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COSMIC RAYS FROM THE SUN

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A number of cosmic-ray flares were observed in the stratosphere at 64° geomagnetic latitude. The flares were due to 100-200 Mev protons, and were preceded by solar chromospheric flares which provided the source of the protons. It is suggested that the protons are carried by solar corpuscular beams with frozen-in magnetic fields.

LARGE increases in cosmic-ray intensity in the stratosphere were recorded at 64° geomagnetic latitude during July 9-21, 1959. These cosmic-ray flares were preceded by solar chromospheric flares with intensity 3^+ (on July 8, 10, 14, and 16, 1959), similarly to the events which had been observed previously, on July 8, 1958 and May 11-15, 1959.[1,2]

The measurments were carried out by means of cosmic-ray radiosondes[3] which rose to the stratosphere. The number of counts in a single Geiger-Müller counter and of double coincidences in a telescope incorporating a 7 mm aluminum absorber was recorded.

Twenty measurements were carried out during the above period, ten of which were made between July 9-14, and ten between July 15-21. Data of the single counter are shown in Fig. 1. The experimental points correspond to data averaged over 2-3 minutes of measurement.

It can be seen from Fig. 1b that, on July 15 and 17, an increase in cosmic-ray intensity was observed even at relatively great depths: on July 15 down to 160-170 g/cm^2, and on July 17 down to 300 g/cm^2. The number of particles increased very rapidly with decreasing pressure. At low pressures, the normal operation of the apparatus was disrupted because of the large counting rate ($> 4 \times 10^4$ min^{-1}). Fully reliable data could, however, be obtained as long as the counting rate was not greater than 1.5×10^4 min^{-1}.

Two measurments with a ~ 2.5 hr interval were carried out on July 11, and two measurements with a 4.5 hr interval were carried out on July 12. It can be seen from Fig. 1a that the results of two measurements on the same day are practically identical. It follows that the amplitude of the cosmic-ray flare remained constant for at least several hours, or changed only little, as happened, e.g., on July 15 and 17 (see Fig. 1b). Taking also into account that the measurements at high altitudes in the stratosphere lasted for about 30-40 min, one can assume that the results of the altitude-variation measurements were obtained for a practically constant flare amplitude. This makes it possible to obtain definite information concerning the nature and spectrum of the primary particles by studying the absorption curve of the additional cosmic rays in the stratosphere.

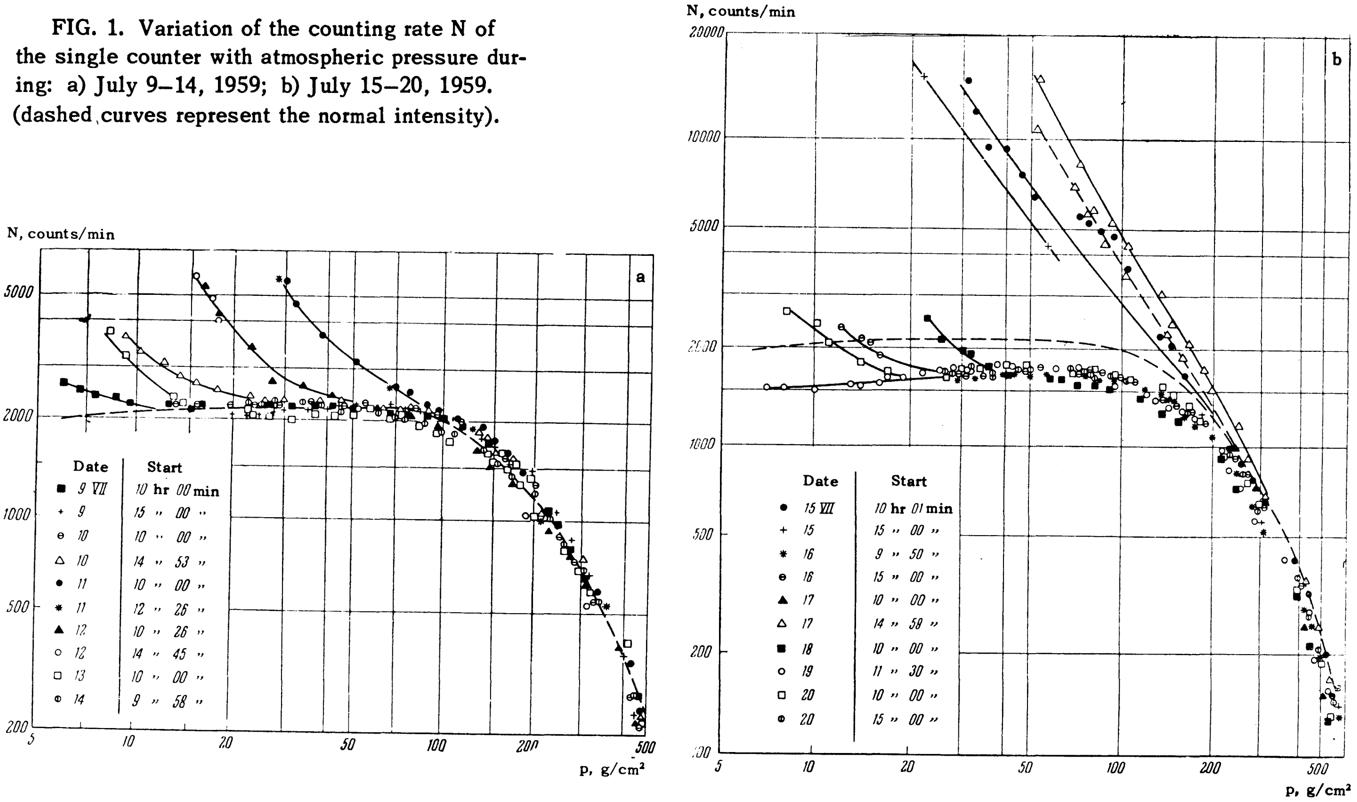
Let us compare the data given in Figs. 1a and 1b. It is clear that the results of the measurements for July 9, 10, and 11 at > 100 g/cm^2 pressure lie somewhat above, or at least are close to the normal intensity curve (dashed line), while the data obtained on July 12 and later lie below that curve. The latter fact is due to the effect of the decrease in main flux of the primary cosmic radiation during magnetic storms which occured after July 11.

