THE TRANSIENT HIGHLY EXCITED
SOLAR FLARE PLASMA

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Abstract. Recent observations of the energetic particles produced in solar flares indicate that the production of electrons, with energies up to about 100 keV, is a fairly common feature of small flares. In those flares the acceleration of protons and other nuclei does not extend beyond about 1 MeV.

The X-ray emission often exhibits two distinct components of which the first one is produced by non-thermal, the second by thermal electrons through bremsstrahlung collisions with the ambient ions. Along with these X rays, radio emission, in the microwave region, is observed. This radio emission is usually interpreted as due to gyrosynchrotron radiation from the same electrons.

In this review a discussion is presented of the processes occurring in solar flares with special reference to the acceleration and radiation processes.

1. Introduction; Composition of the High-Energy Flare Plasma

Solar flare emissions are naturally divided into three separate, although interrelated, categories (see e.g. Bruzek, 1969):

(a) electromagnetic radiation, covering the whole observable spectrum,

(b) energetic particles with energies into the relativistic range,

(c) gas dynamic and magnetohydrodynamic disturbances, propagating through the solar atmosphere and sometimes into the interplanetary medium.

The occurence of energetic radiation and particles, along with the enhanced emission in spectral lines of low excitation potential in the visual part of the solar spectrum, has led to a distinction in the flaring region of two components (e.g. De Jager, 1965, 1969):

(1) The *optical plasma*, which has a temperature of about 10^4 K and electron density up to about 3×10^{13} cm^{-3}, and

(2) the *high-energy flare plasma*, where the temperature exceeds 10^7 K and where the density is about 10^{10} cm^{-3}.

To these two components of the flare, Bruzek (1969) adds a third one:

(3) the *energetic particle flare*, which contains the non-thermal high-energy electrons which are responsible for the impulsive radio and X-ray bursts, but also protons and heavier nuclei.

Considering the three types of emissions mentioned earlier one should add a fourth component for the moving disturbances:

(4) the *propagating flare disturbance*, which may be either observed through its effects on filaments, or other structural details on the solar disk (the so-called Moreton-wave (Moreton, 1960), or as a blast wave in the interplanetary medium (Parker, 1961). This component is probably also related to the radio bursts of spectral type II.

In order to conclude this enumeration of flare components, mention should be made of material ejected; surges, flare puffs, sprays. In this review we will be dealing mainly with the components 2 and 3, to which the term transient highly excited plasma refers.

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As to the third component we will restrict our discussions to those high-energy particles that remain trapped in the flaring region. We will not deal in detail with the plasma clouds, which are something ejected from the flare, e.g. those that give rise to the so-called moving type IV radio bursts.

The region under study then contains two plasma components: the *thermal*, or possibly *quasi-thermal*, and the *supra thermal* plasma, confined by the magnetic field in the active region. In defining these two components we use the same terminology as Blake and House (1971): in a thermal and in a quasi-thermal plasma the velocity distributions of both the ions and the electrons are maxwellian but in the first case $T_e = T_i$, whereas $T_e \neq T_i$ (usually $T_e > T_i$) in the latter case; in a suprathermal plasma the velocity distribution of the electrons (or those of the electrons and the ions) is non-maxwellian. Since most of our knowledge on the high-energy flare is derived from a study of the radiation emitted by the electrons we are unable to distinguish clearly between the thermal and quasi-thermal case.

