DEVELOPMENT OF THE PROTON FLARE AND THE ASSOCIATED HARD X-RAY EMISSION OF NOVEMBER 5, 1970

F. FÁRNÍK, P. KOTRČ, L. KŘIVSKÝ, and B. VALNÍČEK

Astronomical Institute of the Czechoslovak Academy of Sciences
Ondřejov Observatory, Czechoslovakia

Abstract: The positions of the two basic flare ribbons in the H-alpha line were determined and their velocity development was measured. This development was compared with the X-ray emission, measured on the Intercosmos 4 satellite. From elaborated experimental data it was deduced that the flare develops in three phases: In the first and the shortest, both the ribbons are receding from each other with a velocity of about 32 km/sec; in this phase the hard X-ray emission quickly increases until it reaches its maximum. The second phase lasts longer and the mutual velocity of the ribbons is about 14 km/sec; hard X-ray flux begins to decrease. Finally, in the third phase the velocity is about 5 km/sec. Similar phases are also found in the ribbon-width development. The beginning of the first splitting phase was estimated to lie between 03 17 and 03 18 UT (Y-phase). The time development of the X-ray emission and its spectrum shape is amply discussed.

1. Present Results of Investigating the Proton Flare of Nov. 5,1970

A proton flare, connected with an emission of cosmic rays, was generated in a complex of several spot groups on Nov. 5, 1970; the commencement of the flare, importance 3B, was at 03 07 UT, maximum brightness in H-alpha was recorded at 03 29, and the end at 07 20, the mean position being 13°S, 35°E. The development of this flare in H-alpha was also published in the IASY Report on Solar Phenomena 1970 — Tokyo (Moriyama, 1972).

The flare underwent a development typical for similar flares: at the beginning of the rapid development, the Y-phase occurred (the separation of two ribbons), a perfect formation of the flare "channel" with a transverse arc structure in the emission and in the H-alpha absorption was already observed (Křivský, 1963, 1969, 1970). The main release of energy and the acceleration of the very fast particles occurred, according to present investigations, at the time of the Y-phase, i. e. between 03 17 and 03 22 UT (Křivský and Švestka, 1966; Mathews and Lanzerotti, 1973; Ilenčík and Křivský, 1973).

The investigated flare was a source of subcosmic radiation, which was measured directly as a sharp increase by the Venus 7 probe, and the flare was also the source of emissions of plasma clouds, shock waves and magnetic discontinuities, which generated a number of disturbances and effects at the Earth (Forbush's decrease at Deep River with a drop of 6%, and a magnetic storm with an SC at 00 46 UT, Nov. 7, 1970); a comprehensive analysis was presented by Vernov et al. (1972). The beginning of the increase in cosmic radiation was recorded by the Venus 7 probe at 04 43 ± 02 on Nov. 5, 1970, and the commencement of PCA effect was recorded at Kiruna (Sweden) at 04 45 UT (Westerlund, 1973).

The analysis of the X-emissions, observed by the Intercosmos 4 satellite in connection with the flare, and the deliberations on the characteristics of the accelerated electrons are contained in the paper of Livshits et al. (1972).

It was found that during a more expressive flare there exists an impulsive, as well as a slow component of the X-radiation ($h\nu \gtrless 10$—20 keV) (Kane and Anderson, 1970). The impulsive emission precedes the brightness maximum in H-alpha. If the process, associated with the generation of a beam of directional electrons with energies of several tens of keV, develops at the beginning of the flare development, mostly bremsstrahlung emissions occur when the electrons interact with the plasma ions; this emission will be partly polarized (Korchak, 1967; Mandelshtam, 1972). This was observed with several flares already, including the investigated proton flare Nov. 5, 1970. With this flare it was found that at the time of the initial X-emission impulse in the hard intervals (around 03 20 UT) the polarization was the highest ($P=0.26$) and that it then gradually decreased; the plane of polarization was stable at first and only displayed deviations in the latter phase of the flare after 03 34 UT. The polarization maximum indicates that the directional accelerated beams of electrons last several minutes. Part of the accelerated electrons would simultaneously generate a microwave radio emission which is observed at the same time. The process of impulsive nature lasts 10—10^2 sec.

The second X-emission maximum and subsequently the decaying of the emission in the range of several tens of keV is associated with the development of a thermalizational electron process (10 sec) and with the cooling of the heated plasma (3×10 min; Mandelshtam, 1972).