No increase in cosmic-ray intensity was detected during simultaneous measurements in the stratosphere at geomagnetic latitudes of 51° and 41°, where the critical energies for the primary particles are considerably greater than at 64° latitude. On the contrary, a decrease in cosmic-ray intensity was observed at 51° and 41° latitude at the time of the increase in cosmic-ray intensity at 64° accompanied by magnetic storms.

According to the data of July 18, the intensity decrease at 51° latitude reached 26%. This was the greatest decrease observed in the course of our measurements during the IGY.

It should be noted that this maximum cosmic-ray intensity decrease corresponds with the maximum amplitude of the flare at 64°. For the flare of July 15, which had a smaller amplitude, the intensity decrease at 51° and 41° latitude was also somewhat smaller. The decrease in cosmic-ray

FIG. 1. Variation of the counting rate N of the single counter with atmospheric pressure during: a) July 9–14, 1959; b) July 15–20, 1959. (dashed curves represent the normal intensity).



intensity in the stratosphere at 51° and 41° latitude was more limited during the flare of July 8, 1958, whose amplitude was still smaller. The small flares at 64° latitude (July 26 and October 3, 1958 and July 9, 1959) were not accompanied by any noticeable decrease in cosmic-ray intensity at 51° and 41° latitude. It is not possible at present to establish an exact correspondence between the amplitudes of cosmic-ray flares in the stratosphere and the amplitudes of the intensity decreases observed at 51° and 41° latitude. It follows, however, from our data that the two phenomena are interrelated.

Data on the additional number of particles, i.e., the difference between the measured and normal cosmic-ray intensity, are given in Fig. 2. Data for July 8, 1958 and May 11, 1959, are also included in the figure. It can be seen that the measurements taken during the various flares, at different times and at different altitudes, fall rather regularly along straight lines with a practically identical slope. An exception, in this respect, is the data of July 15, when a deviation at pressures in the range 70 — 100 g/cm^2 was observed during a short period of measurements (~ 7 min); later, the experimental points fell again on the straight line. Hence, one can conclude that the nature of the primary flare particles is identical not only during the course of each flare, but also in all flares. Such a conclusion, which in itself is important, makes it also possible to compare rather accurately the amplitude of the primary cosmic-ray flares.

