THE PHASE OF PARTICLE ACCELERATION IN THE FLARE DEVELOPMENT

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Abstract. Evidence is given that the particle acceleration in flares is confined to the initial phase of the flare development preceding the Hα flare maximum and lasting for less than 10 min. The impulsive acceleration process is confined to a relatively small limited volume of about 5×10^{27} cm^3 in the region of highest magnetic gradient in the flare, and its size represents about 0.05 or less of the total extent of the hot condensation which produces the soft X-ray and gradual microwave bursts. About one in fifty particles in this volume is accelerated to energy exceeding 100 keV, the total particle density being $\approx 10^{10}$ cm^{-3}. The accelerated electrons produce the impulsive hard X-ray burst, but synchrotron losses greatly reduce the number of relativistic electrons participating in the bremsstrahlung process. Protons above 20 MeV penetrate to the lowest chromosphere and upper photosphere and temporarily increase the temperature in the bombarded region. As the result a flash of continuous emission appears, which should be most expressive below 1527 Å. The associated white-light emission shows the bottom of the region where the impulsive acceleration process occurs.

The aim of this paper is to determine the time, when > 10 MeV protons and relativistic electrons are accelerated in the flare region, and to inquire about some characteristic features of the phenomena associated with the acceleration process in flares.

1. Observational Evidence of Acceleration Processes

Records of relativistic electrons in space, as well as onsets of GLE's and strong PCA's indicate that the acceleration must occur in the initial phase of the flare development, either close to, or prior to the Hα maximum of the flare. And as direct solar observations are concerned, there are only three phenomena, which can be considered for a direct evidence of an acceleration process in the flare region: the radio type III and type IV bursts, and the hard X-ray burst.

A. TYPE III BURSTS

The type III bursts are so frequent, and their correlation with proton events in space is so loose that they evidently do not reflect the very efficient acceleration process we are interested in. One can suppose that they represent only some acceleration 'flashes', greatly restricted in their size and consequences, like, e.g., moustaches in comparison to flares in the Hα line.

B. TYPE IV BURSTS

On the other hand, there is a very significant correlation between strong particle events and the type IV bursts. There seems to be a general agreement that the metric component of a type IV burst is due to synchrotron radiation of mildly relativistic electrons. Thus its occurrence is direct evidence that an acceleration process has taken

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place in the flare region, and its correlation with proton events strongly indicates that this acceleration has been effective both for the electrons and protons. Since the metric burst can only be observed after the radiating source has emerged above a certain critical level in the corona, its onset does not determine the time of the acceleration process. It sets, however, an upper limit to the time when the acceleration occurs and confirms again that this happens in the early phase of the flare development.

Much better information on the time of acceleration could be obtained from the microwave radio bursts, whose origin, however, is still not completely clear. In the case that the microwave burst also can be ascribed to synchrotron radiation (Takakura, 1960), which seems to be strongly supported by its close association with the hard X-ray bursts (Takakura and Kai, 1966; Holt and Ramaty, 1969), its occurrence presents fairly exact information on the time of the acceleration process. It starts and mostly also reaches its first maximum before the Hα maximum of the flare. This first maximum, usually occurring a few minutes before the Hα peak, seems to be the most important, since it coincides in time with the hard X-ray burst, while any following fluctuations in the microwave flux do not show this X-ray response.

C. X-RAY BURSTS

The flare-associated X-ray bursts show a well-defined energy dependence as far as their duration and maximum time are concerned. The time variation of soft X-rays in the energy range of 1 keV is very similar to that of the flare intensity in the Hα line, and the X-ray and Hα maxima coincide in time; as the X-ray energy increases, however, the life-time of the X-ray burst becomes shorter, and its maximum shifts to an earlier time. In the energy range exceeding 50–100 keV the burst becomes extremely short, its peak energy also decreases, and no X-ray burst has ever been observed for energies above 700 keV.

In fact, as De Jager (1965) suspected many years ago and as the recent high-time-resolution X-ray measurements have clearly shown, the solar X-ray bursts consist of two components (Kane, 1969): a slow one, most probably of thermal origin, which usually disappears for energies above 50 keV, and an impulsive one that remains above these energies, is short-lived and reaches its peak early in the event, in coincidence with the peak in the microwave burst. One can hardly doubt that this impulsive component reflects an acceleration process in the flare, which – during a very short time – gives rise to electrons with energies exceeding the X-ray energy recorded.

As Kane has found, this impulsive component is not present in all recorded X-ray bursts. On the other hand, very intense impulsive components have been recorded in association with several proton flares (Cline *et al.*, 1968; McClinton, 1968; Cline, 1969), so that it is not unreasonable to suppose that this acceleration process may be in close connection with the general particle acceleration in the flare.

In three proton flares, on 7 July and 28 August, 1966, and 9 June, 1968, for which the hard ($>$ 80 keV) X-ray measurements have been published (see references above), the hard X-ray peak preceded the Hα maximum at 3–6 min, always coinciding with the peak in the microwave flux. In 6 smaller flares listed by Kane (1969), and in the set of 46 X-ray bursts listed by Ohki (1969), this time difference was 1.6 and 2.1 min, respectively, on an average, for energies above 10 keV. Thus the acceleration process evidently occurs in the very initial phase of the flare, several minutes before the Hα maximum, which probably can be identified with the onset of Ellison's (1952) flash phase and with Moreton's (1964) explosive phase of the flare development.

Of course, all these phenomena only give evidence on an acceleration of electrons to subrelativistic energies in the flare region. Whether this phase also includes the proton acceleration to subrelativistic, and electron acceleration to relativistic energies, remains an unanswered question.