It cannot be excluded that the occurrence of the impulsive periodical emission in the 90—200 MHz range in the intervals 03 37—03 39 and 03 44—03 47 UT (McLean et al., 1971; Palmer, 1972; Kai and Takayanagi, 1973) has a physical relation to the synchronous occurrence of the fluctuations of the plane of polarization: according to Rosenberg (1970) and McLean et al. (1971) this emission may be generated by synchroton electron mechanisms in the coronal magnetic tube, where modulations are generated due to constantly excited magnetohydrodynamic waves which propagate from bottom to top, thus deforming, narrowing and transversely oscillating the tube. The particles, in particular the electrons, captured in the tube, would be accelerated periodically in the region of deformations (instabilities). However, it cannot be excluded that this complex of both phenomena is connected with the disintegration of parts of the magnetic structures in the region of the flare and above it, because the following relations are remarkable: (a) the occurrence of two series of radio pulsations after the maximum of the X-emission (0.8 Å) of the flare; (b) the occurrence of radio pulsations at the time when the angle of polarization (the angle between the polarization plane and the first photon counter) displayed extraordinarily large values with considerable fluctuations after an interval of small variations and small angles. If this connection is not exceptional (if it is observed with other proton flares as well), it would have an extraordinary significance. This polarization event could be explained by the occurrence in the region of the flare at this time of successive ejections of electrons in different directions due to the perturbation (or decay) of a certain magnetic configuration and to a plasma state, originating after the main initial instability, which could generate quasi-regular radio pulsations at the corona level.

Kai and Takaynagi (1973) presented another possible interpretation of the origin of the pulsating emission on the basis of positional and polarization measurements of the radio emission (including the pulsations), relevant to the flare of Nov. 5, 1970: the source of the continuous emission in the bottom levels is obscured by an absorption arc structure of a weak magnetic field, which periodically modulates the radio emission, radiated by the absorption, on being perturbed by very fast electrons, ejected from below.

The flare of Nov. 5, 1970 has already been investigated from a number of aspects; the present paper concentrates on investigating the development and dynamics of the flare itself in association with the variations of the X-emission in the 40—60 and 60—100 keV ranges.

2. Development of the Flare and Its Location in the Active Region

The Flare and the Active Region

The investigated flare was generated in a complex of three spot groups (J, B, C) with relatively small spots; the groups were generated roughly above one another in latitude (Solnechnye Dannye 11, 1970. Suppl. on magn. fields). It is interesting that on Nov. 5, 1970, when the flare was generated, the individual spot groups did not approach one another (as is usual), but it can be seen that this complex of spot groups constituted necessary condition (cf. Fig. 2). Figure 2 represents the situation of the photosphere and of the magnetic fields, adopted from the publication mentioned and from photographs of the Ussuriysk Observatory (U.S.S.R.). The intensities of the magnetic fields of the spots reached their highest values during this revolution on Nov. 5, 1970, however, they did not exceed 2,500 Gauss. The maximum values of the S and N polarities were balanced again on this day (Křivský and Růžičková-Topolová, 1969). The flare during its initial development has been included into part of Figure 2a, and both the observed splittings of the filaments (Y-phase) can be seen. Figure 2b shows the flare at a later stage of development, when the flare "channel" had already developed perfectly. It is interesting that the development of these flares is always the same, inspite of the spot configuration of the complex being different during the occurrence of proton and cosmic flares: the splitting of the two ribbons, the formation of a transverse loop structure between the two fundamental ribbons, the so-called flare channel (Křivský, 1963, 1968).

It is probable that the conditioning factor for the generation of proton flares is the magnetic configuration and the interaction of a number of antagonistic systems of magnetic fields in a relatively small and narrow space within the large interaction of several spot groups (Křivský and Obridko, 1969).

Method of Computing the Distances of Points on a Filtrogram

The proton flare of Nov. 5, 1970, with a view to the types of motions which occurred in it, can be classified as a so-called expanding flare (Švestka, 1962).

Although the two-hour development of the flare in H-alpha is only demonstrated by five photographs in this paper (Fig. 1), they clearly show that the ribbon structure of the flare formation was preserved over the whole interval of its existence. With a view to the relatively good consistence of the individual flare ribbons, it was possible to observe and measure the positions of the individual selected parts of the flare. Special stress was put on determining the velocities with which the ribbons separated in the flare channel at the time after the splitting (Y-phase) at points Y_1 and Y_3 (Fig. 2).