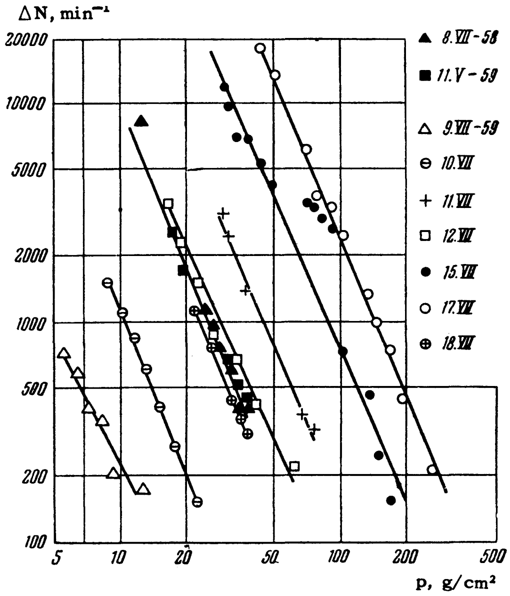


FIG. 2. Variation of the additional number of particles ΔN (single counter) with atmospheric pressure, according to the measurements of July 9–20, 1959.

During the measurements of May 12, 1959, when the telescope apparatus attained a great altitude (p = 6 g/cm^2), it was established that the number

Measurements during July 1959			Previous measurements		
Number	time	m	Date	time	m
9	8 hr 30 min	2.4	17.III—58	11 hr 18 min	35
10	13 » 30 »	7	8.VII	8 » 30 »	40
11	8 » 30 »	200	26.VIII	8 » 30 »	2.4
11	11 » 00 »	200	3.X	8 » 30 »	2.5
12	9 » 00 »	60	11.V — 59	8 » 30 »	40
12	13 » 15 »	60	11.V	11 » 30 »	40
13	8 » 30 »	6	12.V	8 » 30 »	40
15	8 » 30 »	800	12.V	13 » 30 »	35
15	13 » 30 »	350	13.V	8 » 30 »	3
16	13 » 30 »	7	14.V	13 » 30 »	5
17	8 » 30 »	2000	15.V	13 » 30 »	2.5
17	13 » 30 »	2800			
18	8 » 30 »	40			
20	8 » 30 »	24			

of particles in the flare was 40 times greater than normal. In estimating the amplitudes of other flares, we shall use this figure and also the corresponding data of the measurements of May 11 and 12 taken by means of the single counter. (The results of all these measurements are sufficiently close.) The values of m (the relative increase in the primary cosmic-ray flux as compared to the normal), according to the measurements of July 9 — 20, and also our unpublished earlier results, are presented in the table.

The results of the measurement of the number of double coincidences (above the normal rate) as a function of pressure are shown in Fig. 3. It can be seen that the slopes of the straight lines corresponding to the measurements of May 12, and July 12 and 15 are practically identical. The results of the measurements of July 11, 1959 are somewhat different: at small pressures, the slope is smaller; at higher pressures, however, the slope is identical with that obtained in other measurements. It is possible that this feature of the data of July 11 is not due to chance, since the measurements were taken in the absence of a magnetic storm and, consequently, of a Forbush decrease in cosmic-ray intensity on the earth. The other measurements were taken during magnetic storms.

Thus, the observed difference in the slope of the lines can be used as an indication that the spectrum of the primary protons varies, depending on whether the earth is immersed in solar corpuscular streams during the period of measurement. It is found, moreover, that the spectrum of primary protons is softer when this is the case. If similar results are obtained in the future, then this will constitute an additional confirmation of our earlier conclusion[2] that the source of the primary protons are the solar corpuscular streams themselves.

The proton nature of primary particles has already been discussed.[2] Assuming that the primary protons are isotropic at the top of the atmosphere (which follows from emulsion experiments[4]), and using the data of Fig. 3, it is possible to use the altitude dependence to find the energy spectrum of the primary protons, taking their ionization losses in the atmosphere into account. The integral proton spectra obtained in such a way are shown in Fig. 4. The slopes of the lines 1, 2, and 3 correspond to integral energy-spectrum exponents in the range 5.0 — 5.5. The slope of the upper part of the curve 4 corresponds to an exponent equal to 4.0.

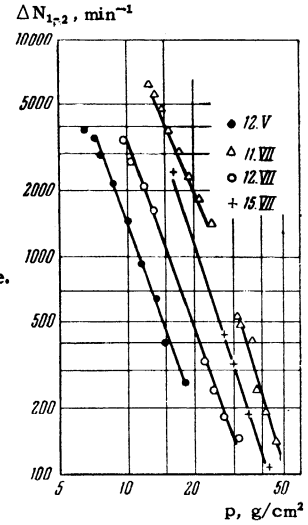


FIG. 3. Variation of the additional number of double coincidences with atmospheric pressure.

In the study of the flare of May 11 — 15, 1959,[2] the measurements of the telescope incorporating a 7 mm aluminum absorber and of the single counter were compared by a suitable recalculation. The comparison showed that the additional cosmic-ray intensity, according to the single-counter measurements, is roughly twice that calculated for a 25 g/cm^2 pressure. Consequently, in addition to the primary protons with range > 7 mm Al, particles with a shorter range are present in the stratosphere.

