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INVESTIGATION OF STRATOSPHERE COSMIC RAY INTENSITY FLUCTUATIONS INDUCED BY PROCESSES ON THE SUN

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COSMIC ray intensity fluctuations observed in the stratosphere can be divided into two classes. The first includes the relatively rare cases of anomalously large increases in cosmic-ray intensity, observed essentially at high latitudes, the so-called cosmic ray flares generated by the sun. During these flares the intensity of the primary cosmic radiation exceeds by tens, hundreds, or even thousands of times the normal intensity.

The second class constitutes fluctuations of cosmic-ray intensity of galactic origin. They have a smoother character and a lower amplitude:

a) 27-day variations with amplitude 5—10%, due to the effect of interplanetary magnetic fields on the galactic cosmic rays. These fields are due to the ejection of particles from the sun and therefore vary with the sun's rotation about its own axis; they are apparently caused by the relatively long-lived active regions of the sun—the flocculas.

b) Sudden decreases in the intensity of cosmic rays during magnetic storms, with amplitudes up to 30—40%; these are called Forbush decreases and are due to the modulating action of electromagnetic fields carried by the solar plasma clouds on the cosmic rays.

c) Secular variation of the intensity of cosmic rays, with an amplitude approximately twice as large, connected with the 11-year cycle of solar activity. The screening action of the interplanetary magnetic fields, which hinder the arrival of cosmic rays on earth, decreases with decreasing solar activity. Therefore cosmic-ray intensity increases in the solar system during the period of decrease in solar activity.

I. COSMIC RAY FLARES

The cosmic ray flares in the stratosphere were observed in the USSR and independently in the USA in 1958, in experiments in the stratosphere over Murmansk, Minneapolis, and Fort Churchill. The intensity of the primary component of the cosmic rays in the Murmansk region exceeded the average value by approximately 2500 times on 3 March and by 40 times on 17 March and 8 July of 1958. In 1959, during the flares of 10, 15, and 17 July, the intensity of the primary component of the cosmic rays exceeded the average value by approximately 200, 800, and 2800 times, respectively. The flare durations ranged from several hours to several days[3-5]. In cosmic space, the cosmic-ray flare was first registered on 7 July 1958 with the aid of apparatus installed on the third Soviet satellite[6].

According to published data, 26 cosmic-ray flares in the stratosphere were registered from 1958 to the beginning of 1962, of which 23 were observed in experiments over Murmansk.

Investigations of cosmic-ray flares are of great interest both in connection with the general problem of generation of cosmic rays and in connection with the study of the physical phenomena on the sun. In addition, these investigations are also of practical importance in problems such as shielding astronauts against the increased radiation during the flares.

The question of shielding astronauts in outer space against cosmic-ray radiation flares could be solved in principle on the basis of the accumulated data on the duration, amplitude, and energy spectrum of the particles in the flares. On the basis of these data it can be asserted that to guarantee protection against solar cosmic rays it would be necessary to use radiation shielding. This, however, would make the spaceships excessively heavy. For space flights in the near future it is therefore very important to find ways of forecasting cosmic-ray flares and to predict the intensity of the flare and the character of its propagation in interplanetary space. This is a new problem, successful solution of which calls for comprehensive and systematic study of solar activity using astronomic or radioastronomic methods and investigations of cosmic rays.

The data presented on cosmic-ray fluctuations are based on more than 4000 measurements carried out in the stratosphere. The instrument which made possible such a large number of measurements, called cosmic-ray radiosonde (RK), is small and weighs about 2 kg[7]. It contains a gas-discharge counter with area 1.8×10 cm. In some instruments a counter telescope is also used, consisting of two such counters. In the latter case periodic measurements of the number of double coincidences and of the number of discharges in a single counter were made alternately in the instruments. The data obtained with the aid of both types of instruments could thus be readily compared with each other.

Regular measurements have been carried out in the USSR since the middle of 1957, in accordance with the program of the International Geophysical Year, first at geomagnetic latitudes 64 and 51° (Murmansk, Mos-

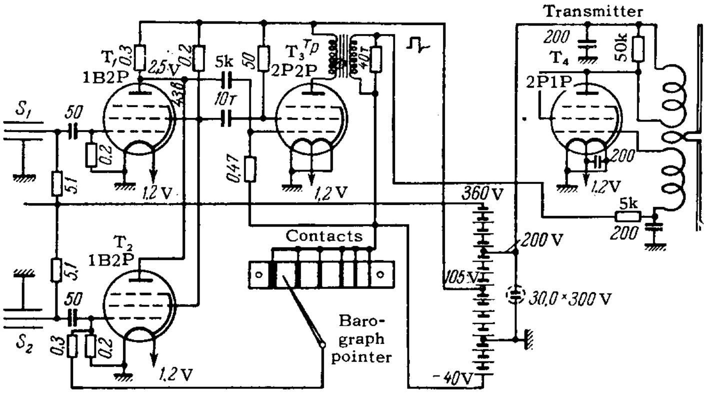

FIG. 1. Diagram of radiosonde.

cow), and since April 1958 also at 41° latitude (Simeiz).

The threshold energies for the primary protons at these latitudes are, in accordance with calculations given in [8], 0.1, 1.5, and 4.6 BeV, respectively.

1. Cosmic Ray Radiosonde (RK)

A diagram of the described radiosonde (RK-2) with counter telescope is shown in Fig. 1. Counters S_1 and S_2 are connected in the grid circuits of tubes T_1 and T_2. The plate and screen-grid circuits of these tubes are interconnected. A univibrator consisting of tubes T_1, T_2, and T_3 is used to shape pulses of the required duration (10^{-3} sec) and amplitude. The pulses at the output of the transformer Tr cause the cut-off tube T_4 of a UHF radio transmitter to conduct. The signals of the transmitter are registered on earth with the aid of a UHF receiver, which feeds a scaler with a mechanical counter.

Data on the altitudes on which the measurements are made are obtained with the aid of a barograph built into the instrument. It is seen from Fig. 1 that whenever the barograph pointer passes over the barograph contacts, tube T_2 is cut off (by a 40-volt bias) and the number of discharges in the single counter S_1 is then measured. When the pointer passes over the insulator, both tubes T_1 and T_2 conduct. Then only the double coincidences $S_1 + S_2$ are registered. Since an abrupt change occurs in the counting rate whenever the barograph pointer moves from the contact to the insulator and vice versa, it is easy to determine from this the instant when the barograph pointer passes over the contact and respectively over the insulators. In the RK-2 instrument the number of double coincidences (with the pointer on the insulator) was measured for 75% of the entire time, while 25% of the time was allotted to measurements of the number of particles by a single counter.

The RK-1 radiosonde, intended for the measurement with the aid of a single counter, has a simpler circuit. In this case there is no need for tube T_1. It is seen from Fig. 1 that when the barograph pointer passes over the contacts a pause occurs in the transmission of the radio signals. By using the fixed instants when these pauses occur, we obtain data on the flight altitudes.

Thus, a radio signal of one type yields information both on the particle-number counting rate and on the altitudes at which the measurement takes place. This procedure has made it possible to simplify the circuitry of both the radiosonde and of the land-based apparatus.

2. Cosmic Ray Flares in the Stratosphere and Phenomena that Correlate with Them

Cosmic-ray flares usually occur in the stratosphere approximately 1—10 hours following the start of solar chromospheric flares, and continue from several hours to several days [3]. A geomagnetic storm and auroras set in approximately one day after the chromospheric flare. Towards the beginning of the occurrence of the magnetic storms, or somewhat later, a sudden decrease usually takes place in the intensity of the cosmic rays registered near sea level, and also in the stratosphere at medium and low latitudes.

Not all the cosmic-ray flares in the stratosphere correlate with the magnetic storms and the Forbush decreases. This correlation has a maximum when the chromospheric flare which gave rise to the cosmic-ray flares occurs in the region of the central meridian of the sun's disc.

Soon after the start of the chromospheric flare, a sharp increase takes place in the radio emission of the sun, accompanied by ionospheric disturbances. This is followed by a period of absorption of cosmic radio emission in the polar region [9,10]. The latter phenomenon is connected with the arrival of protons with energies ~ 10 MeV from the sun [9,11]. As a rule, flares of cosmic rays are accompanied by a burst of radio emission of type IV.

3. Investigation of the Proton Energy Spectrum in Flares

An analysis of the first data, obtained both with the aid of a single counter and with a counter telescope, has shown that the radiation due to the flares, registered in the stratosphere, consists most likely of protons[1,3,4]. Winckler exposed successfully nuclear emulsions in the stratosphere during the cosmic ray flares (12 May 1959) and obtained by this method direct data on the charge distribution of the solar cosmic ray particles[12]. It follows from his experiments that most registered particles are protons. This method was subsequently extensively used in the USA both in experiments on balloons and in experiments carried out with the aid of geophysical rockets[13].

One of the methods for investigating the energy spectrum of the primary protons during the flare is to measure the absorption of these protons in the upper layers of the atmosphere[3,14]. The intensity of cosmic rays of galactic origin in the stratosphere has a maximum at altitudes 16—22 kilometers. At large altitudes this intensity decreases appreciably. During the time of the flares, the intensity of the cosmic rays in the stratosphere at high latitudes has no maximum; it continuously increases with altitude. A so-called absorption curve (the dependence of the number of registered particles on the pressure in the stratosphere) is plotted by subtracting from the particle number measured at different altitudes during the time of the flares the corresponding data prior to the flare. During the time of the flare, the radiosondes are launched into the stratosphere more frequently, in many cases every 3—4 hours. This makes it possible to obtain information on the changes occurring in both the intensity and the spectrum of the primary radiation during the course of time. The plots of Fig. 2 illustrate the form of the absorption curves obtained for certain measurements during the flares of 4 May and 3 September of 1960. The ordinates are the numbers of double coincidences and the abscissas the pressure in g/cm^2. Data on the primary radiation intensity are obtained by extrapolating the absorption curve to a pressure of 5 g/cm^2, which corresponds to the range of 90-MeV protons.