To facilitate the orientation in the flare formation we adopted the following annotations (Fig. 3): the first, less mobile ribbon of the splitting Y_1 is marked A, the second (drifting) is marked B. Ribbon B divided into two parts at point Y_2, which were marked in a similar way: the quasi-fixed B_A and the drifting B_B. At three points of channel Y_1 and two points of channel Y_2 sections 1, 2, 3, 4 and 5 were selected, situated perpendicular to the axis of the appropriate channel of the flare. In each section a sequence of four points a, b, c and d, representing the intersections of the section with the ribbons of the flare formation, was selected in

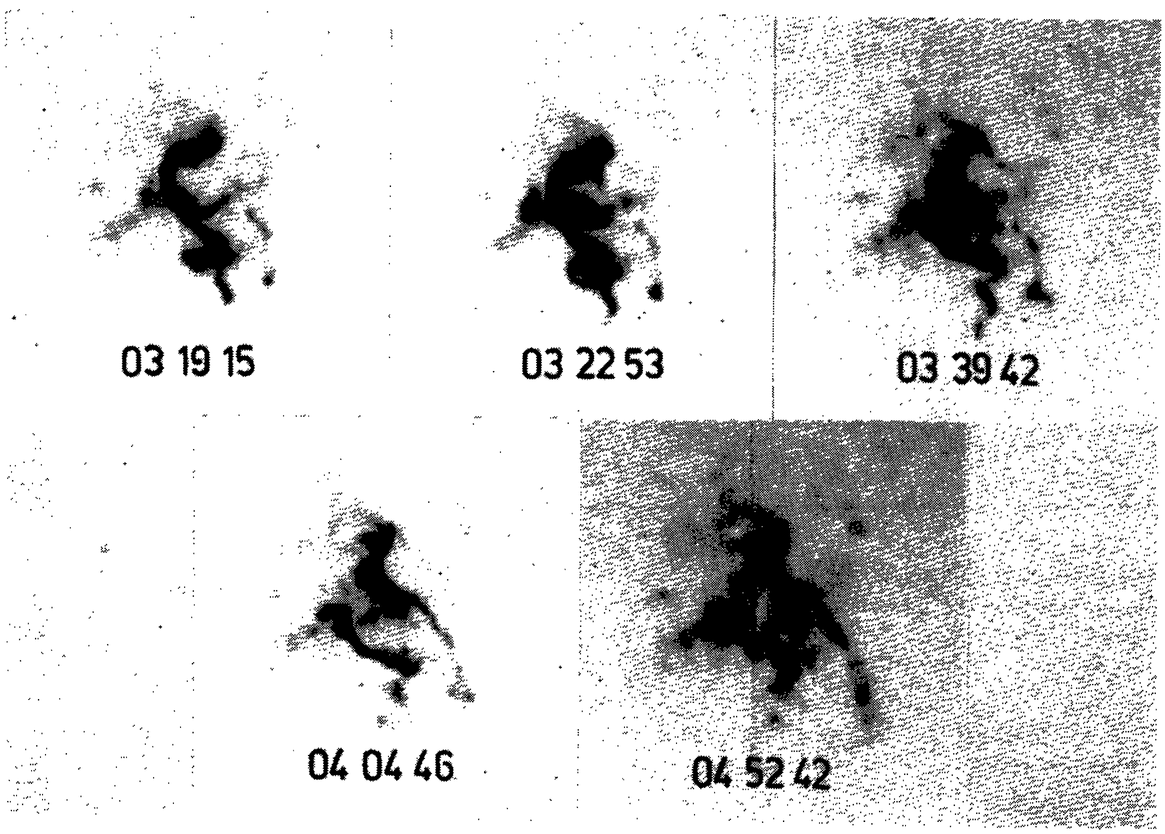

Fig. 1. A selection of 5 photographs, characterizing the development of the flare of Nov. 5, 1970 in H-alpha from Carnarvon Station. The flare is negative.

the direction from the quasi-fixed ribbon to the drifting ribbon. The line segment $\overline{ab}$ then represented the projection of the width of the quasi-

The flare occurred in a region located 35°E from the CM and 13°S from the solar equator. The heliographic latitude of the centre of the solar disk