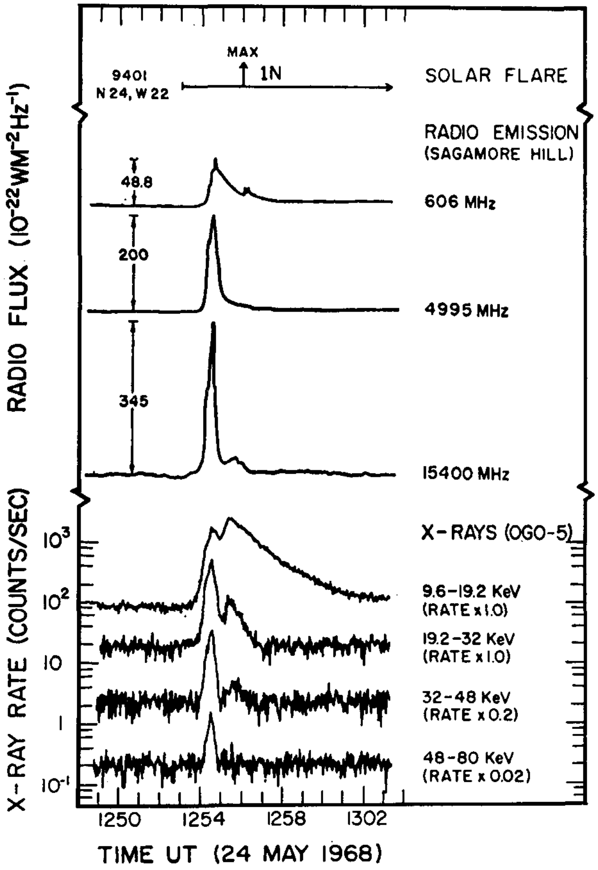
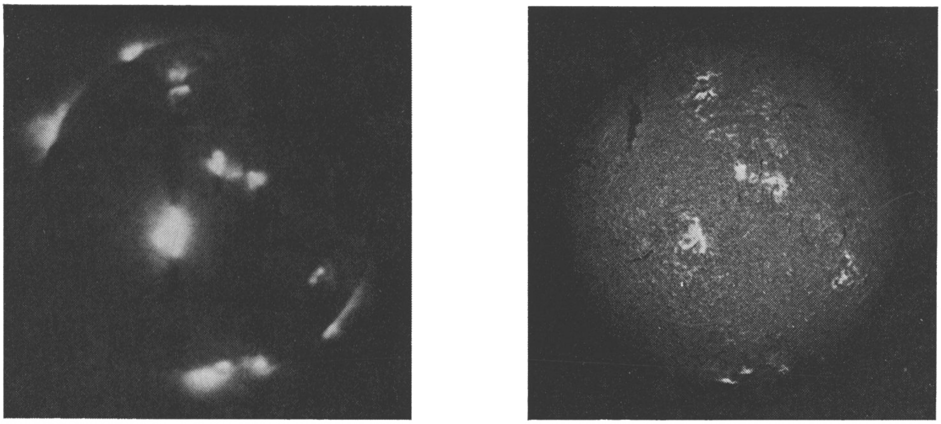


Fig. 1. Combination of observations of X-ray and microwave emission of a small flare on May 24, 1968 (12.54.28 UT). Note the similarity in shape of the impulsive X-ray burst and the impulsive microwave burst (ref. Kane and Anderson, 1970).

From a study of the early observations of X-ray flares De Jager (1965) noted the existence of two classes of X-ray bursts: class I with a lifetime comparable to that of the optical flare and class II, the impulsive bursts, with duration much shorter than the optical flare. He also noted that class I is the common type in the soft X-ray



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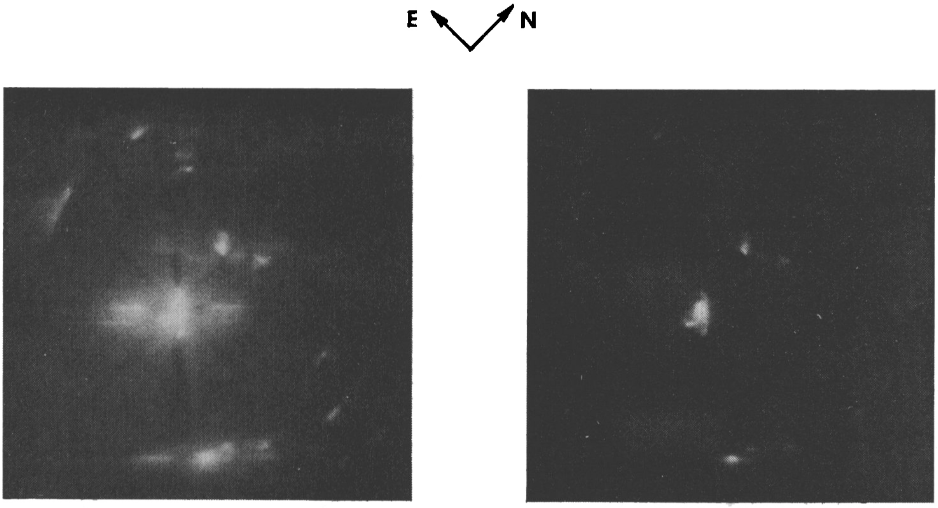
SIMULTANEOUS Hα PHOTOGRAPH
(COURTESY OF ESSA)