What is remarkable about the absorption curves obtained during different times of the flare is that they have slopes which differ little from one another, although the intensity of the primary protons changes appreciably with time. Consequently, the energy spectra of the primary protons experienced no noticeable changes during the course of time. Another surprising fact is that these energy spectra are close to each other also for different flares. This indicates that the formation of the energy spectrum of the solar cosmic rays is governed by a universal law[15,16].

It is difficult to explain the constancy of the energy spectrum of the protons from the point of view that the spectrum is produced during the time of the flare itself[17]. According to Syrovat-skiĭ, the spectrum is more likely to be formed during the time when the particles leave the magnetic trap into which they are injected while accelerated. The energy spectrum obtained on this basis[18] agrees in general with the experimental data. However, in view of the importance of the question of the constancy of the energy spectrum, other possibilities must also be considered. A unique interpretation of the constancy of the energy spectrum of the protons generated by the sun in different flares, is, in our opinion, of great theoretical interest.

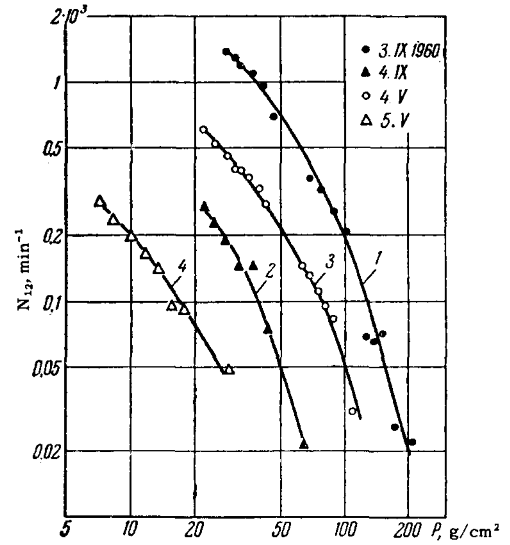

FIG. 2. Number of coincidences N_{12} as a function of the pressure. 1 – 3 September 1960, instrument started 07:00 hours; 2 – 4 September 1960, instrument started 11:56; 3 – 4 May 1960, instrument started 15:00; 4 – 5 May 1960, instrument started 10:20.

The data shown in Fig. 2 were obtained in measurements prior to the start of geomagnetic storms and respective Forbush decreases, in other words, prior to the arrival of the solar corpuscular streams on earth. Figure 3 shows the results of measurements of absorption curves obtained during the time of geomag-

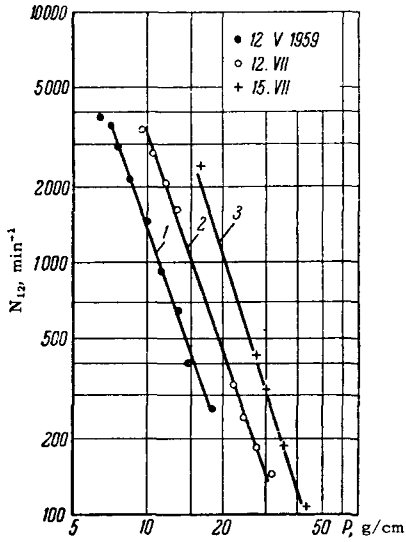

FIG. 3. Measured number of double coincidences N_{12} as a function of the pressure. 1 – 12 May 1959, instrument started 12:00 hours; 2 – 12 July 1959, instrument started 11:45; 3 – 15 July 1959, instrument started 12:00.

netic storms and Forbush decreases (data of 12 May, 12 July, and 15 July 1959). The slopes of the lines drawn through the experimental points also differ little from one another, but the slope of the spectrum is in this case appreciably larger.

Both types of spectra, with the relatively gentle slope prior to the magnetic storm and steep during the time of the magnetic storm for one and the same flare, were first observed in the experiments of 11–12 July of 1959[3,4] A similar result was obtained later from the measurements of the flare of 15 November 1960[19,20] and also in the experiment of Ney and Stein[21] of November 12, 1960 over Minneapolis. We note that in many cases it becomes possible to ascertain that the softening of the proton spectrum during the magnetic storm is accompanied simultaneously by an appreciable increase in the intensity of the registered protons[19,20].

The integral proton spectra averaged over the data of different flares are given in Fig. 4[15,16]. The ordinates are the intensities of the number of primary protons in relative units, while the abscissas are the kinematic energies of the protons in MeV. Spectrum 1 with exponent $\gamma \approx 5.5$ is obtained from measurements during the Forbush decreases . Spectrum 2 corresponds to results of measurements obtained in the absence of a Forbush decrease.

We thus arrive at the conclusion that the energy spectra of the solar cosmic-ray protons differ essentially before and during the Forbush decreases. In the former case the exponent of the integral spectrum is $\gamma \approx 2.0$ and in the latter $\gamma \approx 5.0$.

4. Interpretation of the Softening of the Energy Spectrum During the Forbush Decrease

According to numerous continuous measurements of cosmic rays near sea level, the smaller the cosmic-ray energy, the larger the degree of decrease in the intensity of galactic cosmic rays during the time of the Forbush decrease[22]. Consequently, the energy spectrum of the cosmic rays of galactic origin becomes less steep during the Forbush decrease. For cosmic rays generated by the sun, as shown above, the situation is reversed, and the solar cosmic ray spectrum becomes richer during the magnetic storm with lower-energy particles, so that it becomes softer.

The solar cosmic ray protons arrive on earth before the corpuscular streams from the chromospheric flare which gave rise to this cosmic ray flare. Consequently, by the time that the corpuscular stream arrives on earth, the space around the sun, at least within several astronomic units, is filled with cosmic rays from the sun. The observed softening of the energy spectrum of the protons during the Forbush decrease can be explained only by assuming that there is a new source of protons, connected with the corpuscular stream from the chromospheric flare itself. The corpuscular streams which envelope the earth during that time, originate in the chromospheric flare in which the cosmic rays were generated. We can therefore visualize the following picture: Some of the cosmic-ray protons generated during the time of the chromospheric flare leave the sun and arrive on earth after diffusing in the interplanetary medium. For these protons, the integral energy spectrum has an exponent $\gamma \approx 2.0$. The remainder of the protons, being captured by the magnetic clouds of the corpuscular streams, cannot go freely into the interplanetary space. These particles, captured in unique magnetic traps, are carried away into the interplanetary space together with the corpuscular streams themselves. They are registered when the earth enters these streams. The energy spectrum of the protons in the traps corresponds to a slope $\gamma \approx 5.0$.

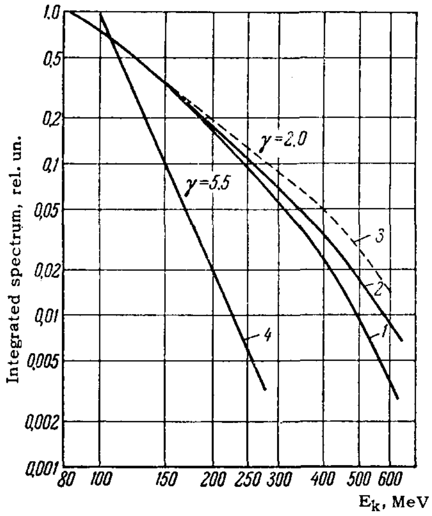

FIG. 4. Integral energy spectra of protons. 1 – Averaged spectrum from measurement data in the absence of a magnetic storm or a Forbush decrease; 2 – the same with absorption of protons in nuclear collisions in the atmosphere included in addition to the ionization losses; 3 – obtained from 2 with approximate allowance for the time of diffusion propagation of the protons in space as a function of their velocity; 4 – averaged spectrum from data of measurements during the time of a magnetic storm and a Forbush decrease.

We thus arrive at the notion that there exist magnetic traps* for fast protons in the corpuscular stream of the chromospheric flare, and that these traps propagate in interplanetary space[3,14-16,19,20].

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*Magnetic traps of corpuscular streams are frequently defined as magnetic fields in the form of loops which extend from the sun as the corpuscular streams propagate (McCracken[23]). Such magnetic "loops," according to the author's description, are giant traps for particles generated during the time of the subsequent chromospheric flare, occurring in the same active region on the sun. As is clear from the foregoing, the magnetic traps which we are discussing are of a different nature and are formed, in particular, in the same chromospheric flare in which the cosmic rays have been generated.