2. The Flare Development in the Hα Line

Let us now compare these radio and X-ray observations with the flare development in the Hα light. It is well known that the flares that produce GLE and strong PCA events, thus being evidently sources of very energetic protons, are characterized by a particular shape of two roughly parallel bright ribbons. These ribbons form first along the zero line of the longitudinal magnetic field in the sunspot group, and then separate one from the other. One can consider them for rows of feet of a system of expanding flare loops, of which only the feet are visible in the Hα line. The expansion is fast at its beginning and slows down after a few minutes, when the bright ribbons begin to enter regions of large sunspots in the active centre. This phase is usually finished shortly before the Hα flare maximum, i.e. it coincides in time with the microwave and hard X-ray peaks (Křivský, 1963; Valníček, 1967; Zirin and Russo Lackner, 1968; Švestka and Simon, 1969; Křivský and Švestka, 1970). In his list of 59 proton flares, Křivský (1965, 1966) has determined the time of splitting of the bright flare ribbons, which can be identified with the phase of their fast separation, and one can verify that in 85% of cases this phase clearly preceded the Hα maximum, similarly to the microwave and hard X-ray bursts.

Nothing conspicuous seems to happen in any later phase of the flare development. In the Hα light the flare decays with the bright ribbons slowly moving apart across the sunspots, if the spots are small, or staying without any motion, if a big sunspot is in the way. Radio flux maxima can still occur, but without any hard X-ray association. Therefore, one can reasonably suppose that the whole acceleration process, including the acceleration to very high energies, occurs in the earliest (flash) phase of the flare development. This is the phase of the fast separation of the bright flare ribbons, which manifests the fast expansion of the flare loops, and/or the phase when this expansion begins to enter the regions of high longitudinal magnetic fields in sunspots and is rapidly slowed down.

3. The White Light Flare Emission

Observations of solar flares in white continuous light are very rare, many events certainly have been missed, and the few existing observations often do not yield sufficient information on the white-light flare characteristics. In fact, after 1930, when Hα and SID observations are also available, one can find eight events only, when the description is good enough to give fairly clear information on the observed white light phenomenon (cf. Švestka, 1966b). These observations then strongly indicate that one has to distinguish two different types of the white-light flare events.

A. LIMB EVENTS

The first type includes flares observed close to the limb, when a bright facula is observed in white light, usually closely resembling the shape of the Hα flare. A good example of this type was the flare of 23 March, 1958 (Becker, 1958), when the brightened facula, at 74 °E, reflected the ribbon-like shape of the Hα emission. Other events of this type were observed on 31 March, 1938 (Dobbie *et al.*, 1938) at 82 °E, on 23 February, 1956 (Notuki *et al.*, 1956) at 79 °W, and on 3 September, 1960 (Angle, 1962) at 88 °E. In these cases we probably meet with a slight overheating of the uppermost layers of the photosphere beneath the flare, as first has been proposed by Mustel (1955), or with an H^- emission in extremely dense and low-temperature lowest part of the flare as suggested by the writer a few years ago (Švestka, 1966a).

B. DISK EVENTS

The second type, however, seems to be much more interesting. It includes events that occurred far from the limb, and in all these cases the white-light emission had a form of one or two short-lived bright points or small areas which appeared in the penumbral region of sunspots. A typical event of this type, and so far best observed, has been reported by De Mastus and Stover (1967) on 23 May, 1967, and similar events were earlier observed on 5 March, 1946 by Martheray (D'Azambuja, 1947), on 3 September, 1957 by Becker (1958), and on 15 November, 1960 by Koyama (Nagasawa *et al.*, 1961). Data on these events are summarized in Table I. In addition to it, Table I also includes two events, on 20 March, 1966 (Monsignori Fossi *et al.*, 1969) and on 28 August, 1966 (McClinton, 1968) when short-lived 1225–1350 Å UV-continuum increases were recorded, very similar in their behaviour to the white-light flare phenomenon (Friedman, 1969).

All the data in Table I strongly indicate that the continuous emission of this type appears at the same time when the first maximum of the radio microwave flux and the hard, non-thermal and impulsive, X-ray burst are observed. It also precedes the Hα maximum, which contradicts the generally accepted statement that the white-light and Hα maxima coincide in time. Due to the concentration of the continuous emission to a region greatly restricted in size, one can suppose that it occurs fairly low in the solar atmosphere. Therefore, one can suspect that the white-light emission of this type and the hard impulsive X-ray burst are closely related, both having their origin in streams of particles accelerated in the same source in the flare region. Then, if we accept this supposition, *the white-light flare location marks optically the region where the most important part of the hard X-ray burst is produced.*

Figure 1 shows the sunspot group of 23 May, 1967, the position of two bright flare

TABLE I

Flares with continuous emission of the second type

Date	Cont. emission			Hard X-ray max.	Micro-wave max.	Hα max.	SID beg.
	Beg.	Max.	End				
White-light flares:							
1946 March 5	1124	1125	1127	N	N	N	1128
1957 Sept. 3[a]	1424		1425	N	1424	1428	1420
	1424		1430				
1960 Nov. 15[a]	0221		0222	N	0222	0221	0218
	0223.5		0224				
1967 May 23	1838	1840	1845	$\leq$1841	1839.5	1844	1835
UV-continuum flares:							
1966 March 20	$<$0956	$\leq$0956		N	0955.7	0958	0955
1966 Aug. 28	1523.5	1527.2		1527	1527.5	1531	1523

[a] Two white-light regions.
N = no observation.

ribbons of the flare in the group, and the two small areas which became visible in the white light (De Mastus and Stover, 1967). Evidently they can be considered for the feet of a loop connecting both the expanding bright flare ribbons and anchored in penumbrae of spots of opposite magnetic polarities.