SLITLESS SPECTROGRAM
12 MICRON BERYLLIUM FILTER

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X-RAY PHOTOGRAPHS OF THE SUN TAKEN BY A
ROCKET-BORNE X-RAY TELESCOPE ON 8 JUNE 1968.

Fig. 2. Pictures of a small flare in Hα and in soft X rays (3.5–14 Å); June 8, 1968 (17.43 UT). Note the similarity of the flare structures in Hα and in soft X rays (ref. Solar Physics Group, American Science and Engineering).

($\lambda \gtrsim 0.5$ Å) region, and suggested bremsstrahlung of a thermal plasma as the production mechanism, whereas class II is more commonly found at hard X rays ($\lambda \lesssim 0.5$ Å) and bremsstrahlung from jets of energetic electrons might be the mechanism by which they are produced. Only recently (Kane, 1969; Kane and Anderson, 1970; Frost and Dennis, 1971) observations with sufficient time resolution have become available to distinguish clearly between the two components. Earlier spectral observations were obtained with a time resolution of about 15 s (Hudson *et al.*, 1969a, b). Also the spectra derived for both components are consistent with the production mechanisms suggested by De Jager; i.e. a thermal spectrum for class I and a powerlaw energy spectrum for class II.

The microwave bursts show similar characteristics, and in many cases there exists