Table I

Date of chromospheric flare	m_{st}	$m_{s.l.}$, %	Date of chromospheric flare	m_{st}	$m_{s.l.}$, %
17.III 1958, $10^h25'$	35	<2	3.IX 1960, $00^h40'$	70	3
7.VII 1958, $0^h58'$	40	<1	12.XI 1960, $13^h22'$	1200	130
11.V 1959, $20^h55'$	40	<1	15.XI 1960, $02^h07'$	500	80
10.VII 1959, 02^h	200	<1	20.XI 1960	7	5
14.VII 1959, 04^h	200	<1	18.VII 1961, $09^h30'$	140	12
16.VII 1959, 21^h	2800	5	20.VII 1961, $15^h50'$	13	3
4.V 1960, $10^h15'$	35	10			

5. Generation of Solar Cosmic Rays with Low and High Energies

Most cosmic-ray flares observed in the stratosphere are not registered by instruments on earth, owing to the absorption of the primary particles in the atmosphere. In many cases, however, flares were also registered simultaneously with land-based apparatus. The question which we are now considering is as follows: Is there a correlation between the amplitudes of the flares measured in the stratosphere and those measured near sea level? A comparison shows that apparently there is no definite connection between them. This is illustrated by the data of Table I, which gives the dates of the cosmic-ray flares, the maximum increase in the intensity of the primary cosmic rays as obtained by stratosphere measurements (in units of normal intensity — m_{st}), and the increase in the cosmic-ray intensity near sea level in per cent (as given by a neutron monitor — $m_{s.l.}$). We see that the flares with the large amplitudes, registered in the stratosphere in 1958-1959, make no contribution to the cosmic-ray intensity on earth. Yet in many cases flares on earth are registered at much lower amplitudes, as obtained from stratospheric data (4 April 1960, 20 November 1960, 20 July 1961).

Figure 5 shows the proton energy spectra obtained from the aggregate of measurements in the stratosphere and on earth, for the flares of 4 May and 15 November 1960. The ordinates represent the number of protons from the sun with energies above a given value, and the abscissas represent their kinetic energies. The dark and light circles correspond to measurements in the stratosphere at 64° latitude. The triangle corresponds to measurements in the stratosphere at 51° latitude. The dark and light squares correspond to measurements on earth. (The results given in the figure correspond to the measurement times for the maxima of the flare amplitudes in the stratosphere and on earth[19,20].)

As can be seen from the figure, the slopes of the spectra in the region of low energies, according to the flares of 4 May and 15 November 1960, are nearly equal in value ($\gamma \approx 2.0$). At high energies, however, they are quite different. The relatively larger slope of the spectrum of the 15 November flare in the high-energy region agrees with the spectral measurements on earth. Yet for the flare of 4 May, there is no such agreement. These contradictory data on the spectral indices in the high-energy region also favor the assumption that in the flares there is apparently no definite connection between the intensities of the protons generated at low and at high energies.

6. Effects due to Penetration of Short-range Electrons into the Stratosphere During the Forbush Decrease

Observations carried out at different stages of development of the flare with the aid of a counter telescope with a 7 mm aluminum filter and with a single thin-wall counter have shown that during the period of the Forbush decrease short-range particles (range shorter than 7 mm aluminum) penetrate into the stratosphere in addition to the protons.[15,16]

During the Forbush decrease the number of particles measured with the aid of the thin-wall counter is approximately double the value obtained with the aid of a telescope. For the flare of 15 July 1959 this ratio reached 6.

This phenomenon has been little studied, although it has been found that it correlates with phenomena connected with the arrival of solar corpuscular streams on earth. But the question whether the appearance of a flux of short-range particles (apparently photons or electrons) in the stratosphere is directly connected

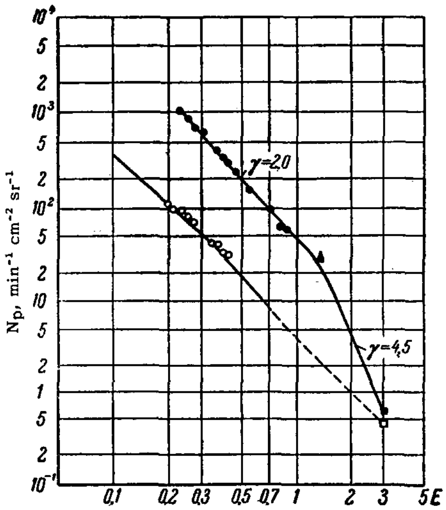

FIG. 5. Integral energy spectra of protons from the aggregate of data of measurements in the stratosphere and near sea level; 1 – flare of 4 May 1960, 2 – flare of 15 November 1960.

with the solar corpuscular streams or whether it is due to phenomena connected with disturbances of the external radiation belt of the earth[24] still remains open.

7. Intensity of Primary Protons as a Function of the Time

With the aid of absorption curves measured during different times of the flare development it is possible to obtain, by extrapolating these curves to sufficiently large altitudes, data on the time dependence of the intensity $N_p(t)$ of the primary protons in the flares. The values of $N_p(t)$ obtained in the measurements of 4–5 May and 3–5 September 1960 are shown in Fig. 6. The time origin $t = 0$ corresponds to the start of the chromospheric flare.

The errors in the data shown in Fig. 6 are connected essentially with the extrapolation of the results of the measurements (to a pressure of 5 g/cm^2). For most points these errors amount to approximately 20–30%. The large duration of the flare in September, compared with the flare in May, is due essentially to the gently sloping portion of curve 2.

It is interesting to compare the $N_p(t)$ data obtained in the stratosphere, for primary protons with energies of several hundred MeV, with the data on the flare of 23 February 1956, obtained for primary protons with much larger energies (> 3–4 BeV). It is seen from the plots of Fig. 6 that the intensity of the protons with higher energies decreases with time approximately 5 times faster than for particles with low energies.

8. Diffusion of Cosmic-ray Protons from the Sun in the Interplanetary Medium. Data on the Diffusion Coefficient. Intensity of the Fields in Magnetic Inhomogeneities

It is well known from the cosmic-ray flares registered near sea level, for example on 23 February 1956, that the additional flux of cosmic rays following the maximum of the intensity is described over a wide time interval by a relation of the type $A/t^{3/2}$. The distribution of the primary radiation in space was found to be almost isotropic during that time[25]. These data show convincingly that the propagation of the solar cosmic-ray protons in the interplanetary medium has a diffusion character. The characteristic dimensions of the magnetic inhomogeneities in interplanetary space, by which the protons with energies of several BeV are scattered, have been determined from data on the time dependence of the development of the flare, obtained by many workers in experiments with continuous registration of the cosmic rays[26,27]. Following the same path and using the results of experiments in the stratosphere, new data have been obtained by now concerning the magnetic inhomogeneities in the interplanetary medium, which are effective with respect to scattering of protons of much lower energies. The solution of the diffusion differential equation for homogeneous space with spherical symmetry

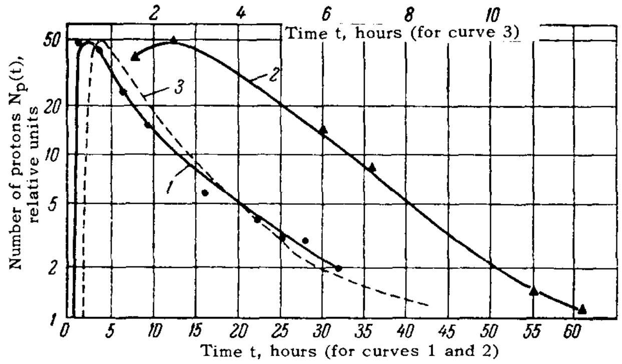

FIG. 6. Intensity of protons as a function of the time, from data in the atmosphere. 1 – Flare of 4 May 1960, 2 – 3 September 1960, 3 – data near sea level for the flare of 23 February 1956 (Chicago).

$$\frac{\partial N_p}{\partial t} = D\left(\frac{\partial^2 N_p}{\partial r^2} + \frac{2}{r}\frac{\partial N_p}{\partial r}\right)$$

where B particles are injected at the point $r = 0$ at $t = t_0$, is of the form

$$N_p(R, t - t_0) = \frac{1}{8} B\,[\pi D (t - t_0)]^{-3/2} \exp\left[-\frac{R^2}{4D(t - t_0)}\right]; \quad (1)$$

$N_p(R, t - t_0)$ is in our case the intensity of the primary protons as a function of the time on earth, R —distance from the sun to the earth, t —time of observation, t_0 —initial time, and D —diffusion coefficient

$$D = \frac{lv}{3}. \quad (2)$$

Here l —mean free path of the protons prior to the scattering and v —proton velocity.

Naturally, for the scattering of protons by magnetic inhomogeneities it is necessary to have $l \geq p/300H$, where H —intensity of the magnetic fields in the clouds and p —the proton momentum.

The assumption made above that the magnetic clouds have a uniform distribution in space ($D = \text{const}$) does not follow from any experimental data. To the contrary, such an assumption apparently makes it impossible to explain some aspects of the experiment. However, for an outline of the main features of the phenomenon this simplification is apparently justified.

For $t - t_0 \ll R^2/4D$ the behavior of $N_p(R, t - t_0)$ in (1) is essentially determined by the exponential term. For this case, data on t_0 are most important. $N_p(t - t_0)$ has a maximum when $t - t_0 = R^2/6D$, and for $t - t_0 \gg R^2/4D$ we have

$$N_p(t - t_0) = \frac{B}{8} \Big/ [\pi D (t - t_0)]^{3/2}. \quad (3)$$

The constant B in this expression is determined experimentally, for example from data on the maximum of $N_p(t - t_0)$. For the flare of 4 May $B = 2.5 \times 10^{32}$ protons, meaning that the kinetic energy carried away by the protons is 6×10^{28} erg.