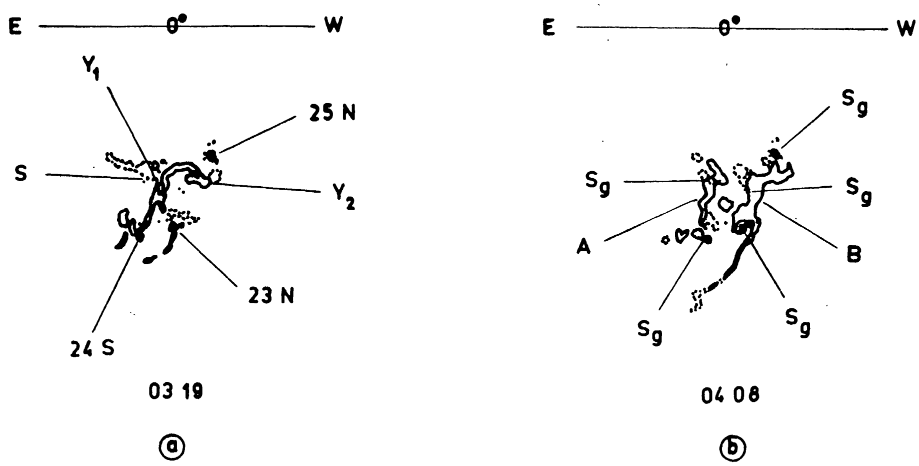

Fig. 2. The proton flare of Nov. 5, 1970 at the time of the flash phase (a) and at the time of the late phase (b). The situation of the photosphere and magnetic intensity of the spots was adopted from Solnechnye Dannye, *11*, 1970 (Suppl. on magn. fields) and from the Ussuriysk Observatory. The flare with the brighter field in H-alpha was drawn just after the Y-phase (03 19 UT) and at the time of the full development of the flare "channel" (04 08 UT), when transverse couplings betwen ribbons A and B in the emission could be observed in the centre of the channel. Figure 2a gives the intensities and polarities of the magnetic fields of the spots and the positions of the splittings, i.e. the Y-phase (Y_1 is the main splitting, Y_2 the subsidiary splitting). In Figure 2b the main ribbons A and B are marked as well as the position of the spot groups (S_g).

fixed ribbon, and the line segment $\overline{cd}$ the projection of the width of the drifting ribbon of the appropriate section. The distance between the centres of

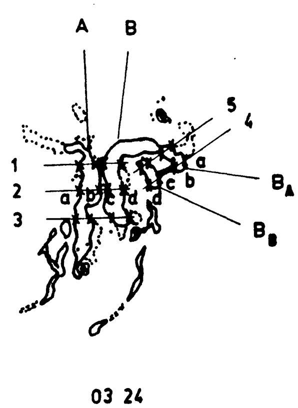

Fig. 3. In the situation of the proton flare at 03 24 UT on Nov. 5, 1970 three sections (1, 2, 3) are marked, in which the width of the main channel of the flare and the widths of ribbons A and B were measured, as well as the subsidiary splitting of ribbon B into B_A and B_B in sections 4 and 5. The measured positions in each section are marked in sequence a, b, c and d. The flare is limited by the full line, the field by the dashed line and also the spots are shown.

the line segments $\overline{ab}$ and $\overline{cd}$ determined the projection of the width of the flare channel in the individual sections.

on Nov. 5, 1970 was +4°. Thus, the flare was located at a distance of 39° from the centre of the solar disk to the south-east. The investigation of the formation in the plane of the filtrogram would include a certain amount of distortion, which can be eliminated.

In order to obtain the projections of all measured distances onto a spherical surface, approximating the surface of the Sun, we adopted the following procedure. In the plane of the filtrogram film we chose an arbitrary Cartesian system of coordinates. Using the least-squares method, the coordinates of the centre of the solar disk were determined from the position of six points at the limb of the solar disk. The reactangular coordinates of any investigated point can be transformed to polar with respect to the determined centre of the disk. It is now easy to change to relative heliographic coordinates (Waldmeier, 1941). The heliographic relative coordinates of two points on the solar disk, determined in this manner, together with the radius of the Sun define the length of the arc, connecting both points. From the above written it can be seen that we will be referring to projections of distances (or velocities) onto the spherical surface, approximating the solar surface, when we shall speak of distances and of the velocities derived from these.