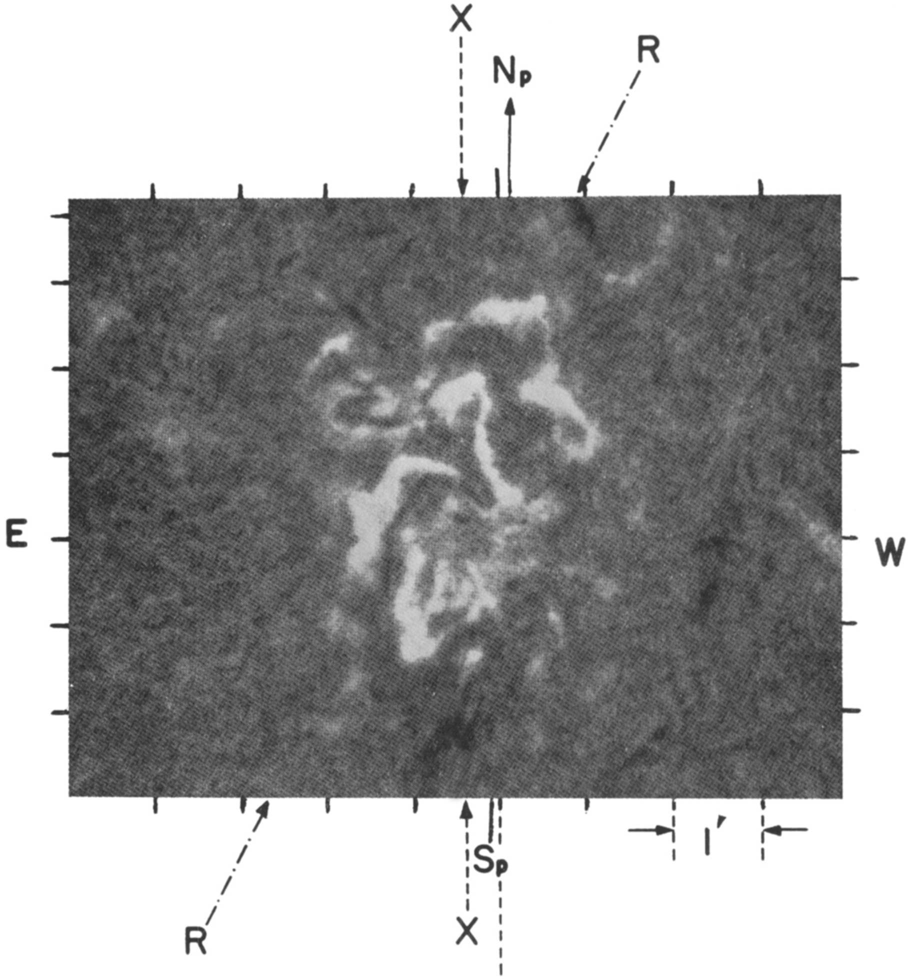

Fig. 3. Hα photograph of flare of September 27, 1969 (03.57.06 UT). with lines indicating the positions of the hard X ray source (20–60 keV) and of the source of the associated microwave burst (ref. Takakura *et al.*, 1971).

a strong correlation between the time profiles of the two types of bursts, as can be seen from Figure 1. The relation between the impulsive bursts in X rays and in microwaves has been extensively studied (e.g. Takakura and Kai, 1966; Snijders, 1968; Takakura, 1969; Holt and Ramaty, 1969) in attempts to derive more information on the suprathermal flare (see also Section 5).

Few observations exist from which positional information on the source region, and of its structure, can be derived. Pictures of a soft X-ray flare, wavelength region 3.5–14 Å, were obtained by Vaiana *et al.* (1968); see Figure 2. These pictures show a close resemblance with the Hα flare. Takakura *et al.* (1971) used a modulation collimator in front of a detector for the region 20–60 keV (0.2–0.6 Å) to determine the position, in one dimension, and the size of a hard X-ray flare. The position line contians a bright knot in Hα not far from the intersection with the position line for the source of the associated microwave burst, derived by Tanaka and Enomé (1971); see Figure 3. Although these observations refer to bursts which did not show the typical impulsive time profiles, they are not inconsistent with the usual assumption that the microwave burst and the hard X-ray burst originate in the same region. The size of the source region, in this case, was 1′, or less.

Polarization measurements of three X-ray flares, at the wavelength region 0.6–1.0 Å, were obtained by means of a Thompson-scattering instrument by Tindo *et al.* (1970). At the initial phases of all three flares polarization was detected, averaging $40\% \pm 20\%$ with a confidence level of 90%. All three flares showed a second maximum, which also emitted partially polarized radiation. More observations have been made with a similar instrument on board the Intercosmos-4 satellite, which confirm the results obtained ealrier, including the prolonged polarization through the second phase of the flare (Tindo *et al.*, 1971). These measurements are indicative of the non-thermal component of the high-energy flare plasma to exist, at least initially, in the form of a directed beam (Korchak, 1967; Elwert, 1968; Elwert and Haug, 1970).

Direct observations of sub-relativistic energetic flare electrons escaping into the interplanetary medium, after their initial discovery by Van Allen and Krimigis (1965), have been extensively discussed by Lin and coworkers (e.g. Lin, 1970a, and Lin, 1970b). The relation of these electron events (energy about 40 keV) with the hard X-ray sources has been investigated by Lin and Hudson (1971). From this study it is concluded that of the accelerated electrons only a minor fraction (0.1 to 1%) can escape from the flare region. Since radiation losses constitute a small fraction of the total energy loss most of the kinetic energy in the electron beam is converted into the heating of the ambient medium through collisions. The escaping electrons are harder than those remaining trapped in the flaring region.