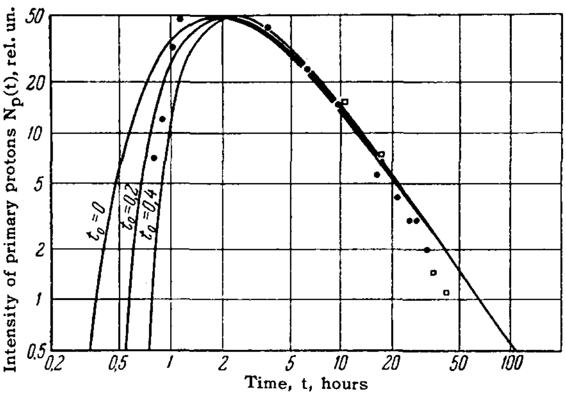

FIG. 7. Intensity of primary protons as a function of the time, calculated from formula (1). $D = 5.5 \times 10^{21}$ cm^2 sec^{-1}, $t_0 = 0$; 0.2, and 0.4; ● – experimental data for flare of 4 May 1960; □ – experimental data for flare of 3 September 1960.

Figure 7 shows plots obtained by formula (1) for three values of t_0, as well as the experimental data on the flares of 4 May and 3 September. The best agreement between the curves and the experimental results is for a diffusion coefficient $D = 5.5 \times 10^{21}$ cm^2/sec. For the flare of 4 May, the time was reckoned from the start of the chromospheric flare. For the data of 3 September, the time origin was taken at 20 hours following the start of the chromospheric flare. The latter is connected with the fact, which can be seen from Fig. 6, that the flare of 3 September was longer than that of 4 May, essentially owing to the gently sloping section of the curve at the beginning. Therefore the comparison should be made only with respect to the coinciding sections of the curve. As can be seen from Fig. 7, the data of both flares almost coincide when the data of 3 September are shifted by 20 hours.

Knowing the value of D and putting $v = 0.5c = 1.5 \times 10^{10}$ cm/sec (for 100-MeV protons) we obtain from (2) for low-energy protons a scattering mean free path $l \approx 10^{12}$ cm, which corresponds to approximately one-tenth a.u. From the condition $H > P/300l$ and $P_1 = 5 \times 10^8$ eV/c we find that the intensity of the magnetic field is $H > 1.5 \times 10^{-6}$ G.

Using formula (3) and the experimental data, we obtain from the descending parts of the curve on Fig. 6 the value of the diffusion coefficient for the high-energy protons (3—4 BeV), which is found to be almost 5 times larger than D_1. The mean free path for the high-energy protons is $l \approx 2.7 \times 10^{12}$ cm. The corresponding magnetic field intensity of the clouds, for the case of high energies, is $H_2 > P_2/300l_2 = 6.2 \times 10^{-6}$ Gauss ($P_2 = 5 \times 10^9$ eV/c).

Comparing the diffusion coefficients D_1 and D_2 for momenta $p_1 = 5 \times 10^8$ eV/c and $p_2 = 5 \times 10^9$ eV/c, we can approximate the dependence of l on the proton momentum p in the following fashion: $l = l_0 p^k$, and accordingly $D(p) = v l_0 p^k/3$, where v —particle velocity, l_0 —constant, and $k \approx 1/2$.

As can be seen from Fig. 7, two experimental points for the start of the flare deviate greatly from the theoretical curve for $t_0 = 0$ and agree better with the curve for $t_0 = 0.3$. We cannot conclude, however, that the generation of the cosmic rays was delayed relative to the start of the chromospheric flare. Such a conclusion is difficult to make, since the calculated curves are insufficiently accurate. This inaccuracy is connected principally with the assumption that the diffusion coefficient is constant in space. Actually it is quite possible that the diffusion coefficient exceeds its average value in the space closer to the sun and is smaller behind the earth's orbit. We can therefore understand qualitatively why the experimental data for the start of the development of the flare lie below the calculated curve for $t_0 = 0$. If we assume that the effective diffusion coefficient for the initial portion of the curve exceeds the average by 30—40%, then we can also describe the experimental data for $t = 0$.

We can therefore say that if the generation of low-energy cosmic rays on 4 May was delayed relative to the start of the chromospheric flare, it was by less than 20 minutes.

For large values of t, as can be seen from Fig. 7, the experimental data lie below the theoretical curve. This result can also be explained by starting with the assumption that the value of D for the space beyond the earth's orbit is somewhat smaller than average.

9. Cosmic Ray Flares Generated on the Opposite Side of the Sun's Disc. Radial Magnetic Fields of the Sun

It is clear that the chromospheric flares during which the cosmic rays are generated occur with equal frequency on both sides of the sun. A study of the generation of cosmic rays on the opposite side of the sun is of interest and will enable us to obtain additional information on the structure of the electromagnetic fields in interplanetary space.

We start from the experimental data which show that the propagation of the solar protons in interplanetary space is of diffusion character. One or two hours following the generation of the cosmic rays on the sun, the radiation of space will be isotropic and the conditions for the registration of cosmic rays registered on the visible and opposite sides of the sun will be approximately the same. Consequently, flares of cosmic rays due to chromospheric flares occurring on the opposite side of the sun should be registered in the stratosphere just as frequently.

If interplanetary space contains also a radial solar magnetic field in addition to the magnetic inhomogeneities which scatter the protons, then the diffuse propagation of the protons from the sun in the interplanetary medium will have an anisotropic character. Therefore cosmic ray flares occurring on the opposite side of the sun, if registered on the earth at all, will have amplitudes lower than those of flares produced on its visible side. This agrees with the experimental data[28].

It is known that many cosmic ray flares in the stratosphere are accompanied by geophysical and radioastronomical phenomena such as magnetic storms, ionospheric disturbances, auroras, Forbush decreases, absorption of cosmic radio emission in the polar cap, and others. Magnetic storms, aurora borealis, and Forbush decreases are connected with the arrival on earth of molecular streams ejected by the sun during chromospheric flares. The direction of motion of the corpuscular streams of the sun is almost radial[29], so that the corpuscular streams arrive on earth only from those chromospheric flares which occur on the visible side of the solar disc. Thus, stratospheric cosmic ray flares accompanied by a Forbush decrease, a magnetic storm, or auroras can be identified as being due to chromospheric flares produced on the visible side of the solar disc. It is also known that chromospheric flares which produce cosmic ray flares are accompanied in most cases by radio emission of type IV[9,30]. Therefore cosmic-ray flares accompanied by radio emission of type IV can also be credited with good cause to chromospheric flares occurring on the visible side of the solar disc.

The cosmic-ray flares selected in accordance with these attributes (from data published up to the start of 1962) are listed in the first part of Table II, which indicates the date of the flare and the maximum measured intensities of the primary protons in units of normal intensity of galactic cosmic rays m. It can be assumed with sufficient justification that the 17 cosmic-ray flares listed in Table II are due to chromospheric flares from the visible side of the solar disc.

In the third column of the table are given flares which cannot be attributed with certainty to chromospheric flares from the visible side of the disc, although some were preceded by chromospheric flares. Thus, the flare of 3 March 1958 was preceded by the chromospheric flare at 9:12 on 1 March, with an intensity of 3 units. There is no information of a type IV radio burst. It is known, however, that starting with 6:00 on 3 March, through 18:00 on 8 March, strong geomagnetic disturbances were observed, and that during the night between 3 and 4 March an aurora was observed in Murmansk. Therefore one cannot exclude the possibility that this flare was also due to a chromospheric flare from the visible side of the sun. Only for three cases (3 October 1958, 21 November 1960, and 9 May 1961) were no corresponding chromospheric flares observed.

Consequently 17 out of 26 flares are known to be due to chromospheric flares from the visible side, and at least 6 of the remaining 9 may also be due to chromospheric flares from the visible side of the solar disc.

We are struck by the amplitudes of the flares of cosmic rays which enter into the first and second parts of the table. With the exception of the case of 3 March, the amplitudes of the flares in the second part of the table are appreciably smaller (by approximately two orders of magnitude) than in the first.

We might therefore assume that cosmic-ray flares from the opposite side of the sun's disc were also registered in the stratosphere, but with much smaller amplitudes. Such a result would offer evidence of a preferred direction of motion of the protons from that side of the sun on which the cosmic rays were generated. This conclusion, however, would not contradict the notion of diffuse propagation of solar cosmic rays, if it is assumed that radial magnetic fields of the sun exist in the interplanetary space along with the magnetic inhomogeneities. If the intensity of the radial magnetic field and of the inhomogeneity fields do not differ greatly from one another, then we can expect an anisotropic diffuse propagation of the protons from that side of the sun on which a cosmic-ray flare was produced. Such an interpretation of the results is in good agreement with the notions advanced by Parker[31] concerning the so-called solar wind, which comes from the sun and apparently carries magnetic fields with predominantly radial directions. As already noted, there are published discussions of data on magnetic fields in the form of loops, which extend radially from the sun during the time of chromospheric flares. The existence of such magnetic fields, according to McCracken[23], follows from data on the directions of arrival of cosmic rays of the sun on earth, and the distribution of cosmic-ray flares over the solar disc. However, the deduced existence of a radial magnetic field, which follows from our data, is not connected with any individual chromospheric flare. These fields

Table II

Date	Registered maximum increase	Date	Registered maximum increase	Date	Registered maximum increase
17.III 1958	35	1.IV 1960	4	3.III 1958	2500
26.III 1958	15	4.V 1960	35	3.X 1958	2
8.VII 1958	40	3.IX 1960	70	9.VII 1959	2
22.VIII 1958	10	12.XI 1960	70	28.IV 1960	7
26.VIII 1958	2	15.XI 1960	500	29.IV 1960	2
11.V 1959	40	12.VII 1961	10	12.V 1960	3
10.VII 1959	200	19.VII 1961	140	13.V 1960	5
15.VII 1959	800	20.VII 1961	10	21.XI 1960	7
17.VII 1959	2800			13.V 1960	5

are more likely to have a stationary character. From this point of view, the result described agrees better with the conclusion that radial magnetic solar fields exist, first made by Vitkevich on the basis of radio-astronomic data concerning the distribution of the electronic inhomogeneity in the space of the solar supercorona[32].

