magnetic traps in which protons with energies of ~2.0 Bev can be trapped.

References

1) A. N. Charakhchyan, The I. G. Y. Proceedings. (In press).
2) A. N. Charakhchyan, V. F. Tulinov, T. N. Charakhchyan (in press).
3) P. L. Marsden, J. B. Crowden, C. J. Hatton, Preprint, December 1960.
4) M. Kadama, Preprint, 1960.

Discussion for Papers II-3B-26 and II-3B-27 is Combined and given after the Paper II-3B-27.

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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part II

II-3B-27. The Energy Spectrum and Time Dependence of the Intensity of Solar Cosmic Ray Protons in Flares

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Introduction

It was established that cosmic ray intensity increases observed in the stratosphere at northern latitudes are due to primary protons generated during large solar flares. For instance, in July 1959 three major class 3+ solar flares occurred following each other in 1-2 days. Considerable cosmic ray intensity enhancements were recorded in July in the stratosphere with the same succession[1),2)].

In the bulk of cases cosmic-ray flares are observed in several hours after a solar flare[1)]. Approximately in a day after solar flares a period usually begins of magnetic storms, ionospheric disturbances and, in a number of cases, aurorae. By the start of a magnetic storm or somewhat later a decrease is observed of the intensity of high energy cosmic rays recorded by ground instrumentation. (This phenomenon is usually called a Forbush-decrease). But there are also cases when cosmic ray bursts in the stratosphere are recorded which are not accompanied by geophysical phenomena. Usually in these cases solar flares occur on the edge of solar disk and corpuscular streams from them miss the Earth. The investigation of cosmic ray bursts for such cases is naturally of interest.

During investigations of cosmic ray increases in the stratosphere the following was revealed: the greater the amplitude of cosmic ray intensity bursts caused by solar protons, the greater the magnitude of a Forbush-decrease[1)]. This was indicative of the existence of a correlation between these heterogeneous phenomena. At the same time it was also established that magnetic storms with sudden commencements accompanied by a Forbush-decrease were not effective as far as the proton intensity decrease in bursts is concerned, as follows from measurements near sea level where the bulk of cosmic ray intensity in due to primary high energy particles arriving from the galaxy[3)]. To explain this fact a supposition was made that protons recorded during a Forbush-decrease do not come from the outside of corpuscular streams, but are carried by solar corpuscular streams themselves. Another step in the elucidation of the properties of solar corpuscular streams was the study of the proton energy spectrum in flares before and during a Forbush-decrease.

If one proceeds from the supposition that during a Forbush-decrease solar protons impinge on the Earth from the outside of corpuscular streams, a more gently sloping spectrum should be expected at this time than before a Forbush-decrease. In fact we have an opposite picture: a steep spectrum during a Forbush-decrease and a gently sloping one before it.

The indication of the existence of such an effect was for the first time obtained by us in July 1959[1]. Below are given new results of investigations of solar proton energy spectra and dependence of proton total intensities in bursts on time.

The Primary Proton Range Spectrum

In Figs. 1 and 2 results of measurements

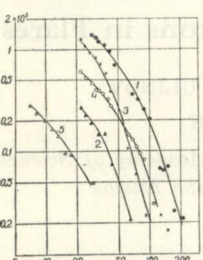

Fig. 1. The number of double coincidences N_{12} as a function of pressure P.

	Data	Starting Time
1.	3. IX. 1960	$7^h00'$
2.	4. IX.	$11^h56'$
3.	4. V. 1960.	$9^h58'$
4.	4. V.	$15^h00'$
5.	5. V.	$10^h02'$

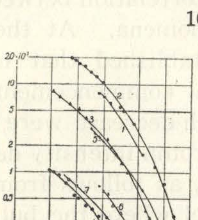

Fig. 2. Dependencies of N (the number of discharges in the single counter) on pressure P.