This result has also been confirmed by new measurements on July 9 — 21, 1959. It was found that the ratio of the rate measurements of the single counter and of the telescope increases with

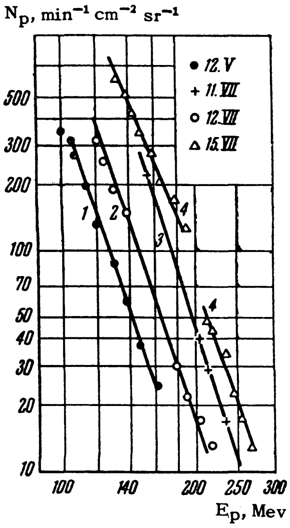


FIG. 4. Integral energy spectrum of primary protons.

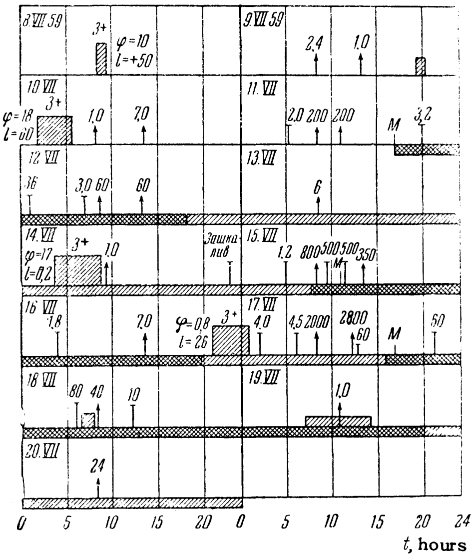


FIG. 5: Data on solar chromospheric flares, magnetic storms and cosmic rays (World Time). The arrows indicate the times of our measurements in the stratosphere, the signs ⊤ – those of Winckler.[5] The numbers above the signs give the ratio of the cosmic-ray intensity during the flare to the normal one.

the atmospheric depth of the observation level. Thus, e.g., the ratio of single-counter discharges to the number of double coincidences in the telescope, according to the measurements of July 15, equals 8 at a depth of 20 g/cm^2, and 30 at 60 g/cm^2.

The origin of the short-range particles (most probably electrons) which are detected by the single counter can be explained[2] by assuming that they are produced in the decay of evaporation neutrons from nuclear disintegrations produced by the primary protons. This hypothesis, however, has, so far, not been substantiated by calculation.

The Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation of the Academy of Sciences, U.S.S.R. has supplied us with the data on chromospheric solar flares and magnetic storms during July 1959. Data referring to the period of July 8 — 20 are shown in Fig. 5. The height of the upper rectangles corresponds to the intensity of chromospheric flares, and the length of the base to their duration (φ and l are the heliographic coordinates of the chromospheric flares). The base of the lower doubly-shaded rectangles corresponds to the duration of magnetic storms and the Forbush decrease in cosmic-ray intensity. Single shading corresponds to the continuation of the Forbush decrease. The letter M indicates the onset of the Forbush decrease.

Disregarding the weak cosmic-ray flare on July 9, let us consider the data recorded after the large chromospheric flare of July 10. It can be seen from Fig. 5 that no increase in cosmic-ray intensity was detected in the measurement carried out on that day approximately 4 hr after the chromospheric flare. An intensity increase of m = 7.0 was found in the second measurement. It is now difficult to decide whether this increase was connected with the large chromospheric flare of July 10, or with the weak flare of July 9. (We believe the first case to be more probable.) One can maintain that the cosmic-ray flare recorded on July 11, 12, and 13 is connected with the large chromospheric flare of July 10, and that the cosmic-ray flare was delayed by more than 4 hr with respect to the chromospheric flare.

A great increase in cosmic-ray intensity on July 11 (m = 200) was recorded before the onset of the magnetic storm and the Forbush decrease which started at about 17:00 on July 11.

Winckler,[5] using an ionization chamber and a scintillation counter, also observed a great increase in cosmic-ray intensity in the stratosphere in Minneapolis (55°N) (see Fig. 5). For a correct comparison of our results with those of Winckler, it is necessary to remember that the critical energies for primary protons in Minneapolis and in Murmansk are 300 and 100 — 120 Mev respectively. In addition, the comparison should be made for a period during which the earth's magnetic field was not perturbed. Thus, the data for July 11 seem most suitable for a comparison.