II. 27-DAY VARIATIONS OF COSMIC RAYS IN THE STRATOSPHERE

Systematic balloon measurements have made it possible to disclose 27-day variations of the intensity of the cosmic rays in the stratosphere[33,34]. These variations are in general not stable. They were observed during the period from July 1957 through February 1958.

Curves of the secular course of the variations were obtained by a moving-average method. The deviation of the results of each measurement from the secular course of the variations was processed by the periodogram method[35]. The results are shown in Fig. 8, where the abscissas represent the previously specified values of the period T of the variation, in days, while the ordinates represent the resultant amplitudes. It is seen from Fig. 8 both from the stratosphere data (curve 1) and from the land-based neutron monitor data (curve 2) (Hurstmoss, England, geomagnetic latitude 53.5°N), that the periodograms show a clearly pronounced maximum of deviations, occurring with a period of 27—29 days. The straight lines on the figure show the average level of the amplitudes, obtained after mixing the sequences of the experimental data with random ones[35]. Thus, during this period there was observed in the stratosphere a 27-day variation of cosmic rays, with an amplitude of 5.5 ± 0.6%. At sea level the amplitude of the 27-day wave, according to the data of the neutron monitor, amounted to 2 ± 0.2%, while the ionization chamber yielded 0.7 ± 0.4%.

To study the correlation of the 27-day variations with the geomagnetic data by the same method of the periodograms the data on the world K index were also processed. The dashed curve in Fig. 8 is the periodogram for the K index. The maximum obtained at T = 23 days is beyond the limits of errors. The periodograms for the K index measured in Moscow and Tashkent have the same form. It is interesting to note that the value T ≈ 23 days obtained for the K index is apparently not accidental, since the maximum in the periodograms for the K index, obtained for other measurement periods from 1 February through 1 July 1958 and from 1 January through 1 July 1959, also range from 22 to 25 days.

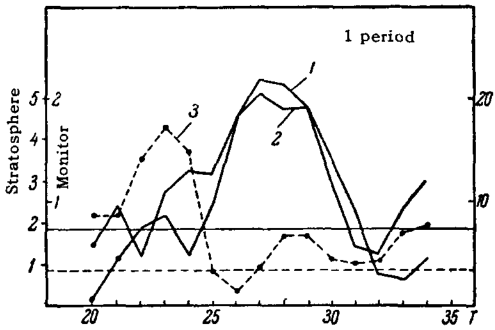

FIG. 8. Periodograms obtained by measurements in the stratosphere at 51° latitude (1), from a neutron monitor reading (λ = 53°) (2), and for the K index (3).

It must thus be conceded that during the period under consideration there was no correlation between the 27-day variations of the cosmic rays and the K index.

Let us stop to discuss the wave form of the 27-day variation of the cosmic rays, plotted for T = 27 days in Fig. 9. The abscissas show the time in days, and the ordinates show the corresponding values of the deviations. The data for the neutron monitor and the automatic space probe are given in accordance with the ratio of their variation amplitudes to the amplitude of the variations in the stratosphere.

It is seen first that, accurate to within 1 or 2 days, the phases of the waves obtained for the different components of the variations agree. Second, the waveform is very nearly sinusoidal (the dashed curve in the figure is a sinusoid).

The question of the correlation between the 27-day cosmic-ray variation and the solar data was considered. Attempts were made to find the correlation with the data on the relative number of sunspots, but no definite correlation was observed. On the other hand, it is apparent that the 27-day wave of the cosmic-ray variation is due to the spin of the sun about its own axis. The long-lived formations on the sun, the flocculas, can cause the 27-day modulation of the intensity of the cosmic rays.

During the period under consideration there were

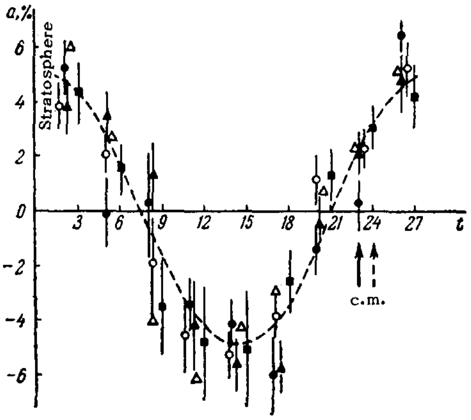

FIG. 9. Waveform of 27-day variation in the first measurement period. ● – for stratosphere, λ = 51°; ▲ – *from a neutron monitor* data, λ = 53°; ■ – from automatic space probe data, λ = 51°; ○ – from data of neutron monitor, λ = 26°; Δ – from data of neutron monitor, λ = 0°. Instants of passage of active regions through the central meridian are marked by arrows.

on the sun two active regions, which lasted 7 revolutions of the sun (according to the "Solnechnye dannye" (Solar Data) bulletins, 1957, nos. 4–6). One of them (latitude 20–23° and Corrington longitude 149–165°) passed for the first time through the central meridian on 19 July (group number 315) and the last time on 27 December 1957 (group number 622). Both regions were surrounded during their entire lifetime by flocculas of intensity 3.

The time of passage of these groups through the central meridian is designated by arrows in Fig. 9. Although there is no full assurance that the observed 27-day variations of the cosmic rays are actually due to the indicated active regions (flocculas), it appears likely that the 27-day modulation was due to corpuscular streams emerging from these active regions on the sun.

The time of delay of the minimum of the intensity of the cosmic rays relative to the time of passage of the active regions through the central meridian, as can be seen from Fig. 2, is approximately 20 days. This delay time corresponds to a corpuscular-stream propagation velocity $\sim 10^7$ cm/sec. The fact that the form of the discussed 27-day wave is not peaked but closer to a sinusoid offers evidence of the large angular spread in which the corpuscular streams leave the sun.

III. DECREASE IN INTENSITY OF COSMIC RAYS IN THE STRATOSPHERE DURING THE TIME OF GEOMAGNETIC STORMS

Until recently a study of the effects involving the decrease in the intensity of the cosmic rays during the time of geomagnetic storms, the so-called Forbush decrease (FD), was carried out almost exclusively with the aid of land-based apparatus which continuously registered the cosmic rays. Owing to the thickness of the atmosphere, the information obtained with the aid of land-based apparatus makes it possible to study only the variations due to a primary cosmic-ray component with energy larger than 4–5 BeV.

No Forbush decrease effects were investigated for the broad spectral interval of the primary cosmic rays with lower energies.

Investigations at high altitudes and outside the atmosphere make it possible to estimate the FD effects for a primary component with much lower energy.

FD data were derived recently from measurements made with artificial earth satellites and space rockets [36,37] outside the atmosphere, and from stratosphere measurements.

During the period from July 1957 through 1962, 35 decreases in the cosmic-ray intensity with amplitudes larger than 5%, correlated with magnetic storms, were registered in the stratosphere. We present below the results of the measurements for the most clearly pronounced FD effects in the stratosphere.

1. Measurement Results

The results discussed were obtained in measurements with the aid of RK-1 radiosondes during the maximum cosmic-ray intensity, at geomagnetic latitudes 51 and 41°. The data at 64° are not considered, since the FD in the stratosphere at latitudes 51 and 41° were accompanied in most cases by cosmic-ray flares at 64°.

The characteristic data on the FD in the stratosphere, obtained during May–August 1959, are shown in Fig. 10. The ordinates represent the deviations of the intensities of the cosmic rays as percentages of the mean-monthly value for July 1959. The circles in the upper part of the figure correspond to measurements in the stratosphere over Simeiz. For comparison, data are also presented from the neutron monitors (n.m.) in Huancayo (Peru, λ = 0.6°) (points) and in Hurstmoss, England, λ = 53°N (continuous line). For the stratosphere, the duration of the measurements amounts to approximately 10 minutes. For land-based stations the 2-hour values are taken for a time which is close to the time of the measurements in the stratosphere.