On the whole 57 photographs of the solar disk in H-alpha from the interval 03 20 38 to 05 21 03 UT were processed by an Ascorecord and the data were processed by a Minsk 22 computer.

If the diameter of the solar disk on the filtrogram amounted to 16 mm, the Ascorecord accuracy used of 10^{-2} mm yields 865 km in the tangential plane at the centre of the solar disk. However, the practical accuracy of the measurements was affected particularly by the possibility of subsequent identification of the given point of the section through the flare formation, the image of which was not very sharp as a result of the diffusive substance of the flare ribbons and a small resolution of the telescope. The real mean error of one measurement will be approximately 4 times as much, i.e. about 3.5×10^3 km.

Development of the Flare (Width of the Flare Channel)

The computed lengths of the arcs, representing the width of the flare channel and the widths of the ribbons in the individual sections, were plotted as a function of time in the graph, three time intervals displaying good possibility of linear approximation. The changes in the individual trends occurred over comparatively short intervals of time, of the order of minutes. A certain velocity of receeding of the flare ribbons corresponds to each trend. The least-squares method was used to fit the individual trend with lines, the slopes of which determine the appropriate velocities. Table 1 gives the velocities at which the ribbons receeded in the given section and in the corresponding time intervals, calculated for

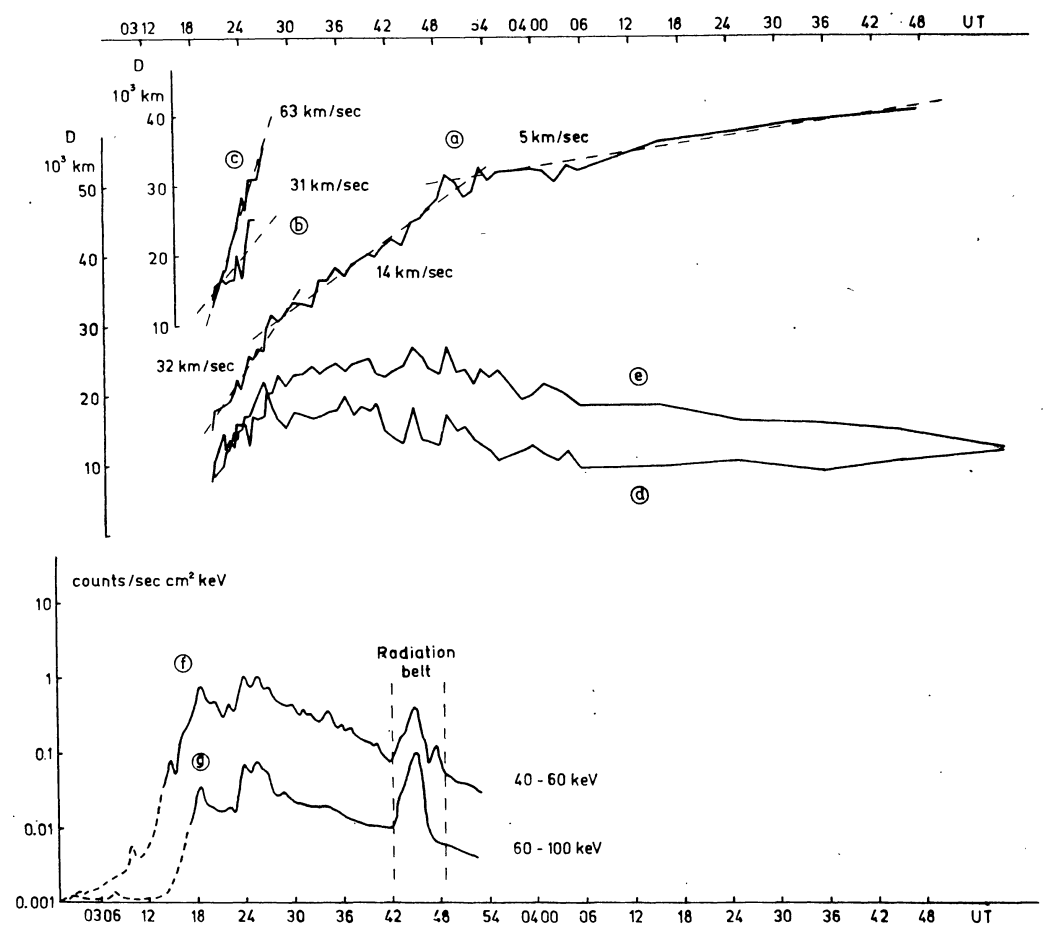

Fig. 4. Curve a represents the mean width of channel Y_1 in section M; b and c the distance of the ribbons of the subsidiary splitting Y_2 in sections 5 and 4, and d and e the measured width of ribbons A and B in channel Y_1, averaged over sections 1, 2 and 3. Curve f gives the time variation of the X-emission flux in the 40—60 keV range, and g the same for the 60—100 keV range.