4. Discussion

The supposition that the whole acceleration process associated with flares is accomplished during the flash phase and is evidenced through the impulsive hard X-ray and microwave bursts and on some occasions also by the white-light emission, seems reasonable and is also supported by favourable time associations between the fastest

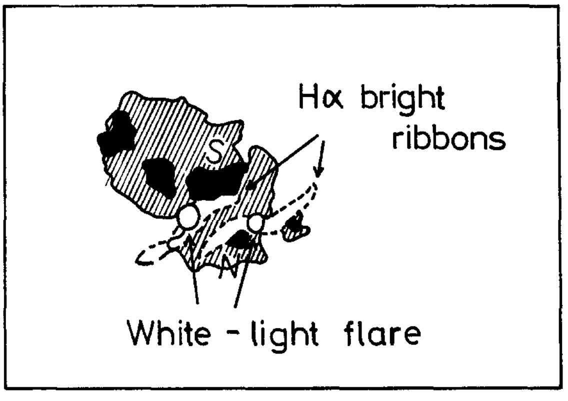

Fig. 1. The white-light flare of 23 May, 1967 (after De Mastus and Stover, 1967). Significant portions of the S and N spots are covered by the flare emission.

particle records in space and the flare development. Nevertheless, one cannot ignore that there exist objections which might be, or have been, raised against this statement.

A. THE HIGH-ENERGY LIMIT OF X-RAY BURSTS

De Jager (1969) argues that no solar X-ray bursts have as yet been observed with energies approaching or exceeding 1 MeV. Therefore, he supposes that only primary acceleration is accomplished in the flash phase, giving rise to accelerated particles up to energies of the order of 100 keV. The secondary acceleration, which increases the particle energy to subrelativistic and relativistic values, only occurs 10 or 20 min later, and is manifested by the occurrence of the metric type IV burst.

1. *The Cosmic-Ray Flares*

Certainly the most suitable set for checking this supposition is represented by the cosmic-ray flares (associated with GLE's), which accelerate protons to relativistic energies, and which are followed with an arrival of particles at the earth within a very short time of the order of 10 min. Table II gives a list of these events from 1956 to 1969. The quantity Δt gives the time interval between the flash phase and the onset of the metric type IV burst, and one can see that this difference was quite small in all these events, and in one-half of them the difference was zero within $\pm$ 1 min. Thus the observations of cosmic-ray flares, which represent the strongest acceleration process on the Sun, do not favour the supposition of a two-step acceleration with a time difference of 10 or more minutes. If the acceleration is accomplished in two or more steps, these must immediately follow one after the other.

TABLE II

Metric type IV onset delay for cosmic-ray flares

Date	Flash phase	Metric type IV onset	Δt	GLE onset
1956 Feb. 23	> 0332 (I)	0335[a]	$<3^m$	0343
1959 July 16	> 2115 (I)	2121	$<6^m$	2250
1960 May 4	1014–1017 (M)	1019[a]	$2–5^m$	1030
1960 Nov. 12	> 1327 (M)	1328[a]	$<1^m$	1340
1960 Nov. 15	0222 (M)	0221	-1^m	0227
1960 Nov. 20	2027 (M)	2027	0^m	2055
1961 July 18	≥ 0947 (M)	0946[a]	$\leq -1^m$	1020
1961 July 20	≥ 1553 (Y)	1552	$\leq -1^m$	1610
1966 July 7	0037 (X)	0042	5^m	0059
1968 Nov. 18	1029–1031 (M)	1027	$\leq -2^m$	1045
1969 Feb. 25	0912 (M)	0904	-8^m	0920

[a] Determined from single-frequency records on metric waves; all the other data are based on records by dynamic spectrographs.
I = only SID onset available, which usually precedes the flash phase.
M = time of the first maximum of the microwave radio flux.
X = time of the hard (> 80 keV) X-ray burst maximum.
Y = time of the Y-phase according to Křivský (1966).

When this is true for the strongest acceleration events, there is no reason why it should not be the case for any other event. The delay of the metric type IV burst is obviously determined only by the speed of penetration of the enhanced region to upper layers of the atmosphere, from which the metric waves have free access to the observer, and the faster is the filling up of the 'visible' atmospheric layers with relativistic particles, the more important is the process of acceleration and the importance of the type IV burst.

2. *The High-Energy Cutoff*

There, of course, remains the question, why no X-ray bursts with energy close to or exceeding 1 MeV have ever been observed. In a discussion at the COSPAR Plenary Meeting in Prague Friedman has expressed an opinion that electrons of high energies simply do not exist in the flare region, because they lose their energy too fast by magnetic bremsstrahlung. Therefore, let us first inquire about the energy losses which relativistic electrons suffer due to synchrotron radiation in the flare region.

The rate of energy loss of an electron with kinetic energy E_k in magnetic field H is under the approximation of a circular trajectory (Takakura and Kai, 1966)

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \nu_H\left(\frac{1}{2}\varepsilon^2 + \varepsilon\right), \tag{1}$$

where $\varepsilon = E_k/mc^2$ and $\nu_H = 3.85 \times 10^{-9} H^2\ \mathrm{sec}^{-1}$. On the other hand, the gain in energy due to the acceleration process can be written as

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{\varepsilon}{\tau_a}, \tag{2}$$

where τ_a is the characteristic acceleration time. Clearly the acceleration process only can give rise to particles with energy $>\varepsilon$ if their supply exceeds the losses, i.e. if

$$\tau_a < 2\,\nu_H^{-1}(\varepsilon + 1)^{-1}. \tag{3}$$

Observations show that the thermal X-ray burst starts before the impulsive one, and therefore, one can suppose that the acceleration sets on in a region where the electron gas is already heated to temperature of the order of 10^7 K. The high-energy tail of these thermally accelerated electrons then enters the impulsive acceleration process so that the electron energy at the acceleration onset can be estimated to a few keV. Let us accept $E_k(0) = 4$ keV as the starting energy, in accordance with the result later obtained in Section 5.B. Then the maximum electron energy, E_{kM}, for which the condition (3) is fulfilled, is given in Table III for $H = 500$ G and 1000 G, respectively, and for four different values of D, where D gives the duration of the acceleration process,

$$D = \tau \ln\left[E_{kM}/E_k(0)\right]. \tag{4}$$

One could object that the magnetic field strength in the region where the acceleration occurs, may be less than assumed in Table III, since relativistic electrons exceeding this cutoff energy have been recorded in space on some occasions. Nevertheless even then, when we accept the supposition that the white-light emission marks the position where also the impulsive X-ray burst originates, the bremsstrahlung process occurs in the penumbral region where 500 G can be taken as the minimum, and 1000 G as the probable value of H. Therefore, the number of highly relativistic electrons entering this region again is strongly reduced, since the supply does not exceed the losses, and we have to expect the high-energy cutoff given in Table III, or at least a great progressive steepening of the energy spectrum as the high energies are approached.

