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LARGE COSMIC-RAY INTENSITY FLUCTUATIONS IN THE STRATOSPHERE

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The energy spectrum of an abnormally large proton flux, more than 20 times normal, was derived from stratospheric measurements. The exponent of the differential spectrum is equal to 6.0 in the 120 — 170 Mev energy range. It is suggested that these protons are due to corpuscular beams with frozen-in magnetic fields, emitted during the solar chromospheric flare on May 10, 1959.

On May 11, 1959, large fluctuations in the cosmic-ray intensity were registered in the atmosphere, and continued, to a varying extent, until May 15, 1959. On May 12, the cosmic-ray intensity at 64° geomagnetic latitude and at high altitudes was approximately 20 times normal.

The measurements were carried out using a radio probe raised to the atmosphere by balloons.[1] The number of discharges in a single counter, and the number of double coincidences in a telescope consisting of two Geiger-Müller counters, were measured.

EFFECTS OBSERVED AT 64° LATITUDE

The evaluation of the measurements at the Loparskaya station on the morning of May 11 (operation of the apparatus was started at 10:10 a.m.) has shown that the cosmic-ray intensity at high altitudes is much greater than the normal one. The results of the measurements are shown in Fig. 1.

On the same day, at 1:00 p.m., a second balloon was sent up and measured mainly double coincidences. During short time intervals, information on the number of particles detected by single counters was also obtained. Data up to the atmospheric pressure $p = 40$ g/cm^2 were obtained, and these confirmed the results obtained in the morning.

Two measurements were also carried out on May 12. The first (instrument started at 10:05 a.m.) was done by means of one counter, and the second (instrument started at 3:00 p.m.) by means of a telescope and a single counter. The measured number of discharges in the single counter are shown in the same Fig. 1. As can be seen from the figure, at low pressures ($p < 50$ g/cm^2), the cosmic-ray intensity remained roughly the same on May 12 as on May 11. However, at higher pressures, the number of detected particles was less than normal.

The decrease in cosmic-ray intensity, also observed at sea level, was related to the strong magnetic storm which began on May 11 at about 11:00 p.m. World Time.

The results of the measurements on May 13 (start 10:00 a.m.) are also shown in Fig. 1. At the time of these measurements, the cosmic-ray intensity was considerably less than on May 11, as a result of which an excessive number of particles was observed only at sufficiently high altitudes. An increase in the number of particles at high altitudes in the stratosphere was also detected on May 14 (start at 3:00 p.m.) and on May 15 (start at 3:02 p.m.). On May 16 and 17 the intensity at high altitudes in the stratosphere was already back to normal.

Thus, the increase in cosmic-ray intensity at high altitudes at 64° latitude detected on May 11 continued, to a greater or lesser extent, for about five days.

RESULTS OF THE MEASUREMENTS AT 51° AND 41° LATITUDE

Simultaneously with the measurements at 64° latitude, measurements were also carried out at latitudes of 51 and 41°, where no increase in the cosmic-ray intensity was observed. It follows from this that the additional primary particles at 64° latitude could not have been photons. On May 12, the number of particles was 12% less than normal at 51° latitude and 8% less than normal at 41° latitude (in the maxima of the intensity curves). The intensity decrease at these latitudes on the