the individual trends. The line, marked as section M, gives the velocity with which the mean distance of the flare ribbons changes at point Y_1, averaged over sections 1, 2 and 3 at each time. The velocities are given in km/sec.

Table 1

Time interval / Section	03 20 38 to 03 28 54	03 29 51 to 03 53 06	03 53 58 to 05 21 03
1	33.3	11.4	3.8*
2	32.9	16.5	5.8
3	31.5	13.6	4.7
M	32.4	13.7	5.3
4	63.3**	—	—
5	30.9**	—	—

* Only until 04 36 19 UT.
** Only until 03 25 47 UT.

Since the individual curves did not differ too much mutually, only a graph for section M is presented (Fig. 4a). Curves b and c in the same figure represent the measured width of the subsidiary splitting Y_2 in sections 4 and 5. Figure 4a shows that during the first seven minutes after the splitting channel Y_1 widened at a rate of 32.4 km/sec; a slower trend of 13.6 km/sec followed and lasted for about 23 min, and finally the last and slowest trend which lasted about 85 min until the motions of the ribbons ceased, corresponds to a rate of 5.3 km/sec. The maximum width of the Y_1 channel amounted to 65,000 km.

Similar initial rate trends of the widening of the flare channel were observed with the proton flare of Sept. 26, 1963. They amounted to 35 and 11 km/sec (Křivský, 1969).

The fastest receeding of the ribbons occurred with the subsidiary splitting in Y_2, where a rate of 30.9 km/sec was observed in section 5 and even 63.3 km/sec in section 4 (cf. Tab. 1 and Figs 4b, c).

Development of the Widths of the Flare Emission Ribbons

Figures 4d and e show the increase in the mean thickness of ribbons A and B, averaged over sections 1, 2 and 3. The thickness of the ribbons also displays three phases, corresponding approximately in time to various trends in the increase of distance of the ribbons in region Y_1. During the first phase the widths of the ribbons A and B changed roughly identically betwen 7×10^3 and 2×10^4 km. During the second phase the widths of the ribbons fluctuated, however, on the average they did not change much; with ribbon A it amounted to about 17,000 km and with ribbon B to about 23,000 km. After 04 03 UT a permanent slow decrease in the ribbon width set in, and lasted until the observations of the flare were terminated.

It is remarkable that the occurrence and duration of the three rate trends of the widening of the channel and of the three trends in the change of the widths of the emission ribbons in H-alpha are in agreement. This agreement indicates the existence of three main physical processes (cf. item 7 of the conclusions). The maximum length which ribbons A and B attained was 120,000 km.

3. The Flare X-emission

The results of the measurements of the X-emission during the flare were obtained by means of an X-ray photometer, located on the Intercosmos 4 satellite. The instrument was equipped with three detectors, the data of which were monitored via 7 channels, covering the energy range of 1—100 keV. The scintillation detector measured over the following ranges: Channel 1, 5—10 keV, Channel 2, 10—20 keV, Channel 3, 20—40 keV, Channel 4, 40—60 keV, Channel 5, 60—100 keV. The gas-filled proportional counter recorded the integral flux in the range 1—15 keV. With a view to the changes of HV during the flight, the data from this detector cannot be reduced and evaluated with sufficient accuracy. The semi-conductor Si-detector was used for a check of the charged particle recording and defined the passage over the South American anomaly.

The values of the flux in the individual energy channels were telemetered in analogue form. The time resolution of the measurements is about 30 sec. A detailed description of the apparatus, its calibration and the processing of the data is given in Valníček et al. (1973).