TABLE III

Values of the high-energy cutoff

H	$D=$ 1 min	2 min	3 min	5 min
500 G	87 MeV	40 MeV	25 MeV	14 MeV
1000 G	18 MeV	8 MeV	4.7 MeV	2.2 MeV

Thus, one can expect a cutoff-like behaviour of the spectrum at energies of the order of 1 or 10 MeV, depending on the speed of the acceleration process, and electrons of higher energies could significantly participate in the bremsstrahlung only if the acceleration time from 4 keV to >10 MeV were shorter than 1 min. The rise times of hard X-ray and impulsive microwave bursts, however, indicate that D is of the order of few minutes (at least about 5 and 2 min in the well-studied events of 7 July and 28 August, 1966, respectively (Cline *et al.*, 1968; McClinton, 1968)).

3. *The Bremsstrahlung Process*

The X-ray flux at $\varrho = h\nu/mc^2$ is proportional to

$$n \int_{\varrho}^{\varepsilon_0} d\sigma(\varepsilon, \varrho)\, N(\varepsilon)\, d\varepsilon\,, \tag{5}$$

where ε_0 denotes the cutoff energy of participating electrons, $d\sigma$ is the cross-section for the bremsstrahlung of an ε-electron giving rise to radiated energy ϱ, n is the mean hydrogen density in the region where the bremsstrahlung is produced, and $N(\varepsilon)$ is the differential electron flux. As Takakura (1969) and Holt and Ramaty (1969) have shown,

$$N(\varepsilon)\, d\varepsilon = C\varepsilon^{-\gamma}\, d\varepsilon \tag{6}$$

with $\gamma = 3$ is a good representation of the X-ray events actually observed. An expression for the cross-section $d\sigma$ for the relativistic case has been given by Jauch and Rohrlich (1955).

In the event of 7 July, 1966, $\varrho = 1$ was the highest X-ray energy measured (Cline *et al.*, 1968), and the X-ray flux corresponded to a total number of about 10^{36}

electrons with energies above 100 keV in the flare region in the maximum phase of the burst (Holt and Ramaty, 1969). In fact, this is the maximum value of N (> 100 keV) under the assumption that the acceleration process completely decays at the burst maximum, and it corresponds to $n = 4 \times 10^9$ cm^{-3}. If this is not the case, N can become smaller and n larger, keeping the emission measure Nn constant and equal to 4×10^{45} cm^{-3}.

In order to get an observable burst of higher energy, the number of electrons must be increased, and Figure 2, computed from Equations (5) and (6) for different values of ε_0 and γ, shows the numbers which are needed for producing X-ray bursts with energies exceeding $\varrho = 1$. Since one can expect that γ increases to higher values with the increasing energy ($\gamma = 3$ was deduced from bursts below $\varrho = 1$), the figure shows that the number of electrons must be about one order higher to give observable bremsstrahlung of energy exceeding 1 MeV. This probably might happen in some flares, but these should have to be quite extraordinary events, because the compared flare of 7 July 1966 itself was an extremely strong event. In three flares of 1962, e.g., Takakura (1969) found only 8×10^{33} electrons with energy above 100 keV.

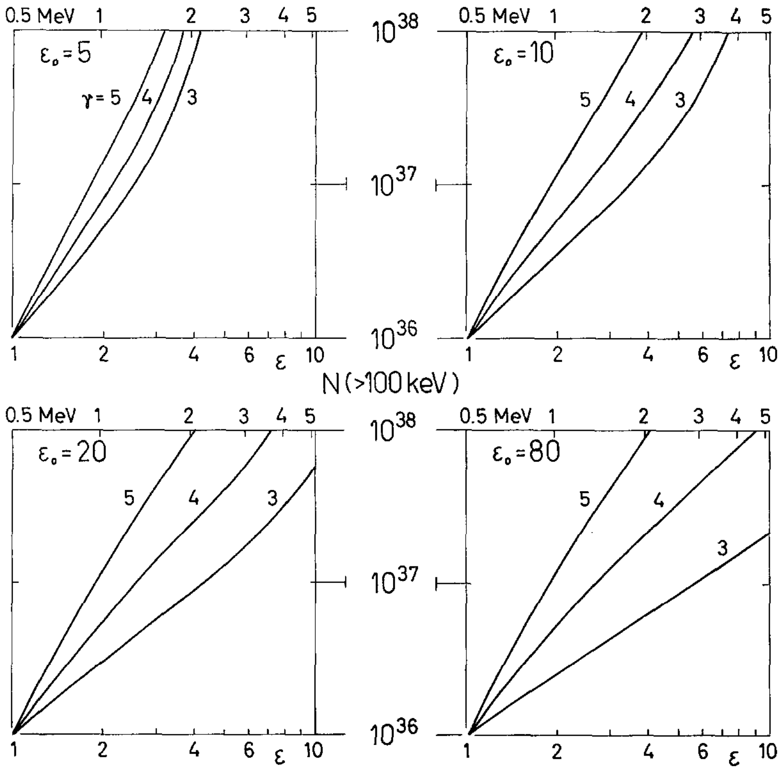

Fig. 2. Total number of electrons needed for creation of observable X-ray burst with energy exceeding 500 keV, for different values of the high-energy cutoff ε_0 and the exponent γ in Equation (6). Within the plotted range of energies the case of $\varepsilon_0 = 80$ is close to $\varepsilon_0 \rightarrow \infty$.