	Data	The Time of Start
1.	3. IX. 1960.	$7^h00'$
2.	3. IX. 1960.	$11^h45'$
3.	4. IX.	$6^h45'$
4.	5. IX.	$6^h53'$
5.	4. V. 1960.	$15^h00'$
6.	5. V.	$1^h00'$
7.	5. V.	$7^h00'$

are given obtained by means of the telescope and the single counter[4] from bursts on May 4 and September 3, 1960. The number of double coincidences (N_{12}) and the number of discharges in the counter per minute are given along the ordinate (minus the normal background of cosmic radiation at the corresponding height). Atmospheric pressure P in g/cm^2 is given along the abscissa. Dots in Fig. 1 and 2 correspond to results of measurements during 3 minutes. As is evident from the figures, the slopes of absorption curves obtained in different stages of the burst little differ from each other. The slope of curve 3 in Fig. 1 is steeper which is connected with time dependence for the beginning of the burst (see below). However, for the portions of curves in the range of large paths a tendency is observed to an increase of their slopes with time. Fig. 3 shows proton integral energy spectra obtained in different outbursts from measupements with the telescope. The number of protons in min^{-1} cm^{-2} sterad^{-1} is given along the ordinate, the kinetic energy of proton is given along the abscissa. In transition from the path to energy ionization energy losses and proton absorption in nuclear collisions in the air were taken into account. Spectra in Fig.

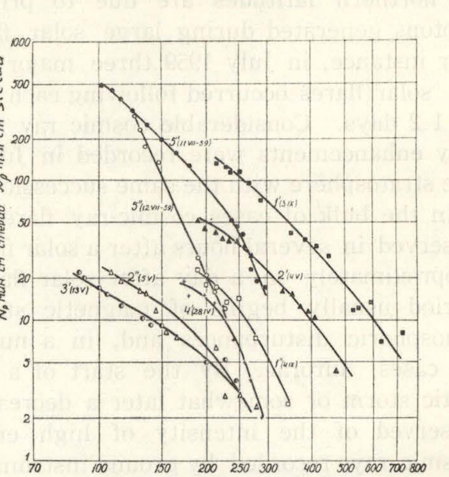

Fig. 3. Proton integral spectra obtained from measurements:
On September 3 and 4, 1960, 1′ and 1″;
On May 4 and 5-2′ and 2″.
On May 13-3′;
On April 28-4′.
On July 11 and 12, 1959-5′ and 5″.

3 (with the exception of spectrum 5) were obtained in measurements when a Forbush-decrease was not observed. Averaged spectra obtained from these data are shown with curves 1, 2 and 3 in Fig. 4 curve 1 is given when only ionization losses of protons are taken into account. Curve 2 is obtained from curve 1 with due consideration of proton absorption in nuclear collisions. Proton nuclear absorption coefficients depending on proton energies are obtained from data[5),6),7)]. According to these investigations proton nuclear absorption coefficients in the air (recalculated from the data in the photographic emulsion and Cu) are equal to 300 g/cm^2 for protons 350-400 Mev[5),6)] and to 170 g/cm^2 for protons 660 Mev[7)]. Curve 3 is obtained from curve 2 with the approximated due consideration of the time of the proton diffusion in space depending on the velocity of protons. After introduction of these corrections, spectrum 3 in the interval 100-400 Mev has exponent γ close to 2.0 spectrum 4 obtained during a Forbush-decrease has exponent $\gamma \simeq 5.0$.

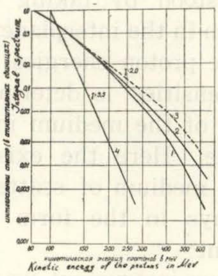

Fig. 4. Proton integral energy spectra.

1. an averaged spectrum obtained from results of measurements with the absence of magnetic storms and Forbush-decreases.
2. The same as 1, when not only ionization losses, but also proton absorption in nuclear collisions in the air are taken into account.
3. obtained from 2, the time of the proton diffusion in space is approximately taken into account depending on the velocity of protons.
4. An averaged spectrum from results of measurements during magnetic storms and a Forbush-decrease.

Intensities Obtained from Measurements With the Telescope and the Single Counter

Data of the measured number of double coincidences N_{12} were transformed according to Gross into a proton global stream for different heights. N_{12} values and the number of discharges in the single counter were taken in experiments conducted during the same flight of the instrument. It turned out that with the absence of a Forbush-decrease intensities measured by the single counter coincided with results obtained with the telescope. But during periods of a Forbush-decrease intensities obtained by means of the single counter exceeded those expected on the basis of the transformation. This is illust-

Table I.