Figures 4f and g show the X-emission flux in Channel 4 (40—60 keV) and Channel 5 (60—100 keV). Evident increases occurred at 03 09 UT (Channel 4) and 03 16 UT (Channel 5). However, one cannot exclude a slight increase in flux several minutes earlier, because of the relatively high background noise and fluctuations in these channels. The softer energies already display an increase at 03 03 UT (Channel 1) and the first maximum at 03 12, which can be clearly distinguished in Channels 1 to 4. At 03 21 UT the flux reached a value which exceeded the scale in Channels 1 and 3, and Channel 2 became oversaturated at 03 24 UT. The softer channel data is not published here, because it was published in Livshits et al. (1972).

The results in Figure 4 are only approximately reduced for the efficiency of the detector to 1 cm^2 of the area of the window and to unit width of the energy channel (1keV). The approximate shape of the spectrum just prior to the flare and just prior to the maximum was obtained from the data, modified in this manner (Fig. 5).

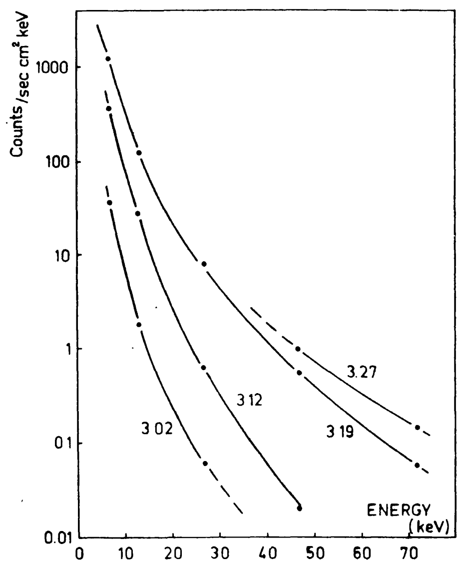

Fig. 5. Time variation of the spectrum of X-radiation during the initial phase of the flare.

4. Conclusions

1. The investigated proton flare displayed the usual typical development, the formation of the flare channel and the transverse structure; the flare was generated in the region of several adjacent spot groups without their close interaction.

2. The development of the width of the channel of the flare displays three phases in H-alpha: I — the shortest trend in the rate of splitting of the flare ribbons about 32 km/sec, II — a slightly longer interval with a rate of about 14 km/sec, and finally III — the longest interval with rates of about 5 km/sec. The subsidiary splitting at the edge of flare ribbon B displayed a higher rate of about 60 km/sec.

3. The same three phases, identical with the time intervals of the rate trends mentioned, were displayed by the thicknesses of the two main flare ribbons, bounding the "channel": I — the thickness of the emission filaments increased at first, II — the thickness was roughly constant with fluctuations, III — the thickness gradually decreased.

4. The beginning of the phase of rapid splitting of the ribbons, which is denoted as the Y-phase, is apparently associated with the development of the main instability and the acceleration of particles, was determined at 03 17 — 03 18 UT, and the second, subsidiary splitting at 03 21 — 03 22 UT.

5. The ranges of the very hard X-emission (40—60 and 60—100 keV), recorded by the Intercosmos 4 satellite, display two maxima: the first, and lower one, at about 03 19 UT, and the second and main at about 03 25 UT. The first maximum is roughly identical with the occurrence of the X-emission polarization maximum (Tindi et al., 1972). This time relation could indicate that the first hard X-emission maximum is mostly of bremsstrahlung origin, caused by directional anisotropic beams of accelerated particles.

6. A spectrum corresponding to several moments of the initial phase of the flare was constructed and used to derive that the contribution of the non-thermal radiations, which occur at energies of over 15 keV, increases gradually with the time development in the investigated initial interval, which agrees with the present findings.

7. One may consider as an important finding that the duration of the initial phase (I) of the rapid widening of the channel (after the Y-phase), as well as the increase in the thickness of the ribbons in H-alpha, agrees with the occurrence and duration of the increase in the X-emission of the very hard channels (40—60 and 60—100 keV), from the beginning of the flare to their main maxima. One may assume that the dynamics of the flare in H-alpha also reflects the main phases of the physical processes, which develop in the whole region of the flares. The interval of this first phase would indicate the duration of the main physical process of the development of the instability and energy release. Phase II would characterize another phase of the physical process, during which energy is also released, however, as a result of the initial violent process, which has already ceased to be active. Phase III represents the decaying of the process in the chromosphere and lower corona and complete attentuation.

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