In any case, these computations show that an absence of X-ray bursts with energies above 1 MeV cannot be considered as evidence that particles are not accelerated at the same time to substantially higher energies. The absence of X-ray bursts of higher energy is simply due to the fact that the number of electrons needed for their production is too high to be reached in the flare region, the more so that synchrotron losses cut off the high-energy tail of the spectrum.

4. *Space Observations*

Let us check our results by direct observations of relativistic electrons in space. According to Cline and McDonald (1968) the highest flux of >3 MeV electrons recorded in space from November 1963 to May 1967 corresponded to about 5×10^{31} electrons with energy above 3 MeV in the flare region. Then one needs $\gamma \simeq 4$ in Equation (6) to get $N(>100 \text{ keV}) = 10^{36}$ as observed on 7 July, 1966, hence the space observations do not contradict the conclusions made in the preceding Section.

B. CORRELATION BETWEEN X-RAY AND PARTICLE EVENTS

Another objection which might be raised is the fairly loose correlation between X-ray bursts and particle events in space, emphasized by Arnoldy *et al.* (1968). There certainly exist exceptional cases, when fairly strong X-ray bursts do not produce any particle flux in space or when particles occur in space without any associated X-ray burst. This, however, at least to some extent, also is the case with the type IV bursts (Fritzová and Švestka, 1966). These anomalies obviously are due to the very complicated structure in the active regions, of which our present knowledge is still very unsatisfactory.

Generally, however, a correlation between the X-ray bursts and particle events in space does exist. A statistical comparison cannot be made for the hard X-ray bursts, where observations are still fairly incomplete. But one can demonstrate it on the systematically observed 2–12 Å bursts, as shown in Table IV. Since strong hard X-ray

TABLE IV

Association of soft (2–12 Å) X-ray bursts with particles in space

Peak ratio to quiet Sun[a]	Number of bursts[a]	Percent association with particles[b]
10–19	47	13 %
20–29	15	33 %
30–49	9	44 %
50–79	6	67 %
>80	5	80 %

[a] Recorded by Explorers 33 and 35.
[b] Recorded by Explorer 34.
Both sets of data from *Solar Geophysical Data* (ESSA, Boulder, Colo.), for the period from Feb. 1968 to Feb. 1969.

bursts need a great number of electrons and start from a hot condensation, from which these electrons are accelerated, one can presuppose a correlation between the intensity of the impulsive hard and slow soft X-rays. And Table IV confirms that the percent association of the particle events with X-ray bursts significantly increases with the increasing X-ray intensity.

5. Source of the Continuous Flare Emission

Let us now inquire what may be the source of the continuum flare burst in the optical and UV spectral regions. Since this emission, as to its time of occurrence and duration, is closely associated with the hard X-ray burst, and it only appears in association with the strongest events, we have to suppose that the continuous flash is a consequence of the existence of particles (electrons or protons) accelerated to extremely high energies in the flare region.

A. MAGNETIC BREMSSTRAHLUNG

Let us first assume that these particles are relativistic electrons. Particles of this kind could produce the observed continuum burst by synchrotron radiation, as was first proposed by Gordon (1954) and applied to the continuous flare emission by Severny (1957) and Stein and Ney (1963).

A 10% increase in brightness near 5000 Å is equal to an energy $E_\lambda = 3.6 \times 10^5$ erg/cm^{2}sec ster Å. In the UV region, an increase in the continuum near 1300 Å of at least 3×10^{-3} erg/cm^{2}sec Å has been recorded in the two flare events listed in Table I. Thus, with the white-light flare area $A = 8 \times 10^{17}$ cm^2 (after De Mastus and Stover, 1967), we have to explain origin of total energy

$$AE_\nu = 2.4 \times 10^{12} \text{ erg/sec ster at 5000 Å}$$

and

$$AE_\nu = 7.6 \times 10^{11} \text{ erg/sec ster at 1300 Å.}$$

Assuming circular orbits of the radiating electrons and the electron distribution given by Equation (6) with $\gamma = 3$, we find

$$C = 8.7 \times 10^{22}\, AE_\nu / GH, \tag{7}$$

where

$$G = \int_E E^{-3}\, F(E)\, \mathrm{d}E,$$

$$F(E) = g(E) \int_{g(E)}^{\infty} K_{\frac{5}{3}}(x)\, \mathrm{d}x,$$

and

$$g(E) = 6.2 \times 10^{-8}\, \nu / HE^2,$$

with E in MeV. For $H = 1000$ G the observed AE_ν values need $C = 1.2 \times 10^{37}$ at 1300 Å and $C = 9.5 \times 10^{36}$ at 5000 Å, respectively.

Figure 3 shows the participation of electrons with different energy in the AE_ν flux. Obviously these are electrons greatly exceeding the high-energy cutoff deduced in Table III. Nevertheless, let us assume that electrons of these energies can be produced in the flare region, which would need a very fast acceleration process in a weak magnetic field. Then we can deduce from C and Equation (6) the corresponding total number of electrons with energy exceeding 100 keV. For $\gamma = 3$ we get $N(>100 \text{ keV}) = 5.9 \times 10^{38}$ and 4.8×10^{38}, respectively, and these values must be still increased for $\gamma > 3$. A comparison with Figure 2 immediately shows that this number of electrons should produce an X-ray burst with energy exceeding 10 MeV and, of course, also the X-ray flux at lower energies should be many times stronger than observed. Therefore, the burst of continuous light in the optical and UV region cannot be due to synchrotron radiation, as also has been shown by Korchak (1967) by computing the inversed-Compton-effect radiation produced by the electrons necessary for the magnetic bremsstrahlung process.