Date of Measurements.	Time of Measurements.	Pressure P g/cm^2	The measured number of particles min^{-1} (N^1) by the single counter	The expected number of particles min^{-1} (N) according to the transformation	$\frac{N^1}{N''}$	Data Obtained.
4. V. 60	$17^h03'$	18	2,600	2,900	0.9	In the absence of a magnetic storm and a Forbush-decrease
	16 28	53	680	580	1.2	
3. IX. 60	8 32	20	7,500	8,000	0.94	
	8 04	57	1,600	1,600	1.0	〃 〃
12. V. 59	13 23	23	900	320	2.8	During+a magnetic storm and Forbush decrease.
12. VII. 59	13 42	17	2,950	1,440	2.0	
	13 11	52	82	48	1.7	
15. VII. 59	13 20	21	13,200	2,200	6	
	13 01	57	2,180	60	36	〃 〃

rated by Table I where P is the value of the pressure at which data are obtained N_1 is the measured number of discharges in the single counter, N'' is the number of protons according to transformation. In the sixth column the ratio of the measured number of the calculation to the expected one according to the transformation is given. In the seventh column data on magnetic storms and Forbush-decreases are presented. The appearance in the stratosphere of an additional short-path radiation is possibly connected with the electrons of the Earth's outer radiation belt[8] which is disturbed by the arrival of solar corpuscular streams.

$N_p(t)$—Intensities of Primary Protons as a Function of Time

The $N_p(t)$ values obtained from measurements on 4–5 May and 3–5 September, 1960. are presented in Fig. 5. The $N_p(t)$ value in relative unities is given along the ordinate, time in hours is given along the abscissa. The beginning of corresponding solar flares is taken for the starting point $t=0$. Curve 3 shows the same dependence $N_p(t)$ for the burst on February 23,1956, for Chicago[9]. Intensity maxima of bursts are matched with each other. The errors of the dots indicated in Fig. 5 are connected with the extrapolation of the results of measurements to the top of the atmosphere. Apparently for the bulk of the dots these errors constitute about 20–30%.

As evident from Fig. 5, curves have portions of approximately equal intensities, the duration of which was 3–5 hours for the event on May 4 and 10–20 hours for the event on September 3.

The longer duration of the event in September is explained mainly by longer gently sloping portion of curve 2. But $N_p(t)$ decrease rates on sloping portions are close to each other (in Fig. 5 $\Delta t_1 = \Delta t_2$). The latter can be understood by taking resort to the proton diffusion in the interplanetary medium. With the same proton energies the decrease of proton intensities is determined only by the properties of the medium in which protons propagate. Here the existence in the interplanetary medium of scattering centres for cosmic rays in the form of magnetic clouds is meant[9),10)].

On May 4 our instrument was at an altitude of 15 km when the maximum of cosmic ray intensity enhancement was recorded with neutron monitors: 10+2% in Prague[11] and 8% in Leeds[12].

Data referring to the development of the burst in the stratosphere are obtained from altitude dependence N_{12} shown by curve 3 in Fig. 1. A sharp increase in N_{12} with a decrease of pressure was observed when the instrument was at an altitude where pressure $P<90\ \mathrm{g/cm^2}$. The arrival of low energy primary proton into the stratosphere should be

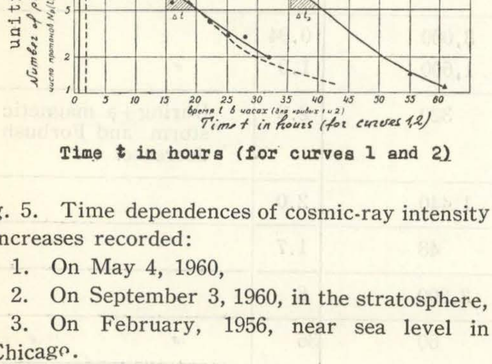

Fig. 5. Time dependences of cosmic-ray intensity increases recorded:
1. On May 4, 1960,
2. On September 3, 1960, in the stratosphere,
3. On February, 1956, near sea level in Chicago.

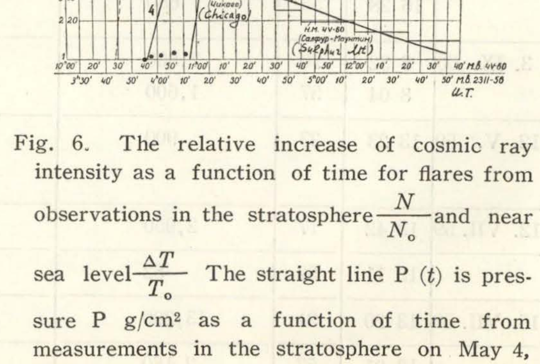

Fig. 6. The relative increase of cosmic ray intensity as a function of time for flares from observations in the stratosphere $\frac{N}{N_0}$ and near sea level $\frac{\Delta T}{T_0}$ The straight line P (t) is pressure P g/cm² as a function of time from measurements in the stratosphere on May 4, 1960.