The nucleonic component of the suprathermal particle beam cannot be investigated in the same way as the electron component since nuclei do not radiate X rays and radio waves as efficiently as electrons. It has been suggested that the protons could account for part of the X-ray emission through inverse bremsstrahlung (Boldt and Serlemitsos, 1969); however, these X-rays cannot be distinguished from those produced by electrons, essentially no information on the proton component can be derived from a study of X-ray bursts even if this process would be of importance. Gordon (1954) suggested that the visible flare could be the result of heating of the chromosphere by energetic protons penetrating into these layers. According to Lingenfelter (1969) such a situation would lead to the production of neutrons and γ-ray lines with fluxes detectable at the Earth; moreover there would exist a direct relation between these fluxes and the energy output in the optical spectrum. Since no positive observations of neutrons nor of γ-ray lines have been obtained we are not in a position yet to prove, or disprove, Gordon's suggestion on these grounds. A study of the visible continuum of flares, observed in localized regions of large flares, prompted Švestka (1970) and Najita and Orrall (1970) to conclude that in those cases energetic protons were produced that penetrated into the upper photospheric layers. As was shown by De Feiter and Švestka (1971) fluxes of neutrons and γ-ray lines, detectable near the Earth, will be produced by the same energetic particles that contribute to the heating of the upper photospheric layers through collisions. Assuming this to be an extreme case, in a more general situation, where also protons are accelerated to energies insufficient to penetrate into the photosphere but still sufficiently high and sufficient in number for heating coronal and chromospheric regions to the temperatures required for the production of the thermal X-ray burst, one is tempted to conclude that also protons above ~ 10 MeV are present in the suprathermal beam. On observational grounds however, there is doubt about this. According to Kane and Anderson (1970) the electrons producing the non-thermal X-ray burst do not have energies above 100 keV, at least their spectra steepen considerably beyond that energy. Also, the actually measured electrons, at 1 AU, show such an apparent cut-off (Lin, 1970a; Lin and Hudson, 1971). Besides the low-energy electron events there exist events where relativistic electrons are observed (Meyer and Voigt, 1962; Cline and McDonald, 1968; Datlowe, 1971). Whereas the low-energy electron events are fairly common, the relativistic electrons are observed only concurrently with high-energy proton events (Lin, 1970b). This strongly suggests that in many flares the acceleration does not extend beyond about 100 keV and that this limit holds for protons as well as for electrons. It can also mean that the acceleration process which generates the electrons responsible for the non-thermal X-ray burst does not generate protons above 100 keV, but that this acceleration can be followed by a second process of energization that extends into the relativistic energy domain. Such a two-stage acceleration mechanism has been proposed by Wild *et al.* (1963) and by De Jager (1969). Also more recent X-ray observations favour this two-stage process (Frost and Dennis, 1971).

The above-mentioned observational results are in accordance with a classification of solar flares proposed by Anderson *et al.* (1971). The following three types, of which the characteristic features are summarized in Table I, are distinguished:

(1) Flares which produce no non-thermal particles: 'thermal' flares.

(2) Flares which produce electrons with energies between 10 and 100 keV and no protons above 1 MeV: 'electron' flares.

(3) Flares which produce protons with energies between 1 and 100 MeV, relativistic electrons and heavy nuclei: 'proton' flares.

TABLE I

Characteristics of thermal, electron and proton flares.
(Mainly according to Anderson *et al.* 1971)

Source of Information	Thermal flares	Electron flares	Proton flares
Hα filtergrams	Small area; not especially bright; no flash phase	Small area; bright; flash phase present	Mostly large bright flares, often exhibiting the characteristic two-ribbon structure
X rays	Emission often restricted to the soft X-ray region; no impulsive non-thermal component	Non-thermal impulsive component present especially in hard X rays	Multiple flashes of non-thermal X rays often present
Radio	Weak, or no, type III emission. Slow microwave burst without impulsive component	Often strong type III emission; Impulsive microwave burst No. type II emission	Radio emission of types II, III, IVμ and IVm are often present
Particle emission	No energetic particles	Electrons ~40 keV are observed in interplanetary space if escape conditions are favourable	Relativistic electrons and energetic nuclei are observed in interplanetary space

We propose to refer to these types as θ, ε, and π flares. Although this classification probably oversimplifies the actual situation, it may reflect the existence of three distinct physical processes occurring in solar flares; i.e. (1) heating of chromospheric and coronal regions without explosive phenomena, (2) impulsive acceleration to energies not exceeding ~100 keV, and (3) more gradual acceleration of particles extending, in some cases, into the relativistic energy domain, accompanied, by violent gas movements. The remainder of this paper will be mainly dealing with the electron flares.