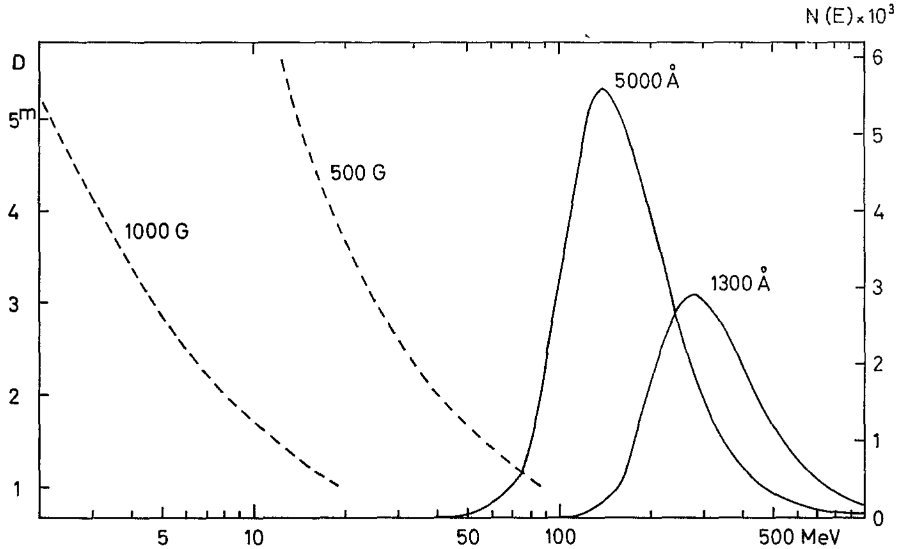

Fig. 3. The full curves (the right-hand scale) show the relative participation of electrons of different energy in synchrotron radiation producing the observed continuous emission in a field of 1000 G at 5000 Å and 1300 Å, respectively ($\int N(E)\, dE = 1$, E in MeV). The curve for 1300 Å also represents the distribution for 5000 Å and $H = 260$ G, and similarly, the curve for 5000 Å also represents the distribution for 1300 Å and $H = 3830$ G. The dashed curves (the left-hand scale) show the cutoff energy for different values of the duration D of the acceleration process, for $H = 500$ G and 1000 G, respectively.

B. PROTON PENETRATION INTO THE PHOTOSPHERE

From the analyses presented by Korchak (1967) and Stein and Ney (1963) one can also conclude that there is no other effect, through which the relativistic electrons could produce enough radiation in the UV and optical spectral regions. Therefore, let us inquire what effects could be produced by high-energy protons.

1. *Energy Required*

One can suppose that electrons and protons are accelerated on some height in the solar atmosphere, and from there a part of the accelerated particles flow down along the loop-like lines of force. Due to the increase of the magnetic field strength with depth this particle stream will be concentrated to progressively smaller area as penetrating to larger depths. This may prohibit particles with large pitch-angles from penetrating to regions of high field strength. Nevertheless, unless the pitch-angle distribution is greatly anisotropical, about 20% of the downward streaming particles still penetrate to the depth where H is as much as 10 times increased, and the actual increase probably is much smaller.

The electron component produces the impulsive X-ray burst as passing through the atmosphere, and the total energy of the electrons involved in the bremsstrahlung process can be estimated to

$$\int_{10\,\mathrm{keV}}^{10\,\mathrm{MeV}} N(E)\,E\,\mathrm{d}E \simeq 3 \times 10^{30}\ \mathrm{erg}$$

in strong events like that one of 7 July, 1966. A significant part of this energy must be completely transformed to other energy forms during the relatively short duration of the impulsive burst (while the remaining part goes to the thermalized assembly of electrons, decaying for much a longer time). This transformed energy will be released almost completely above the height of 1000 km over the base of the chromosphere, and there is no obvious process which might transform it to continuous emission of the strength and spectral distribution observed. On the other hand, however, protons in the stream can penetrate up to and below the bottom of the chromosphere, and their energy will be mostly transformed through collisions to kinetic energy of the colliding low-energy nuclei. Thus the proton stream will lead to a heating of the region where the collisions occur.

Assuming black-body radiation, a 10% increase in brightness at 5000 Å needs an increase in temperature of about 130 K in the layer in which this radiation is formed. Taking 10^{17} cm^{-3} as the average density and 10^{7} cm as thickness of this layer, an additional energy of about 3×10^{10} erg/cm^{2} is necessary for the observed increase in brightness. Near 1300 Å the radiation is formed on much higher altitude (Gingerich and De Jager, 1968), in a layer of about 2×10^{7} cm thickness and 10^{15} cm^{-3} average density. The observed energy in continuum, corresponding to 0.8 erg/cm^{2}sec near the earth (Monsignori Fossi *et al.*, 1969) and to an emitting area of 8×10^{17} cm^{2} (De Mastus and Stover, 1967), needs $T = 9870$ K. Assuming an overestimated increase from 5000 K, an additional energy of about 2×10^{10} erg/cm^{2} is needed, about the same as in the preceding case. Thus additional energy of about 10^{11} erg/cm^{2} must be supplied to an atmospheric layer of about 600 km thickness and $\sim 8 \times 10^{17}$ cm^2 cross-section area to produce the continuum increase observed.

2. *Energy Available*

Records of strong particle events in space, such as on 28 August and 2 September, 1966, give about 10^4 protons with energy above 1 MeV/cm^{2}sec ster as the maximum flux near the earth (Švestka and Simon, 1969). When the time development is taken into account, one can estimate the total number of these particles on the Sun to $\sim 10^{34}$, which corresponds, for $\gamma = 3$, to 10^{36} protons with energy above 100 keV, in agreement with the number of electrons above this energy, deduced from the hard X-ray burst. This is a very rough estimate, of course, but it allows us to assume that electrons and protons are accelerated to the same energy in the flare region.

Collision computations show that protons with energy exceeding 20 MeV penetrate into the very low chromosphere and upper photosphere, where the continuous radiation is formed (Schatzman, 1965). For $N(>100\ \text{keV}) = 10^{36}$ and $\gamma = 3$ this high-energy tail of the proton stream carries energy

$$\int_{20\ \text{MeV}}^{\infty} N(E)\, E\, \mathrm{d}E = 10^{33}\ \text{MeV} = 1.6 \times 10^{27}\ \text{erg}.$$

Assuming again the cross-section area of 8×10^{17} cm^2, we get 2×10^9 erg/cm^2, an energy too small when compared with the amount required.

