufficient dimensions. Within the limits of payload that can be carried so far by a satellite, the production of this type of apparatus is hardly feasible (we disregard the possibility of producing magnetic analyzers in which superconducting coils are used, producing a field intensity up to 50—100 kOe [131–132]).

Another way of separating the positrons from the electrons in cosmic rays is based on the use of proton annihilation. One of the schemes of such an experiment was proposed in [133]. It must be noted, however, that in addition to the great experimental difficulties, most positrons registered in this case would be of low energy, since the annihilation cross section decreases rapidly with increasing positron energy. Thus, the annihilation method of positron registration can apparently be used only in years of minimum solar activity.

The development of equipment which registers effectively electrons with energies $E_e \gtrsim 10^{10}$ eV against the background of the large proton flux (shower-production effect) uncovers in principle the following possibility of determining the ratio of the fluxes of positrons and electrons at these energies. By observing the direction dependence of the flux of the light particles, and by using the east-west asymmetry effect, it is possible to determine the ratio of the electron and positron fluxes.

Such measurements are best carried out in the equatorial region, where the effect of the east-west asymmetry is the largest. In measurements on the equator, the difference in the intensities of the fluxes arriving from the east and from the west will be zero when the number of the positrons and electrons is equal, and will amount to, say 35% of the vertical flux if the positrons constitute 25% of the number of electrons, and 55% in the absence of positrons (measurements at an angle 60° to the vertical, integral energy spectrum of the electrons taken in the form $E_e^{-1.5}$). In setting up the experiment it is necessary, of course, to bear in mind that such factors as the albedo of the earth's atmosphere etc. will lead to a smearing of the effect and may make it difficult to interpret the results. Some control is afforded by simultaneous measurements (with the same instrument) of the east-west asymmetry for protons.

Note Added in Proof. The first experimental results, on the number of positrons in cosmic rays, obtained with the aid of balloons, were reported at the last International Conference on Cosmic Rays (India, December, 1963)[134]. According to these data, the number of positrons in the interval $0.3 < E < 1$ BeV amounts to 16±4 per cent of all the light particles (electrons and positrons). The relative number of positrons increases at lower energies. The value given is the upper limit for the ratio $N^+/(N^+ + N^-)$ in the flux of the primary cosmic rays, since the secondary light particles of atmospheric origin were not separated in [134] from the primary ones. The possible role of the electrons of solar origin is likewise unclear. In one way or another, the percentage of positrons in the electronic component of the primary cosmic rays patently does not exceed 10 to 20 per cent. This result agrees with the deduction made in[125]. At the same time it must be emphasized that by virtue of the secondary processes in the interstellar medium one must expect the appearance of some number of positrons in the electronic component of the galactic cosmic rays (up to 20–30 per cent when $E \approx 10^8$ eV and up to 2–3 per cent when $E \sim 10^9$ eV). The measurement of the number and of the spectrum of the positrons thus remains one of the most urgent problems in research with satellites.

New data were also reported at the India Conference [135–137] on the relative flux of the He^3 nuclei. The values reported for the ratio $He^3/(He^3 + He^4)$ are: 0.20±0.03 in[135], 0.1 in [136] (for the interval E_{kin} = 155–320 eV/nucleon) and even 0.06±0.03 in[137] for the interval E_{kin} = 260–360 MeV/nucleon). Taking these results into account, we can apparently assume that $He^3/(He^3 + He^4) \lesssim 0.20$ in the primary cosmic rays.

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