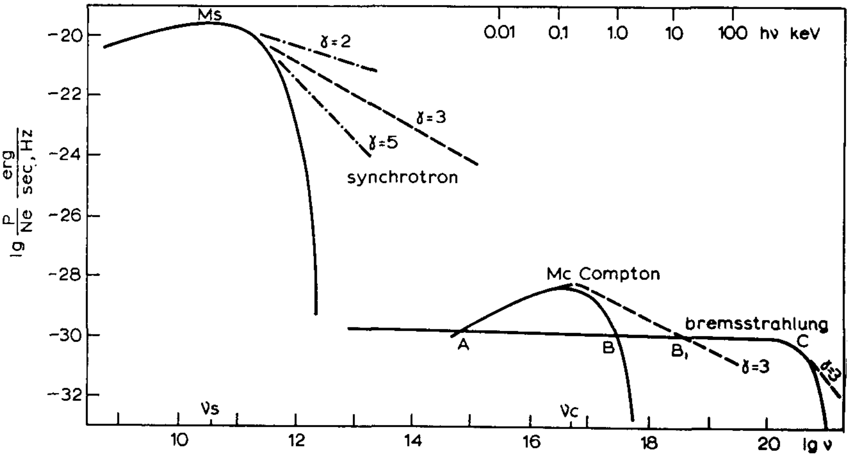

Fig. 4. Radiation mechanisms of importance for solar flares, (ref. Korchak, 1971).

A discussion of the radiation mechanisms of the high energy plasma has recently been published by Korchak (1971). Figure 4 refers to this work. It can be seen that the most important mechanisms are synchrotron radiation and Coulomb bremsstrahlung. The inverse compton effect can be excluded from our considerations, since we will be dealing mainly with low-energy electrons ($E_k \lesssim 100$ keV).

2. Morphology of the Flaring Region

It is very likely that the flare energy, before its outbreak, is stored in the magnetic field through a deviation from its minimum energy configuration. Structures of flares are closely related to those in the magnetic field. Large flares, like those of type π, form near the zero-line of the longitudinal field in the well-known double ribbon configuration. Also bright flare knots occur in regions of strong vertical electric currents (Moreton and Severny, 1968). It is conceivable therefore that the high-energy flare plasma will be confined to regions determined by the magnetic field. The determination of the position and shape of these regions, however, is no easy task. Coronal magnetic fields can, at this moment, only be determined by extrapolating the measured photospheric fields under the assumption of these fields being current free, or at least force free (see Altschuler and Newkirk (1969) for details about this method). The fields derived in this manner can only serve to bring out some similarities in the structures observed on X-ray photographs with those in the fields (Vaiana and Giacconi, 1969).

Since many loop structures, possibly connecting photospheric regions of opposite magnetic polarity, are seen in soft X-ray photographs (Van Speybroeck *et al.*, 1970) a plausible configuration for the confinement of the high-energy flare plasma is in such a loop structure.

It should be noted that this structure only refers to the region where the high-energy plasma is confined; the initial acceleration need not have taken place within this loop. In the model used by Strauss and Papagiannis (1971), which is essentially that discussed by Sturrock (1966) and Sturrock and Smith (1968), the initial disturbance is located in the current sheet along a neutral line formed in the region of open field lines drawn out into the corona by the excess pressure of the solar wind. The energetic particles then are injected into the region of closed field lines. A similar structure has been discussed by Hyder (1967). In Syrovatskii's model the current sheet, in which the disturbance takes place, is a neutral line which may be in a plane perpendicular to the lines of force (Syrovatskii, 1971). From the observations it is not clear, what the actual morphology is and it is not ruled out that it is the magnetic morphology of the flaring region which determines the differences between the ε and the π flares.