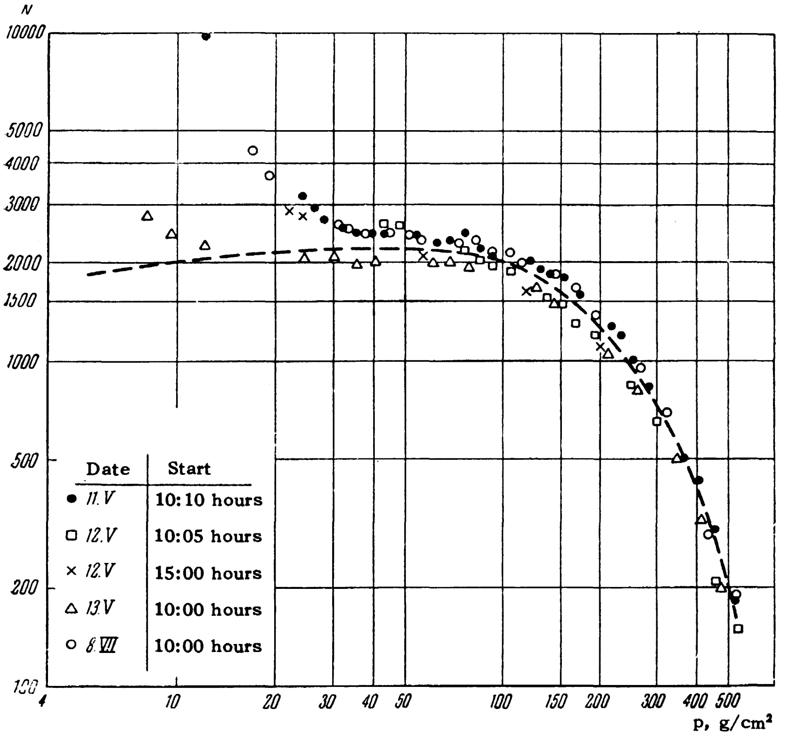

FIG. 1. Variation of the number of pulses per minute N with the atmospheric pressure from data obtained on May 11–13, 1959, and on July 8, 1958 (Moscow time). The dashed line represents a normal intensity, according to the data of May 4, 5, and 7, 1959.

following days was also roughly within the same limits.

NATURE AND SPECTRUM OF PRIMARY PARTICLES

It can be seen from Fig. 1 that an increase in cosmic-ray intensity occurred on May 11 at pressures $p = 100 - 200$ g/cm^2. The same result was obtained during the fluctuations observed on July 8, 1958.[2] Therefore, the results obtained at 100 — 200 g/cm^2 cannot be considered accidental.

As can be seen from the results of the measurements on May 11 (Fig. 1) a very sharp rise in the number of particles occurred in the range of low pressures, while the increase was considerably smaller in the range of high pressures. It seems, therefore, that the spectrum of primary particles consists of two different branches, corresponding respectively to low-energy particles absorbed in 10 — 20 g/cm^2 of matter and to particles of relatively high energies, with a range of 100 — 200 g/cm^2. Moreover, it has to be kept in mind that the particle-absorption curve in the atmosphere is related to altitude effects, and not to time variations.

It follows from Fig. 1 that the fluctuations observed on July 8, 1958 and on May 11, 1959 are practically identical. Such a coincidence of the data obtained for two fluctuations which have occurred at different times is astonishing. Similar results can be obtained only if the spectrum of the primary particles remains stable for at least several hours, preferably for ten hours. It can therefore be assumed that the observed variations in the number of particles are related not to time fluctuations but to the altitude effect.

The analysis of the absorption curve at high altitudes obtained from the measurements of the single counter (May 11) shows that the intensities obtained can be explained to the same extent either by assuming a proton nature for the primary particles with energies from 100 to 300 Mev, or by assuming that the detected particles are bremsstrahlung photons produced by electrons in the range 100 — 200 kev. However, the data obtained from the measurements using a telescope with a 7 mm aluminum absorber cannot be attributed to γ rays produced by electrons in the above-mentioned energy range.

The spectrum of the primary particles is best studied from the measurements made on May 12 by means of the telescope. On that day, the radiosonde reached an altitude of 35 km. Low-pressure data and the corresponding differences between the measured and normal intensities, are shown in Fig. 2. (The numbers to the left and to the right of the y axis represent the number of particles per minute and the ratio of the additional intensity to the normal one, respectively.) It can be seen from the figure that the number of particles increases sharply with the altitude. In the range of 15 — 7 g/cm^2, the number of particles increases by a factor of almost 8. At pressures less than 7

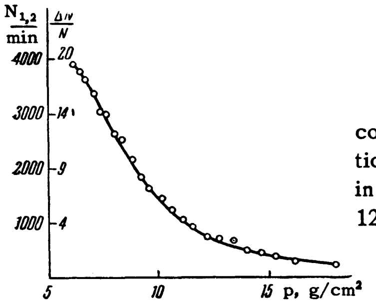

FIG. 2. Number of double coincidences $N_{1,2}$ as a function of the pressure according to data obtained on May 12, 1959.

g/cm², the curve becomes somewhat less steep.