From the data of Fig. 10 we see clearly cases of sharp decreases in the intensity of the cosmic rays in May and in July 1959. We also see a very good agreement between the results obtained in the stratosphere at 41° and the land-based measurements (the neutron monitor in Hurstmoss). The data obtained in the stratosphere at 41° latitude and on earth were close to each other. This result can be interpreted as meaning that the threshold energies of the primary cosmic

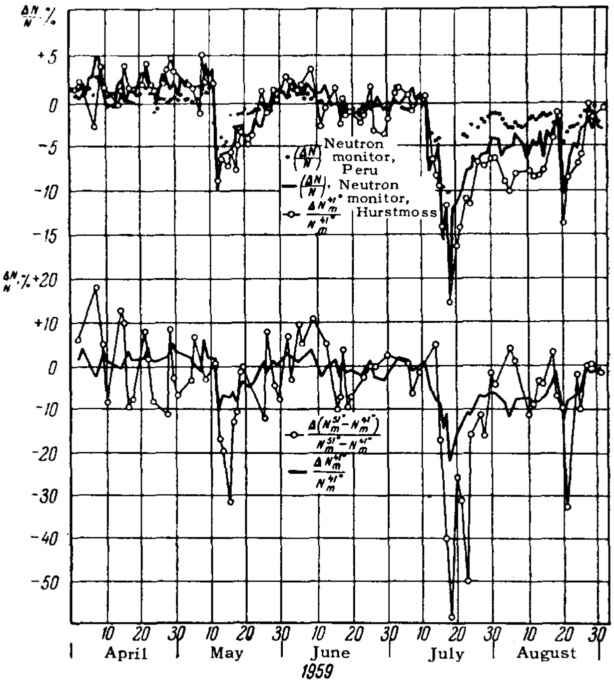

FIG. 10. Relative changes in cosmic-ray intensity.

rays were close to each other for the two types of measurements. Thus, the data obtained on the variations in the stratosphere at 41° (in per cent) are more or less equivalent to the results of land-based measurements of the neutron monitor. Therefore data on the variations of the primary cosmic rays with lower energies were obtained by using the results at 51°, where the critical energy for the primary protons is 1.5 BeV.

By studying the variations of the difference of the number of particles $N^{51}_{m} - N^{41}_{m}$ (obtained after subtracting the data for 41° from the measurement data for 51°) we investigate by the same token the variations due to the primary cosmic rays with energies lying in the interval from 1.5 to 4.6 BeV.

In the lower part of Fig. 10 the circles represent data on the variations for the difference $N^{51}_{m} - N^{41}_{m}$, in per cent. The continuous line is for 41°. We see that the fluctuations in the difference are appreciable. They occur not only in the FD periods but also in the usual periods. The nature of these large fluctuations is still not clear. They cannot, however, be completely attributed to statistical measurement errors. It is seen from Fig. 10 that the deviations for the difference are practically three times larger than for N^{41}_{m}, and that the intensity of the primary cosmic rays in the energy interval from 1.5 to 4.6 BeV during the FD time in May 1959 decreased below the normal value by approx-

Table III. Relative decrease in intensity of cosmic rays (%)*

Date	Neutron monitor	Stratosphere	
		$\lambda=51°$	$\lambda=41°$
September 1957			
2.IX	6.6	9.5	
5.IX	9,0	10	
6.IX	7.5	9,8	
7.IX	8,5	8.7	
9.IX	4,7	15.3	
12.IX	4.7	9.8	
14.IX	4.7	10.1	
March 1958			
27.III	7.5	10,8	
28.III	7,5	4,0	
31.III	5.5	5,8	
April 1958			
1.IV	5.0	3.9	
2.IV	3.6	7.0	
5.IV	5,0	5.1	
6.IV	5,0	7.8	
7.IV	2.6	6,2	
August 1958			
19.VIII	3.4	5,3	
20.VIII	1.9	4.8	
23.VIII	2.8	7.2	
25.VIII	8,0	8.6	8.8
26.VIII	5.2	3.5	2.0
27.VIII	5.7	9.1	
28.VIII	6.6	7,5	6.5
29.VIII	5.2	4,7	
30.VIII	4.5	4,9	
February 1959			
12.II	5,2	7,0	10.7
13.II	5,1	9,7	8,5
14.II	4,3	10,2	6,9
16.II	5.1	13.7	4.4
17.II	5.1	14.7	6.9
18.II	4.7	7.7	3.9
19.II	4.1	11.2	5.9
20.II	4.1	7,6	5.7
21.II	3.5	9,3	
23.II	3.2	4.5	3.1
May 1959			
12.V	10,0	10,9	9,0
13.V	4,0	8.6	5.0
14.V	5.7	9.1	
15.V	5,6	12,9	7.1
16.V	5.7	7,5	5.8
17.V	4,8	8,5	7.8
18.V	2,9	3,9	4.7
August 1959			
20.VIII	10.2	12,6	13.4
21.VIII	7.9	14.0	8,1
22.VIII	5.6	4.1	
24.VIII	4,9	5,7	6.6
25.VIII	2.7	6,8	5.6
July 1959			
13.VII	6.0		6.2
14.VII	6,1	5.2	8.2
15.VII	4.9	12,7	9.4
16.VII	15,7		14
17.VII	12,3	18.4	11,5
18.VII	20.3	31,3	22.6
19.VII	12.5	17,3	16,1
20.VII	11.3	18,7	14.0
21.VII	10.3	18.1	
22.VII	9.4	15.8	10.7
23.VII	7.6	20.3	
24.VII	7.4	12.5	11.3
25.VII	6.0	12,8	
April 1960			
1.IV	8.2	8.7	9,7
4.IV	6,3	6.2	6.0
5.IV	3,2	5.6	4.0
November 1960			
14.XI	7.4		5.5
16.XI	7.8	14.4	9.6
17.XI	4.7	12,9	5,9
18.XI	5.6	18,6	6.5
19.XI	4.6	7.9	5.5
20.XI	4.1	5.6	10.7
22.XI	3.8	5.3	4.9
23.XI	4.4		4.8
24.XI	3,8	8.7	6.3
July 1961			
14.VII	6,7	10.9	9.5
17.VII	3.4	2.7	5.4
20.VII	5.5	6,7	6.5
21.VII	7.1	6.3	
24.VII	5.1	6.8	4.2
27.VII	10.2	12.2	6.9
28.VII	7.8	8.8	12.5
31.VII	3.1	8.5	7.2
August 1961			
1.VIII	4.4	3,2	5,7

*For the storms listed in the table, 100% is taken to be the intensity obtained during the measurements on the following days:

Sept. 1957 —29.VIII 1957
Mar. 1958 —25.III 1958
Aug. 1958 —16.VIII 1958
Feb. 1959 —10.II 1959
May 1959 — Mean monthly values for June 1959
July 1959 — Mean monthly values for June 1959
Aug. 1959 — Mean monthly values for June 1959
April 1960 — Mean monthly values for Mar. 1959
Nov. 1960 — Mean monthly values for Oct. 1960
July 1961 — Mean monthly values for June 1961

imately 30%, while in July it decreased by almost 60%.

A summary of the data for many cases of FD in the stratosphere, obtained by measurements over Moscow and Simeiz, is listed in Table III. The table lists also data corresponding to land-based measurements by the neutron monitors in Deep River and in Hurstmoss[38,39]. We note that the presented stratosphere data agree with the American data. Winckler found over Minneapolis on 26 March 1958 a 23% decrease in the cosmic-ray intensity (pressure 10 g/cm^2)[40]; McDonald and Weber obtained on 16 May 1959 a decrease of 24% in the number of particles (at 6 g/cm^2) for protons and alpha particles with rigidities larger than 1.1 BeV/c[41]. Simpson, found a decrease of 15% in the intensity of the cosmic rays in experiments with the satellite "Explorer VI" [36] and a 28% decrease in experiments with the space rocket "Pioneer V" on 1 April 1960 [37].

2. Discussion of Results

Using the aggregate of the results of the FD measurements for each case, we obtain the quantities

$$\eta = \frac{\sum\limits_{i=1}^{i=n} \delta_i^{51}/\delta_i^{41}}{n} \text{ and } x = \frac{\sum\limits_{i=1}^{i=n} \delta_i^{51}/\delta_i^{\mathrm{n.m}}}{n},$$

which characterize the hardness of the variation spectrum. Here δ_{i}^{51} and δ_{i}^{41} —decreases in the intensity of the cosmic rays at the maximum in individual measurements at latitudes 51 and 41° (in per cent), n — number of measurements in the stratosphere, and $\delta_{\mathrm{i}}^{\mathrm{n.m}}$ —decreases obtained in land measurements with the aid of a neutron monitor. The values of η and x are listed in Table IV. The errors are the mean-square deviations of the individual measurements from the average over all the measurements. As can be seen from this table, except for the cases of February 1959 and November 1960, the values of η and x do not vary from storm to storm, within the limits of errors. This result agrees with the data of land-based measurements[42,43].

One of the physical characteristics in Forbush decreases is the form of the energy spectrum of the variation ΔD/D, where ΔD —differential spectrum of the primary component which has experienced deviations and D —the primary spectrum before the variation. Depending on the particular theoretical model used to explain the modulation of the cosmic rays due to the magnetic and electric fields carried by the plasma streams of the sun in interplanetary space, the forms of ΔD/D will be different.

Table IV

Forbush decreases	x	η
September 1957	1.8±0.3	
March 1958	1.5±0.2	
August 1958	1.5±0.2	1.3±0.2
February 1959	2.2±0.2	1.7±0.2
May 1959	1.6±0.2	1.3±0.2
July 1959	1.8±0.2	1.3±0.1
August 1959	1.5±0.3	1.2±0.2
April 1960	1.3±0.3	1.1±0.2
November 1960	2.1±0.3	1.6±0.3
July 1961	1.3±0.2	1.1±0.2
Average . . .	1.66±0.08	1.33±0.08

According to numerous results of land-based measurements, for primaries with energies approximately larger than 7 BeV, $\Delta D/D \approx A/\epsilon$, where ϵ is the total energy of the primary protons[42,44]. Using the presented data for the stratosphere, we can obtain information on the spectrum variation in the region of lower energies, too, to 2.5 BeV. The method of coupling coefficients, developed by L. I. Dorman[25], enables us to find the connection between the measured variations of the cosmic radiation in the stratosphere and the variations in the primary energy spectrum. The energy spectrum of the variations was obtained by using this method and data on the coupling coefficients for the maximum of the global intensity, given in [5]. For an energy spectrum ΔD/D in the form A/ϵ^{α}, the stratospheric experimental data yield $\alpha = 0.6 \pm 0.1$.