referred to this period. As far as data for $P > 90\ \mathrm{g/cm^2}$ are concerned, there is no sharp altitude dependence for them. We believe that in moments for $P > 90/\mathrm{g\ cm^2}$ in the stratosphere low energy protons were absent. For $P < 90\ \mathrm{g/cm^2}$ measured values of N_{12} were transformed for primary intensity of protons with energies above 100 Mev. These results are presented in Fig. 6. For $P > 90\ \mathrm{g/cm^2}$ data of N_{12} in Fig. 6 are given without transformation into primary intensity (blackened circles). In Fig. 6 data are given obtained in Sulphur-Mountain on May 4, 1960, as well as data on February 23, 1956, in Leeds and Chicago. We see that on May 4, 1960, and on February 23, 1956, cosmic rays lag approximately by 15 minutes behind the start of a solar flare. Maxima in cosmic ray intensities are reached in 8-10 minutes. As compared with the arrival of high energy protons, low energy protons lag behind by 25-30 minutes. This time is not great, if one should take into account that the bulk of protons have velocities $\beta = 0.5$ in the stratosphere and $\beta \simeq 1.0$ on the Earth. Therefore it is possible that low and high energy proton generations on the Sun on May 4, 1960, took place simultaneously.

Disscusion of Results on Time Dependence $N_p(t)$

On the basis of the results of measurements in connection with the burst on February 23, 1956, many authors have revealed that the intensity of cosmic rays from the Sun beyond the maximum of the curve in a large time interval is described by the function $A/t^{3/2}$ and the distribution of primary protons in space at this time is isotropic. These two facts can be explained if one proceeds from the assumption that the decrease of the intensity of primary protons recorded near the Earth, takes place due to their diffusion in interplanetary space. From this point of view let us try to describe experimental data in the stratosphere for low energy protons.

The solution of the diffusion differential equation for homogeneous space with spherical symmetry $\partial N_p/\partial t = D\nabla^2 N_p$ with the initial injection of particles in point $r=0$ with $t=t_0$ and with the total number of particles B has the following form:

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

where $N_p(R, t-t_0)$ in our case is the intensity of protons depending on time near the Earth, R is the Sun Earth distance, t is observational time, t_0 is the initial time of the event, D is the diffusion coefficient, $D = lv/3$, l is the proton free path length before scattering, v is the velocity of protons.

The scattering of protons by magnetic clouds at distances l would be effective, if $H > P/300\,l$ where H is the intensity of magnetic clouds, P is the impulse of protons. The supposition made about the homogeneity of magnetic cloud distribution about the Sun does not follow from any experimental results. On the contrary, some of the experimental results cannot be explained with this supposition. However, for revealing the basic features of the phenomenon such simplification seems to be justified.

The behaviour of $N_p(t-t_0)$ in (1) for $t-t_0 \ll R^2/4D$ is in the main determined by the exponential function $\exp[R^2/4D(t-t_0)]$.

Knowledge of the exact value of t_0 is very important in this case. $N_p(t-t_0)$ has maximum with $t-t_0 = R^2/6D$. If $t-t_0 \gg R^2/4D$, then we have:

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

Constant B is determined from $N_p(t)$ maximum in the experiment. $B = 2.5.10^{32}$ protons for the event on May 4, 1960. The energy carried away with protons will amount to 6.10^{28} ergs.

In Fig. 7 graphs are given obtained according to formula (1) for values t_0 and $D = 5.5\times10^{21}\ \mathrm{cm^2/sec}$. Dots and squares in Fig. 7 correspond to results of measurements on May 4 and September 3, respectively. For May 4 time is measured from the beginning of the solar flare. For data on September 3 the time in 20 hours after beginning of the solar flare is taken as the origin. This is connected with the fact that longer duration of the burst on September 3 compared to the burst on May 4 can be explained by the great duration of the proton outflow directly from the source (see Fig. 5). In order to have approximately equately initial conditions for diffusion for events on May 4 and September 3 it is certainly necessary to exclude this time. Thus, knowing the value of D, we can find the proton free path length $l_1=1.1\times10^{12}$ cm ($V_1=1.5\times10.^{10}$ cm/sec).