If we assume that the detected particles are protons, and that the main energy loss is due to ionization, we can find the energy of these particles from the absorption curve in Fig. 2. The differential energy spectrum obtained is shown in Fig. 3.

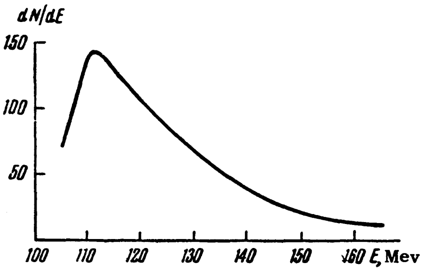

FIG. 3. Differential energy spectrum of protons

In the 120 — 170 Mev range the curve can be approximated by a power function with an exponent equal to 6.0. The spectrum has a maximum at an energy corresponding to the critical energy of primary protons at this latitude (100 — 120 Mev).

Before the present article had been prepared for publication, P. T. Kellog and later J. R. Winckler were kind enough to inform us that on May 12 they detected, by means of emulsions, in the latitude of Minneapolis, a large number of protons with energies in the 110 — 220 Mev range. The proton energy spectrum in the 110 — 220 Mev energy range observed by them had an exponent $\gamma = 4.8$.

Anderson,[3] by means of an ionization chamber and a telescope consisting of Geiger-Müller counters recorded, on August 22, 1958 and at an altitude corresponding to a pressure of 10 g/cm², a ten-fold increase in the cosmic-ray intensity. This, as shown by his analysis, was due to protons having energies of about 170 Mev.

The question whether a cut-off exists in the primary proton spectrum is of great interest. For such a steep spectrum, assuming that it continues in the same manner in the low-energy range, the flux of primary protons at extreme northern latitudes will be exceptionally great. However, data pointing to a cut-off in the proton spectrum can most probably be obtained from measurements carried out by means of artificial satellites during chromospheric flares.

On May 12, measurements with a single counter were carried out at high latitudes, practically simultaneously with the telescope readings. The total intensity of the protons at pressures of 22 and 24 g/cm² was calculated, using the spectrum of primary protons obtained. The cosmic-ray intensity observed by the single-counter measurements at these latitudes was found to be twice the intensity obtained by the above calculation. Consequently, in addition to protons detected by the telescope, particles with a range less than 7 mm Al (absorber in the telescope) are present in the stratosphere.

The origin of these short-range particles, which are most probably electrons, can be explained in the following manner. The primary protons produce, with a certain probability, stars in the upper layers of the atmosphere, and thus produce evaporation neutrons. The absorption mean free path of these neutrons is considerably greater than the range of primary protons, and thus the neutrons reach greater depths. The evaporation neutrons produce hard γ rays in inelastic collisions with the nuclei of the atmospheric atoms. The energy of these γ rays is, however, not high enough to produce electrons that can be detected efficiently with a telescope containing a 7 mm Al absorber.[4] Preliminary estimates show that the above-mentioned difference between the cosmic-ray intensity measured on May 12 with a single counter and the expected intensity under the assumption that the additional particles are protons can only be due to effects produced by evaporation neutrons. From this point of view, it is natural to assume that this increase in the number of particles detected on July 8, 1958 and on May 11, 1959 by means of single counters at 100 — 200 g/cm² is primarily due to the short-range electrons. In such a case, the assumption that the primary proton spectrum has a "kink" is no longer necessary.

DISCUSSION OF RESULTS

It should be noted that the increase in cosmic-ray intensity studied by us had a very long duration, and that its amplitude was practically constant for many hours. These features did not characterize the cosmic-ray fluctuations previously observed on earth, e.g., on February 23, 1956.

The fluctuations in cosmic-ray intensity observed on May 11 — 15 were evidently due to a large chromospheric flare which occurred on May 10, 1959. The Research Institute for Terrestrial Magnetism, Ionosphere, and Radio-Wave Propagation of the U.S.S.R. Academy of Sciences has supplied us with information obtained on chromospheric flares and magnetic storms during May 1959. Some data referring to the observations during the period from May 10 to May 15, 1959 are shown in Fig. 4. The height and base of the top rectangles represent the intensity and duration of the chromospheric flare, respectively. The top rectangles (double shading) refer to the region of heliographic coordinates $\varphi = +15°$ and $l = -50°$; the unshaded rectangles refer to other heliographic coordinates. The lower rectangles (single shading) refer to magnetic storms. The arrows indicate the time of the measurement when an increase in cosmic-ray intensity was observed in the stratosphere at 64° latitude.