IV. SECULAR VARIATIONS OF COSMIC-RAY INTENSITY

It is well known that the intensity of cosmic rays is subject to secular variations connected with the 11-year cycle of solar activity[46]. The intensity of the cosmic rays decreases during the period of high solar activity and increases during the minimum. The amplitude of the variations of the muon component at sea level is approximately 5%, while that of the nucleon component is 20%. The variations of the nucleon component on earth are due to the modulation of the primary cosmic radiation at energies essentially above 5 BeV. The variations of the muon component are due to a primary component of much higher energies. The data on the variations of the intensity of primary radiation with particle energy smaller than 5 BeV can be obtained from measurements in the stratosphere. The high-latitude cosmic-ray intensity high in the stratosphere is approximately half as large during the period of the maximum of the solar activity as during the period of the minimum[34]. The results presented below are based on a large number of measurements. They have made it possible to obtain for the first time continuous data on the secular variation of the cosmic-ray intensity in the stratosphere, registered simultaneously for different latitudes. The results of more than 3000 measurements made with a single gas-discharge counter incorporated in the RK-1 radiosonde have been processed.

To increase the measurement accuracy and to exclude the possible errors in the determination of the altitude with the aid of the barograph, particle-number data for the maximum of the altitude curve were subsequently used. At 64°, 51°, and 41° latitudes these

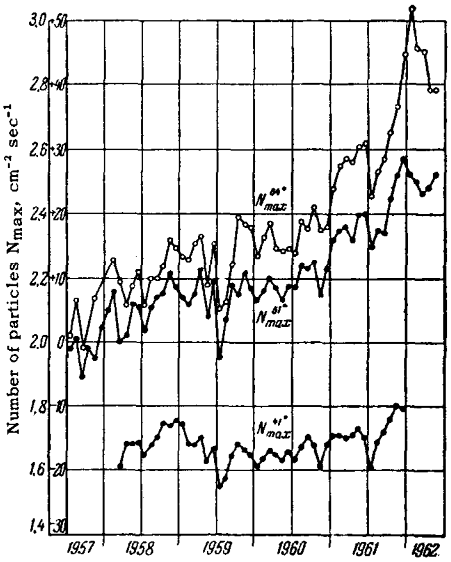

FIG. 11. Mean monthly values of the intensity of cosmic rays in the stratosphere during the time from July 1957 through July 1962.

maxima were located at depths near 50, 60, and 70 g/cm^2 of pressure, respectively.

The reduction did not cover results obtained during flares of cosmic-ray intensity in the stratosphere, nor results distorted by radiation from radioactive clouds produced by atomic explosions in the atmosphere. Figure 11 shows the average monthly maxima of cosmic-ray intensity at three latitudes. The ordinates represent the number of particles in sec^{-1} cm^{-2}, and the abscissas represent the time.

The points on Fig. 11 correspond to average values of the measurements made in more than 10 flights per month (1957–1958), and 15 flights and more monthly starting with 1959. Such a measurement frequency, with the observations at the maximum lasting approximately 8 minutes, results in a statistical measurement error of approximately 0.25%. The results of each measurement were corrected for the difference in the counter efficiency[33].

From Fig. 11 we see that there are many irregular fluctuations in the cosmic-ray intensity, and in most cases these are correlated at different latitudes. The correlation is particularly high for the latitudes 51° and 64°. At 41° the secular variation of the cosmic-ray intensity, with the exception of the results pertaining to the second half of 1958, correlates well with the data of land-based measurements with a neutron monitor (Deep River)[38]. Some fluctuations are due to magnetic storms and the accompanying Forbush decreases in the stratosphere. These are, for example, the data for September 1957, March–April and July 1958, May and July 1959, April and November 1960, July 1961, and others.

We see, however, an over-all increase in the intensity of the cosmic rays against the background of irregular fluctuations. The higher the latitude of the place of observation, the greater the increase in intensity. The intensity of the cosmic rays at the end of 1961 increased compared with 1957 by approximately 40% at 64°, and 25% at 51°.

For 41° latitudes this increase over 1958 was less than 10%. It follows therefore, that the increase in the intensity of cosmic rays in the stratosphere is due predominantly to primary particles with energies smaller than 4.6 BeV.

As can be seen from Fig. 11, the increase in the number of particles with time, at latitudes 51° and 64°, is not continuous. During the period from July 1957 for approximately two years, that is, to the end of 1960, it remained practically constant. However, in January–February 1961 a sharp increase occurred in the level of cosmic-ray intensity, while in November of the same year the level again increased abruptly. Thus, the secular changes in the intensity of the cosmic rays in the stratosphere have in the period under consideration a step-like and discontinuous character. We shall consider below how this correlates with the variations of the solar activity.

1. Secular Changes of the Particle-number Difference

Figure 12 shows the particle-number differences $\Delta N_m^{64-41°}$ and $\Delta N_m^{51-41°}$, obtained as a result of subtracting the number of particles for 41° latitudes from the numbers of particles for 64° and 51°. These differences are given for flights made at the same time at the corresponding latitudes (approximately 80% of the total number of flights). The secular variations for the difference in the number of particles are due to the secular variations of the intensity of the primary cosmic rays with particle energies from 0.1 to 4.6 and from 1.3 to 4.6 BeV. We note that approximately 70% of the number of the primary particles have energies less than 4.6 BeV.

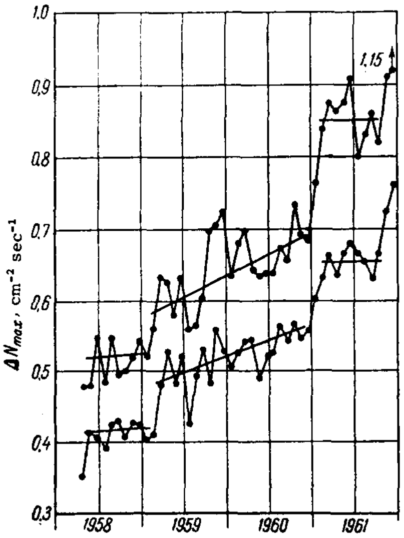

FIG. 12. Differences of mean monthly values of cosmic-ray intensity.

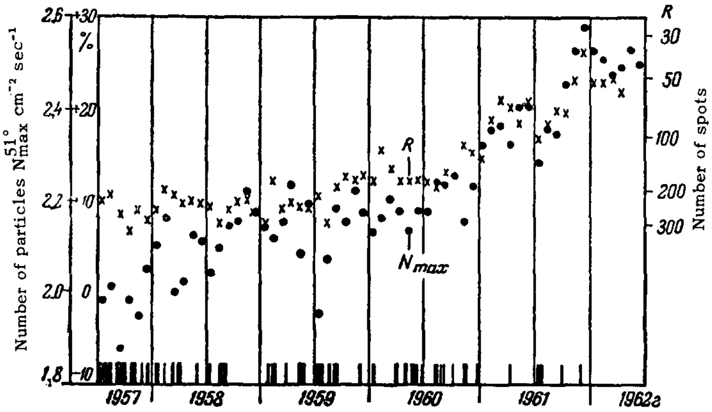

FIG. 13. ● – mean monthly values of intensity of cosmic rays at 51° latitude; × – mean monthly data on the number of sunspots; ▮ – Forbush decreases from neutron monitor data.

As can be seen from Fig. 12, a steplike secular variation is characteristic also of the particle-number difference.

From the data of Fig. 12 we find that $\Delta N_m^{51-41°}$ increased in December 1961, compared with 1958, by approximately 80%, while $\Delta N_m^{64-41°}$ increased by almost 100%. At the same time the increase in the total number of particles registered at 51° was merely 20% in the same interval. Naturally, the increase in the intensity of the primary component during the period in question was even larger.

2. Correlation with Solar Activity

Flares of solar cosmic rays and decreases in cosmic-ray intensity during the time of magnetic storms correlate with the chromospheric flares on the sun, while the secular variation correlates with the 11-year cycle of solar activity.

The ordinates of Fig. 13 represent the mean monthly values of the maximum number of particles at 51° latitude (full points, scale on the left) and the mean values of the number of sunspots R (crosses, scale on the right—logarithmic scale). The rectangles along the abscissa axis show the data on the Forbush decreases with amplitude more than 3% and lasting more than three days (neutron monitor in Deep River).

It is easy to note on Fig. 13 that there is a clearly pronounced correlation between the changes in the intensity of the cosmic rays and the change in the number of sunspots. With the exception of the period from July 1957 through the middle of 1958, which will be discussed later, the secular variation in the number of sunspots and in the intensity of the cosmic rays is practically the same. The steplike increase in the cosmic-ray intensity in 1961, referred to above, is also characteristic of the sunspot number. The steps in the secular variation of R occur at approximately the same time as for cosmic rays. We note also that the delay in the changes in the intensity of the cosmic rays relative to the changes in the number R is less than one month.

It is interesting to note that the intensity of the cosmic rays depends logarithmically on the number of sunspots, that is, the change in the number of sunspots R influences the intensity of the cosmic rays the more, the smaller R itself.