It can be seen from Fig. 5 that, on that day, we have m = 200 for our two measurements, while, according to the data of Winckler, m = 2, i.e., a difference of about 200 in the additional flux is observed. One can easily see that the difference can be explained on the basis of the energy spectrum of primary protons with power exponent 5.0 and the values of the critical energy at the two latitudes. A comparison of our and Winckler's data obtained during magnetic storms will be less definite, since the additional flux of primary protons recorded in Minneapolis will vary very strongly with the perturbation of the earth's magnetic field because of the very steep spectrum of primary protons. This is the reason why the time variations of the flare amplitude, obtained at that latitude, do not, to a sufficient extent, reflect the true character of the time variations of the flare.

A strong chromospheric sun flare was again detected on July 14. Stratospheric measurements were carried out by us on that day towards the end of the flare. It was found that $m = 1$, which is natural if one takes the long delay of cosmic rays into account. However, the measurements on July 15 revealed a great increase in cosmic-ray intensity ($m = 800$); moreover, the amplitude of the flare decreased faster than in the previous case.

Another strong solar chromospheric flare was recorded on July 16. It was followed by a very strong ($m = 2800$) cosmic-ray flare. On July 18, the intensity decreased to $m = 40$. It can be seen from Fig. 5 that periods of magnetic storms with a sudden onset and Forbush decreases in the cosmic-ray intensity occured after the three large solar chromospheric flares which produced cosmic-ray flares in the stratosphere.

Thus, during the period of July 8 — 20, four chromospheric flares, each of several hours duration, caused cosmic-ray flares which continued, to various degrees, for 12 — 13 days.

The time variation of the cosmic-ray flare amplitudes is shown in Fig. 6. The time corresponding to the center of the chromospheric flare has been taken as zero-point reference. Curve 1 refers to the flare of July 10. For comparison, data for May 11 — 15, 1959 (curve 3) are also given, in addition to measurements at sea level of the cosmic-ray flare on February 23, 1956 (curve 2). It can be seen that considerable differences exist in the time variations for the stratospheric flares and the one detected at sea level.

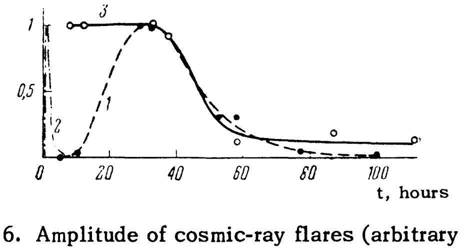


FIG. 6. Amplitude of cosmic-ray flares (arbitrary units) as a function of time. 1, 3 – stratospheric measurements, 2 – measurements at sea level on February 23, 1956.

The following conclusions may be drawn:

1. Great increases in cosmic-ray intensity (flares) observed in the stratosphere at northern latitudes are due to primary protons of solar origin. The energies of these protons, which follow from the measurements at 64° geomagnetic latitude, are greater than 100 — 120 Mev, and the differential energy-spectrum exponent equals 6.0. The energy spectrum of the primary protons differs little for the various flares.
2. All the five large cosmic-ray flares observed were preceded by solar chromospheric flares of maximum intensity (3^+).
3. Cosmic rays are delayed with respect to the chromospheric flares by more than 4 — 5 hours, but apparently less than 10 — 15 hours. Such long delays are not compatible with the velocities of primary protons.
4. The detected cosmic-ray flares are correlated with magnetic storms having a sudden onset, and with Forbush decreases of cosmic-ray intensity on the earth.
5. Magnetic storms have little influence on the primary-proton intensity in flares. A direct correlation has been established between the amplitudes of cosmic-ray intensity increases in the stratosphere at northern latitudes (64°) and the amplitudes of cosmic-ray intensity decreases in the stratosphere in more southern latitudes (51° and 41°).
6. The observed cosmic-ray flares have a duration of the order of days.

In order of explain satisfactorily all available data, it is necessary to assume that the solar corpuscular streams with frozen-in magnetic fields are themselves the source of the primary protons. The frozen-in magnetic fields constitute traps which can contain protons with the energies under consideration, produced or accelerated during solar chromospheric flares. Because of the fact that the protons in this energy range leave the corpuscular streams before these reach the zone of action of the earth's magnetic field, it is necessary to make the additional assumption about the existence of a magnetic medium in the interplanetary space.

In conclusion, the authors express their gratitude to Corresponding Member of the U.S.S.R. Academy of Sciences S. N. Vernov for his comments and his interest in the present article.

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[3] Vernov, Tulinov, and Charakhch'yan, Dokl. Akad. Nauk SSSR **122**, 788 (1958), Soviet Phys.-Doklady **3**, 980 (1959).

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52