This energy, however, can be very much increased, if the value of γ decreases. Due to much smaller energy losses one can suppose that γ for protons will be smaller than γ deduced from the electron flux. If $\gamma = 2$ is accepted for the proton distribution, with the same number of $N(>100\ \text{keV}) = 10^{36}$, one gets, with high-energy cutoff at 1 GeV,

$$\int_{20\ \text{MeV}}^{1\ \text{GeV}} N(E)\, E\, \mathrm{d}E = 3.9 \times 10^{35}\ \text{MeV} = 4.7 \times 10^{29}\ \text{erg}, \tag{8}$$

which yields $\sim 6 \times 10^{11}$ erg/cm^2, a value of the order required. In fact, $\gamma = 2$ was observed in the initial phase of the 7 July, 1966 event (Heristchi *et al.*, 1969).

3. *Spectral Distribution*

Since the total radiation energy of the sun amounts to 6×10^{10} erg/cm^{2}sec, the supply of 6×10^{11} erg/cm^2, if completely transformed into continuous emission, would be sufficient to keep the solar radiation enhanced at 10% within the whole spectral range for 100 sec. Thus, since only a fraction of the supplied energy is reradiated back in the form of continuous emission (or, in the words of Section 5.B.1, only a part of the proton energy is used to the heating of the atmosphere), obviously only a very hard proton spectrum with high cutoff energy can produce the white-light flares, as actually is observed.

One can expect, however, that the continuum brightening appears more easily at wavelengths at which the continuum is formed in higher atmospheric layers. Figure 4 shows the wavelength variation of the depth in which, in the undisturbed atmosphere, $\tau = 1$ in the continuum (Gingerich and De Jager, 1968). The relative intensity of the continuum burst should follow an analogous spectral distribution. Hence observations near 1400 Å up to 1527 Å should be most sensitive to the continuum enhancements.

4. *Particle Density*

There, however, still remains a problem, whether such a high number of energetic particles can be concentrated into such a relatively very small area. If, as assumed, the white-light flare area of $\sim 8 \times 10^{17}$ cm^2 defines the bottom of essentially the whole

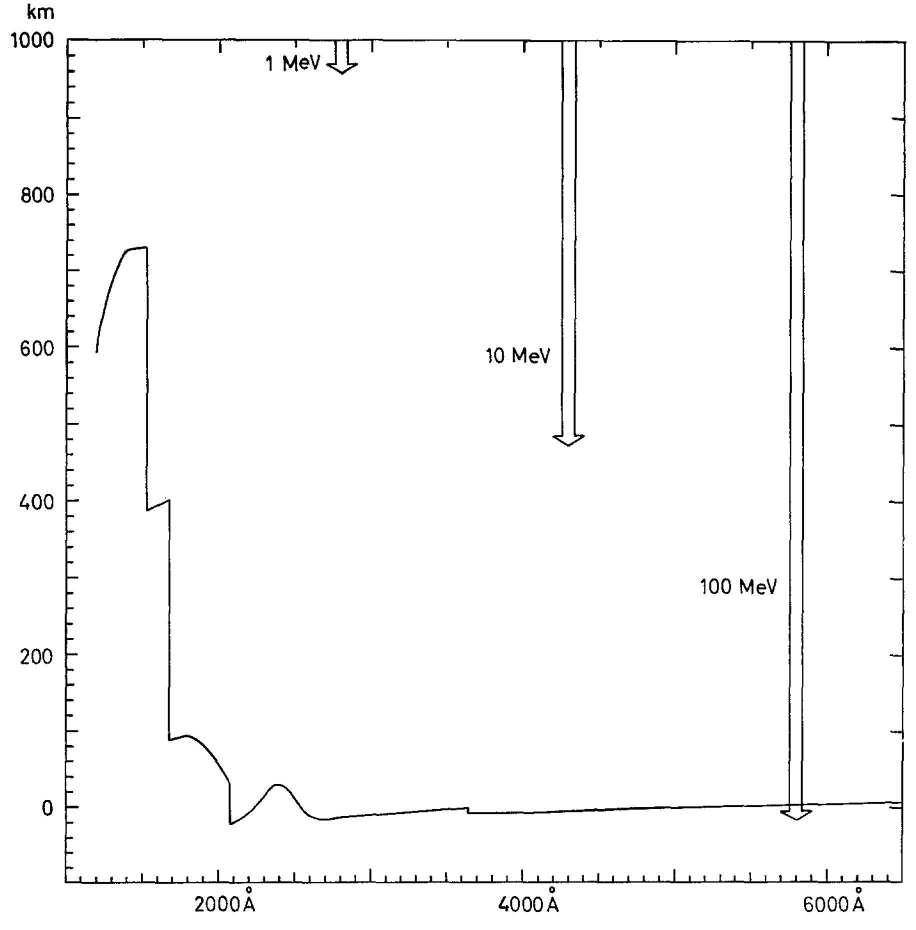

Fig. 4. Height in the solar atmosphere at which $\tau = 1$ for different wavelengths (after Gingerich and De Jager, 1968). Zero level corresponds to $\tau = 1$ at 5000 Å. The arrows show the depth to which protons of different energy (with zero pitch-angle) penetrate in the solar atmosphere (after Schatzman, 1965).

region in which the hard X-ray burst is produced (Figure 5), about 10^{36} electrons and protons with energy above 100 keV should be present in a volume of about 5×10^{27} cm^3. This corresponds to a density of $\sim 2\times10^8$ cm^{-3} of electrons (or protons) with energy exceeding 100 keV in the maximum phase of the acceleration process.