Let us stop to discuss the data pertaining to the period from July 1957 through the middle of 1958 (see Fig. 13). In this time interval the correlation between the number of sunspots and the intensity of the cosmic rays is lost. However, as can be seen from the data on the figure, this period is characterized by rather frequent Forbush decreases. In many cases several individual Forbush decreases are superimposed on one another. These frequent decreases are probably the main cause of the loss of correlation between the intensity of the cosmic rays and the number of sunspots, which can be clearly seen after the middle of 1958.

3. Character of Variation of the Energy Spectrum of Primary Particles with the Solar Activity Cycle

Information on this question can be obtained from the altitude dependence of the number of particles in the upper layer of the atmosphere. Since the main increase in the number of particles in the stratosphere occurs during the time of decrease of solar activity as a result of low-energy primary particles, it is advantageous to investigate the altitude dependences differentially, by excluding from the measurement data the number of particles which is due to the primary particles of high energy. Two series of altitude dependences, pertaining to different measurement periods, are shown in Fig. 14. These curves have been obtained by subtracting from the results of the measurements at 64° the data at 41° (curves 1–4) and the data at 51° (curves I–III). The ordinates represent the number of particles in cm^{-2} sec^{-1}. The abscissas represent the pressure in g/cm^2. The procedure for subtracting the data for 41° latitude from the measurement results at 64° makes it possible to obtain altitude curves which vary little at low pressures. In addition, it can be assumed that the procedure of subtraction will make it possible to decrease, and perhaps practically eliminate the contribution of the albedo particles in the case of the particle-number difference.

What is remarkable in the data of Fig. 14 is that

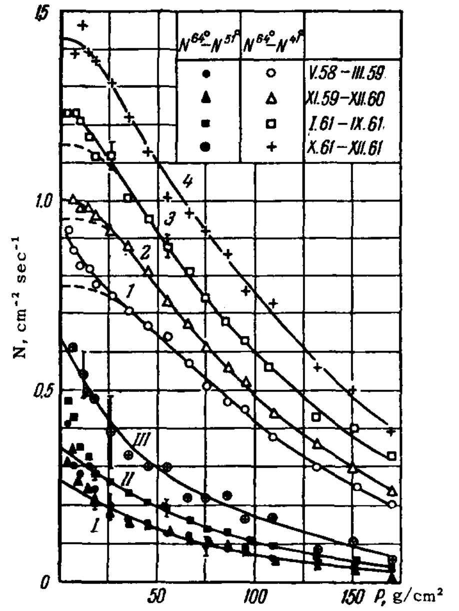

FIG. 14. Altitude variation of intensity of cosmic rays in the stratosphere. I, II, III – for the difference in the particle number Murmansk-Moscow; 1, 2, 3, 4 – for the difference in the particle numbers Murmansk-Simeiz.

with the total number of particles increasing on curves I—III by a factor 2.5 and on curves I—IV by a factor of 2, the altitude dependences in the entire range of the pressures under consideration remain so to speak parallel to each other (the higher points for the curves I—III at pressures less than 15—20 g/cm^2 are more readily due to particles from weak solar cosmic-ray flares). Thus, the altitude curves obtained favor the assumption that the energy spectrum of the primary cosmic rays which arrive additionally on earth during the minimum of solar activity does not differ strongly from the initial spectrum, and that the knee of the high-latitude cutoff does not shift appreciably in either direction with the solar-activity cycle.

To obtain data on the absolute intensity of the primary cosmic rays near the top of the atmosphere, the following processing procedure was used. Curves I—III of Fig. 14, drawn through the points, represent the exponentials e^{x/x_0}, where x is the pressure and $x_0 = 80$ g/cm^2. These curves intercept the ordinate axis at the values of the particle fluxes with energies from 0.1 to 1.5 BeV on the top of the atmosphere, without noticeable admixture of the cosmic-ray solar component. The intensities of this component correspond to the differences of the ordinates of the points and the curves I, II, and III in the region of pressure below 15—20 g/cm^2. The dashed sections of curves 1, 2, and 3 have been drawn after making corrections for the solar cosmic rays. These curves intercept the ordinate axis at the values of the intensities of the primary particles with energies from 0.1 to 4.6 BeV. Table V lists the corresponding data on the intensity of the primary radiation for four measurement periods. The errors in the data are mean-square relative to the measurements in the pressure region 5—15 g/cm^2. The total flux of the primary component with $E \geq 0.1$ BeV is obtained by adding the intensity obtained from curves 1—4 to the intensity corresponding to the primary energies $E > 4.6$ BeV as given in [47] ($N(E > 4.6) = 0.30$ cm^{-2} sec^{-1} (1955) and 10% lower for the 1958 period).

CONCLUSION

1. The main cosmic-ray intensity fluctuations in the stratosphere are due to processes occurring on the sun.

2. The appearance of cosmic-ray flares in the stratosphere is due to the generation of cosmic rays on the sun during the time of chromospheric flares. Cosmic-ray flares generated on the sun have an explosive character and cause the intensity of the primary cosmic rays in interplanetary space to increase by tens, hundreds, or even thousands of times. The flash durations, according to observations in the stratosphere, vary from several hours to several days.

3. A study of the cosmic-ray flares is also of practical significance for radiation safety of astronauts in outer space. The forecasting of cosmic-ray flares and prediction of their intensity and character of radiation propagation in interplanetary space is one of the practical problems of modern astronautics.

4. Cosmic-ray flares in the stratosphere correlate with many geophysical phenomena such as the absorp-

Table V. Intensity of primary cosmic radiation, cm^{-2} sec^{-1}*

ΔE_k, BeV / Measurement periods	$0.1<E_k<4.6$	$0.1<E_k<1.5$	$1.5<E_k<4.6$	$E_k>0.1$
1. (V 1958—III 1959)	0,77±0,03	0.26±0,03	0.51±0,04	1,04±0,03
2. (XI 1959—XII 1960)	0.95±0,02	0.26±0,02	0,69±0,03	1.21±0,02
3. (I 1961—IX 1961)	1,15±0,02	0.35±0,02	0,80±0,03	1,43±0,02
4. (X 1961—XII 1961)	1.43±0,04	0,63±0.06	0.80±0,07	1.73±0,04

*The data in this table are in good agreement with the results of measurements made on the Soviet automatic interplanetary stations "Mars-1" and "Luna-4" [48].

tion of galactic radio emission in the regions of the polar cap, geomagnetic storms, ionospheric disturbances and decreases in the intensity of galactic cosmic rays—Forbush decreases.

5. The energy spectra of the protons generated in the flares remain practically constant in time. These spectra are close to each other also in different flares, thus offering evidence that the energy spectra of the cosmic ray protons are produced on the sun in accordance with a universal law.

6. Measurements before and during geomagnetic storms point to the presence of two strongly differing forms of flare-proton energy spectra. In the first case the integral energy spectrum, depending on the kinetic energy of the protons, is approximated by a power-law dependence with exponent $\gamma \approx 2.0$, while in the second case $\gamma \approx 5.0$.

7. The energy spectrum with exponent $\gamma \approx 2.0$ is ascribed to the protons which propagate freely from the sun in interplanetary space. The energy spectrum with exponent $\gamma = 5.0$ is ascribed to protons which are localized and are transported in the corpuscular stream by the chromospheric flare that gives rise to the cosmic rays. The latter conclusion suggests the existence in the corpuscular stream of a chromospheric flare of unique magnetic traps of fast protons that are generated in the sun.

The time variations of the intensity of the flare protons, measured in the stratosphere, correlate well with the data of the theory of diffuse propagation of cosmic-ray protons from the sun in a medium with magnetic inhomogeneities. The mean free path of the protons with energy ~ 0.2 BeV prior to scattering by the magnetic inhomogeneities is approximately $\frac{1}{10}$ a.u.

An approximate relation is obtained between the proton diffusion coefficient D in the interplanetary medium and the proton momentum:

$$D = \frac{1}{3} v l_0 p^k,$$

where v is the velocity, p the proton momentum, and $k \approx 0.5$.

The total kinetic energy carried away by the stream of protons generated in a moderate flare is $\sim 10^{29}$ erg.

10. The cosmic-ray intensity amplitude is approximately twice as large in flares generated on the visible side of the solar disc as in flares from the opposite side. The interpretation of this phenomenon leads to the conclusion that solar radial magnetic fields exist in interplanetary space. The intensities of these fields are estimated at $\sim 10^{-6}$ G.

11. The 27-day variation of the cosmic-ray intensity in the stratosphere was investigated. This variation exists only during a definite period of time. The most clearly pronounced effect was observed in the period from July 1957 through February 1958. The amplitude of the 27-day variation was found to be 5 ± 0.6%. The waveform was close to sinusoidal. The most probable treatment of the phenomenon is connected with modulation by the corpuscular streams emerging from the long-lived active regions of the sun (lifetime seven revolutions of the sun).

12. Fluctuations of the intensity of the cosmic rays in the stratosphere were investigated during the time of magnetic storms and of Forbush decreases in the stratosphere. The average spectrum of the intensity variations of cosmic-rays with energies $\epsilon > 2.5$ BeV, during the time of the Forbush decrease, is approximated by a power-law dependence $\Delta D/D = A/\epsilon^{\alpha}$, where ϵ —total energy and $\alpha = 0.6 \pm 0.1$.

13. The increase in the intensity of the primary cosmic rays with decreasing solar activity has a step-like character and correlates well with the general activity of the sun (as measured by the number of sunspots). In the period of decreasing solar activity under consideration (from 1958 to the start of 1962), the intensity of the primary cosmic rays has increased by ~ 1.7 times. This increase is due to the primary component, essentially with energies smaller than 4 BeV (for protons).

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