If $H_1>P_1/300\,l_1$ and $P_1=5.10^8\,eV/c$ then, we obtain the lower value for the magnetic field intensity as $H_1<1.5\times10^{-6}$ gauss.

Using formula (2) and data of the experiment on sloping portions of curves 1 and 3 in Fig. 5 we find that the diffusion coefficient D_2 for protons with high energies (3-4 Bev) is approximately by four times greater as compared to D_1. Then we find the free path length of high energy protons $l_2=2.2\times$ 10 cm. Correspondingly, $H_2>P_2/300\,l_2=7.6\times10^{-6}$ gauss ($P_2=5.10^9 eV/c$) Data on l_1 and l_2 and hence the values of H_1 and H_2 lead to the situation when in rough approximation the density of magnetic clouds in space can be assumed to be inversely proportional to the intensity of magnetic fields in clouds.

For $t<1$ calculated data in Fig. 7 agree better with data of the experiment with $t_0=0.3$. But the meaning of this agreement is not clear. The cosmic ray intensity increase in Sulphur Mountain is recorded in 15 minutes after a solar flare. Taking into account the time of proton propagation in free space to the Earth, we obtain an interval 0-7 minutes or about 0.1 hour during which proton outflow could start from the source on the Sun. But for $t_0=0.1$ two first experimental dots in Fig. 7 fall out from the calculated curve. Does this mean that slow proton generation takes place later ($t_0=0.3$) or this is a result of ignoring heterogeneity of magnetic cloud distribution in space (the density of magnetic clouds near the Sun is a little bit higher than near the Earth)? It is difficult to answer with certainty. Let us note that the discrepancy between the beginning of a cosmic-ray flare near the Earth and the expected beginning of the proton ejection on the Sun, is also characteristic of protons with high energies according to data on the event on February 23, 1956. It seems reasonable that such discrepancy of data for $t<1$ is a result of the fact that the great density of magnetic fields near the Sun is not taken into account.

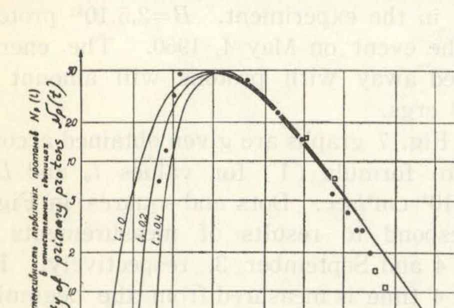

Fig. 7. Graphs according to formula (1) for $D=5.5.\ 10^{21}$ cm²/sec. $t_0=0;\ 0.2;\ 0.4$
● ● experimental data for the burst on May 4.
□ □ experimental data for the burst on September 3.

For great values of t, dots in Fig. 7 lie lower than the straight line. This result can also be interpreted as a consequence of a decrease in magnetic cloud density at great distances beyond the Earth's orbit.

On the Energy Spectrum of Protons With High Energies in the Flare

It is clear that low energy protons recorded in the stratosphere and high energy protons responsible for the increase of cosmic ray intensity near sea level on May 4, 1960, were generated during the same solar flare. But the question is not clear whether there was the common generation and the common energy spectrum of protons with high and low energies. Let us consider the data obtained on the proton spectrum.

Assume that a 10% enhancement of cosmic ray intensity (in maximum) recorded in Prague on May 4 by a neutron monitor can be explained by the action of primary protons with energies above 3 Bev. Such an enhancement corresponds to 0.5 primary protons cm^{-2} min^{-1} sterad^{-1}. The intensity of primary protons with energies, for instance, 400 Mev in maximum according to data in the stratosphere amounted to 30 protons cm^{-2} min^{-1} sterad^{-1}. From these values we find exponent γ of the proton spectrum equal to 2.0 to energy 3.0 Bev. Data on the burst on February 23, 1956 give approximately the same results[13]. Such a low value for γ seems to be of low probability since the primary proton energy spectrum from measurements near sea level usually has exponent $\gamma=5.0$.

The low value of γ obtained by us is may be a result of incorrect supposition about the common spectrum of high and low energy protons generated on the Sun. The independence of the mechanisms of generation of low and high energy protons is, for instance, confirmed by the flare on September 3 in the stratosphere whose primary proton spectrum practically coincided with the outburst on May 4, but whose amplitude was approximately by two times greater, but no increase of cosmic ray intensity near sea level was detected.