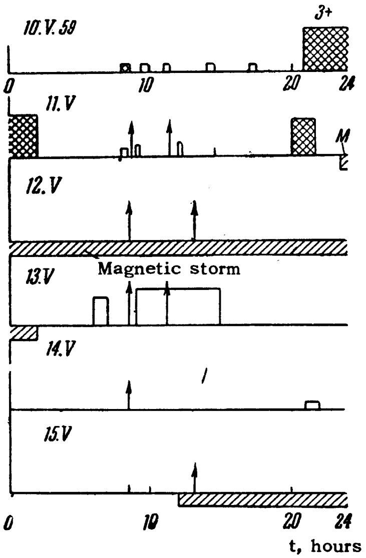

FIG. 4

As can be seen from Fig. 4, the first data about the increased cosmic-ray intensity were obtained 11 hours after the beginning of the chromospheric flare on the sun on May 10. For the given case, it is impossible to draw any conclusions about the decay of the arrival of cosmic rays relative to the chromospheric flare on the sun. Better data on this subject are available for the flare of July 8, 1958. The increase in cosmic-ray intensity detected on July 8, 1958 was preceded by a chromospheric flare on the sun on July 7, 1958 of intensity 3^+ and duration from 0:58 a.m. to 4:14 a.m. World Time.[5] However, measurements carried out on July 7, 1958 at high altitudes in the stratosphere at 8:30 a.m. World Time did not show an increase in cosmic-ray intensity. Consequently, the delay in the arrival of cosmic rays relative to the chromospheric flare was greater than 4 hours.

Winckler et al.[6] report an event in which an increased intensity of cosmic rays in the stratosphere at 55° latitude was observed on March 26, 1958, about three days after a chromospheric flare on the sun. The authors interpret this fact as showing that particles accelerated during the chromospheric flare are kept either in the solar corona or in the gas clouds ejected from the sun.

It can be seen from Fig. 4 that a very strong magnetic storm has set in about 27 hours after the chromospheric flare (intensity 3^+, heliographic coordinates $\varphi = +15°$ and $l = -50°$) which began on May 10. The letter M in the plot for May 11 shows the beginning of the decrease in cosmic-ray intensity on the earth. As has been explained, the cosmic-ray intensity decreased during the first measurements in the stratosphere on May 12 at altitudes corresponding to pressures > 100 g/cm^2 (while, at the same time, the cosmic-ray intensity remained anomalously high at relatively low pressures), which is in agreement with the observations on the earth.

The decrease in cosmic-ray intensity during very strong magnetic storms can be explained satisfactorily by the influence on the cosmic rays of the frozen-in magnetic fields carried by solar corpuscular streams.[7,8] While the earth is submerged in the corpuscular stream, the frozen-in magnetic fields scatter cosmic particles, which leads to the observed decrease in cosmic-ray intensity.

As can be seen from Fig. 4, two measurements were carried out at high altitudes before the onset of the magnetic storm on May 11, and two measurements were made on May 12 during the magnetic storm. In spite of this, data on the cosmic-ray intensity at high altitudes are practically identical for May 11 and May 12. It seems as if the magnetic storms led to a decrease in the intensity of high-energy cosmic rays, but had no effect on those primary protons having considerably lower energies. In order to resolve the contradiction between these two facts, it is necessary to assume that the solar corpuscular streams carrying the frozen-in magnetic field are themselves sources of fast protons. Due to magnetic fields in the solar corpuscular streams, fast protons are trapped in them, and then fall upon the earth both during and before the time when the earth is submerged in the corpuscular stream. This assumption is strengthened by the great intensity of cosmic-ray flares and their delay relative to the chromospheric flare.

It seems that the study of cosmic-ray flares in the stratosphere offers new experimental possibilities for the study of electromagnetic properties of solar corpuscular streams.

In conclusion, the authors express their thanks to I. K. Marshanov and to Yu. N. Komarov for carrying out the measurements.

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