This value, though very high, is not impossible. Let us suppose that the acceleration process occurs in a thermal condensation with temperature 4×10^7 K. Under these conditions $N(>4$ keV) is just half the total number of electrons. With $\gamma=2$, which can be supposed for the low-energy end of the electron energy spectrum, the value of $N(>100\text{ keV})=2\times10^8$ cm^{-3} corresponds to $N(>4\text{ keV})=5\times10^9$ cm^{-3}, hence the total number of electrons in the region, where the acceleration occurs, results to 10^{10} cm^{-3} (or, since only some of the electrons participate in the bremsstrahlung process, it is of the order of 10^{10} cm^{-3}). This is exactly the electron density found by Takakura (1969) in a hot coronal condensation responsible for the soft X-ray burst and gradual burst on microwaves. The volume of this thermal condensation, of course, is much larger, about 10^{29} cm^3 in the maximum of its development, i.e. about 20 times larger than the limited volume in which the impulsive acceleration process occurs.

It is easily possible that the actual conditions in flares somewhat differ from the values deduced in this consideration. The area of the white-light flare determined by De Mastus and Stover (1967) may be overestimated due to the irradiation effect. This would lead to a still smaller volume of the region where the acceleration occurs, in better agreement with Křivský's (1969) value of $<4\times10^{27}$ cm^{-3} estimated from the Hα observations. Then the density would be higher, which also would be the case for the acceleration occurring in a condensation with lower temperature than 4×10^7 K. On the other hand, as we have mentioned in Section 4.A.3, the value of $N(>100$ keV) $=10^{36}$ may be (and probably has been) overestimated, which would compensate this density increase.

6. Conclusions

Thus, on the basis of the preceding considerations, we can propose the following model of the initial phase of the flare development:

The flare starts with the formation of a hot condensation which reaches a temperature $\sim 4\times10^7$ K in a region with a particle density of $\sim 10^{10}$ cm^{-3}. The volume of this condensation expands and reaches about 10^{29} cm^3 in the maximum of its development. It probably has a prolongated form along the $H_{\parallel}=0$ line, which later on is manifested in the Hα line by two bright ribbons parallel to the $H_{\parallel}=0$ line which represent rows of feet of loops going from the condensation down into the chromosphere (Figure 5). This condensation produces the soft X-ray and gradual microwave bursts.

In a limited volume of this condensation, the size of which can be estimated at about $\frac{1}{20}$ or less of the maximum total extent of the excited volume, a strong impulsive process occurs shortly after the flare onset. This process accelerates protons and electrons in the high-energy tail of the condensation energy spectrum to much higher energies up to the relativistic range at electrons and, in very strong events, up to the relativistic range at protons. The resulting energy spectrum takes the power-law form (6), where at big flares $\gamma = 2$ for protons in the maximum phase. For electrons, the value $\gamma = 2$ at the lowest energies increases with the increasing energy due to energy losses the electrons suffer in the atmosphere, and this increase becomes very pronounced in the range of relativistic electrons due to heavy losses caused by magnetic bremsstrahlung. If the acceleration process is not fast enough ($\lesssim 1$ min duration) and/or does not occur in a relatively low magnetic field ($\lesssim 500$ G), there must exist a highenergy cutoff in the electron energy spectrum near the energy of 10 MeV.

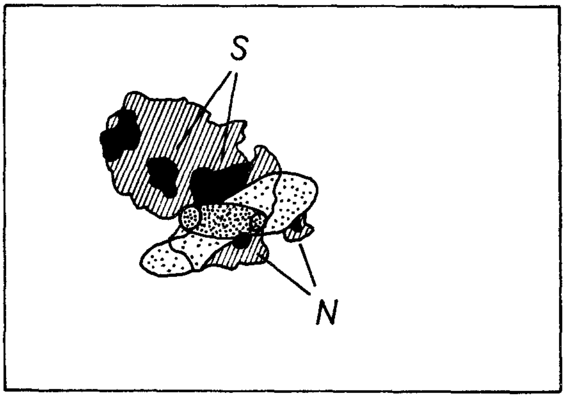

Fig. 5. Schematic drawing of the hot condensation (lightly dotted area) and of the region, where the impulsive acceleration occurred (heavily dotted area) in the flare of 23 May 1967 at about 18^h40^m UT. Analogically to Figure 1 the two circles denote the white-light emission areas. (Compare Figure 1.)

The electrons with energy above ~ 10 keV produce the impulsive hard X-ray burst and the impulsive microwave burst. The total number of electrons with energy above 100 keV is about 10^{36}, which corresponds to 2×10^8 cm^{-3}, i.e. each one of 50 electrons (or protons) in this limited volume is accelerated to an energy exceeding 100 keV.

Protons accelerated to energies above 20 MeV, for which no high-energy cutoff exists below the energy order of 1 GeV, penetrate down to the lowest chromospheric and upper photospheric layers and produce a heating of the atmosphere in the limited bombarded region, which can be observed as short-lived increases of continuous radiation in the UV and optical spectral region. The most intense radiation of this type should be observed near 1400–1500 Å. The occurrence of the white-light emission in the penumbrae of sunspots shows that the limited volume in the condensation, where the impulsive acceleration occurs, is located at the place of the highest magnetic gradient, where two sunspots of opposite magnetic polarity are situated very close one to the other.

This impulsive acceleration phase is fairly short, as well as the associated hard X-ray, microwave, and continuum impulsive bursts. The accelerated electrons penetrating to higher altitudes give rise to the type IV burst up to metric waves, and part of them, as well as the accelerated protons, escape to interplanetary space. The remaining part of electrons is thermalized in the magnetically confined condensation, which reaches its maximum temperature and emissivity a few minutes after the acceleration process, approximately in time coincidence with the flare maximum in the Hα light. The fast separation of the Hα bright flare ribbons indicates that the whole flare region expands during the initial period, and this expansion is slowed down or stopped as soon as the expanding loop system enters the regions of high longitudinal magnetic fields. One cannot exclude the possibility that just this interaction of the expanding flare region with increased longitudinal magnetic component gives rise to the impulsive acceleration process.

After this flash phase the flare begins to decay, so that the whole physically important flare phenomenon seems to be restricted to a fairly short time of the initial phase of the flare development, lasting for less than 10 min.

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