Results

1. Solar proton energy spectra in bursts in April 28, May 4, May 13 and September 3, 1960, are measured. It is determined that these spectra for different flares are similar to each other and do not undergo considerable changes during the whole period of the existence of an outburst (2-3 days). The integral energy spectrum of protons depending on the kinetic energy E can be described by the power law with exponent $\gamma=2.0$ for E from 100 to 400 Mev.

2. The effect of the softening of the solar proton energy spectrum in bursts during a Forbush-decrease is revealed. The softening of the spectrum of protons of solar origin and at the same time the hardening of the spectrum of cosmic rays of galactic origin during a Forbush-decrease show that solar corpuscular streams which carry magnetic fields frozen inside them are also carrierd of protons of cosmic rays generated on the Sun. To explain this phenomenon it is necessary to suppose the existence of magnetic traps in solar corpuscular streams.

3. During a Forbush-decrease besides protons other particles intrude into the stratosphere whose paths are lower than 7 mm Al. The origin of these short-path particles appearing in the stratosphere only during a Forbush-decrease is not clear.

4. Time dependencies of the intensity of primary protons during outbursts in the stratosphere are in fair agreement with calculations based on the proton diffusion theory in the interplanetary medium with scattering centres in the form of magnetic clouds which are responsible for the scattering of protons with energies of 0.2 Bev in interplanetary space.

References

1) A. N. Charakhchyan, V. F. Tulinov, T. N. Charakhchyan, J. Exp. Theor. Phys. (U.S.S.R.) **39** (1960) 249.
2) J. R. Winckler, P. D. Bhavsar, L. Peterson, Preprint, October 1960.
3) A. N. Charakhchyan, V. F. Tulinov, T. N. Charakhchyan, J. Exp. Theor. Phys. **38** (1960) 1031.
4) A. N. Charakhchyan. The I. G. Y. Proc. (in press).
5) G. Birnardiny E. T. Booth C. J. Lindenbaum, Phys. Rev. **85** (1952) 826.
6) A. M. Perry Phys. Rev. **85** (1952) 497.
7) M. G. Meshcheryakov, S. B. Nurushev, J. D. Stoletov, J. E. T. P. **31** (1956) 361.
8) S. N. Vernov, A. E. Chudakov, Proc. of the Inter. Cosmic Ray Conf., **111** p. 17.
9) P. Meyer, E. N. Parker, J. A. Simpson, Phys-Rev. **104** (1956) 768.
10) L. I. Dorman, Cosmic Ray Variations, The State Publishing House for Techn. Literature, Moscow, 1957.
11) J. Hlady, J. Klaczen, L. Krivsky, P. Mocry, Nuovo Cimento, 17. N 4, 1960.
12) M. Kodama, Preprint, 1960.
13) A. N. Charakhchyan, V. F. Tulinov, T. N Charakhchyan, the I. G. Y. Proc. (in press).

Discussion (for Papers II-3B-26 and II-3B-27)

Meyer, P.: The September. 3 flare particles were observed on September. 8 after the Forbush decrease of September. 4. A detailed measurement of the proton spectrum between 75 and 350 mev shows a power low exponent of 2.2 (differential energy spectrum) which agrees with the expopent observed in the early stages of particles arrival by the NASA group.

Ney, E.P.: I would like to point out that Charakhchyan's results on the slope of the energy spectrum are in qualitative agreement with the results we reported in to 6 and quiet spectra with exponents of 3. Charakhchyan finds exponents of 5.5 and 2 respectively.

Ogilvie, K.W.: I should like to make a few comments.

1. In connection with the suggestion by Prof. Singer that the secondaries, very low energy particles observed in the rocket shots

(a) Those showing in the first shot could not have arrived from the flare.

(b) Those showing in the second shot have only 1.1/2 times the direct transit time in which to travel to the earth.

(c) The intensity at 10 Mev was still rising after the third shot.

These fact seem to show that these low energy particles are a seperate component. Low energy particles are present at the time of all the rocket shots.

I should also like to give a few results on the November 15 event allow us to examine the fall off of intensity with time. This appears to be approximately as $1/t^3$, indicating easy passage from the sun. This and the fact that the intensity above 2 Mev goes up by at least a factor of 2 when the earth enters the trapping region generally support the propagation model discussed.

Ehment, A.: The change of slope of the spectrum of low energy solar protons by a magnetic storm is just the same as the change of the slope of high energy spectrum as deduced from the different records for the 12 November solar radiation. Higher magnetic fields within a cloud guiding solar particles seem to favour the arrival of low energy particles.