3. The Acceleretion Process

The ε flares studied by Kane and Anderson (1970) and by Lin and Hudson (1971) were all associated with small flares, optical importance one or less, since the OGO-5 detectors reached saturation for the larger events. Typically these events show two distinct components, of which the first one has a non-thermal spectrum produced by about 10^{35} electrons with energies between 10 and 100 keV, and the second exhibits a thermal spectrum at a temperature of about 2×10^7 K. The acceleration for the first phase takes place in a time of the order of 10 s, or less. The flare discussed by Frost and Dennis (1971) obviously was of a different character; it displayed two consecutive non-thermal phases, of which the first one has the same characteristics as the impulsive components of small flares. The second phase of this hard X-ray event seems to be associated with a type II metric radio burst, which occurred at the transition of the two components. This seems to indicate that Fermi acceleration, resulting from collisions of electrons with the moving shockfront which also excites the type II burst, can provide the electrons producing the second non-thermal phase. It is not clear to what extent this flare is representative of a particular type where a two-stage acceleration does take place. In order to be conclusive in this respect more observations are needed.

The apparent cut-off in the spectrum of the electrons producing the non-thermal impulsive burst, at about 100 keV, and the absence of high-energy protons in the beam of energetic particles observed in association with hard X-ray events is indicative of acceleration by an electric field. A possible mechanism for this acceleration can be the process of current interruption proposed by Alfvén and Carlqvist (1967) and further discussed by Carlqvist (1969) and Stenflo (1969). In this hypothesis, an interruption of the current through a loop can occur, where the plasma density drops below a critical value. For a current of I ampère, an inductance of the loop of L Henry an acceleration in a time τ can occur to energy

$$V = L(I/\tau) \text{ eV}. \tag{1}$$

The total energy produced is given by

$$W = \tfrac{1}{2}LI^2 \quad \text{Joule}. \tag{2}$$

For the impulsive event of May 25, 1968, the total kinetic energy of the electrons was 6×10^{27} erg (Kane and Anderson, 1970). With $\tau = 10$ s, $V = 100$ kV, we find: $I = 10^{15}$ A and $L = 10^{-9}$ Henry. These values are completely out of order since this low value of the inductance would correspond to a loop with a diameter of 1 cm only. Takakura (1971) considers currents around the edge of thin filaments (Skin-effect). By a process analogous to that of Alfvén-Carlqvist he obtains more realistic values of the currents and inductance needed for the acceleration process here discussed. Another estimate of the electric field can be obtained from a consideration of the run-away electrons. According to Kahler and Kreplin (1971) the energy of the electrons that can be accelerated by an electric field E_f in a plasma of density n should exceed a critical value

$$E_c = 7.8 \times 10^{-15}(n/E_f), \tag{3}$$

Where E_c is in keV and E_f in $V \text{ cm}^{-1}$ (cf. also Spitzer, 1962). In order to accelerate a fraction α of the electrons from a thermal distribution at a temperature T, E_c should be below a value E_1 given by

$$\left(\frac{E_1}{kT}\right)^{3/2} \gamma^*\left(\frac{3}{2}, \frac{E_1}{kT}\right) = 1 - \alpha, \tag{4}$$

where $\gamma^*(3/2, E_1/kT)$ is a function related to the incomplete gamma function (1964, Abramowitz and Stegun). For $T = 10^6$ K and $\alpha = 10^{-3}$, we find $E_1 \sim 2kT \simeq 0.2$ keV. Hence

$$E_f/n = 4 \times 10^{-14} \text{ V cm}^2 \tag{5}$$

The cross-section of the volume from which 10^{35} energetic electrons can be accelerated is independent of the density, as can be easily seen; its value is 4×10^{19} cm^2. Only at coronal heights the volume, in which the acceleration supposedly takes place, is stretched; at lower levels the configuration so-derived resembles more that of a huge flat condensor (see Table II).

TABLE II

Minimum electric field strength, E_f, length, l, and magnetic fieldstrength, B, in the accelerating region as a function of height in the solar atmosphere, specified by the density n

n (cm^{-3})	E_f (V cm^{-1})	l (cm)	B (G)
10^8	4×10^{-6}	2.5×10^{10}	14
10^{10}	4×10^{-4}	2.5×10^8	140
10^{12}	4×10^{-2}	2.5×10^6	1400

It is interesting to compare this result with Alfvén's discussion of the properties of magnetospheric neutral surfaces (Alfvén, 1968), in which a comparison is made with a flat condensor. It is shown that the current density derived from Maxwell's equation equals the drift current, due to the crossed electric and magnetic fields, provided the following equation holds

$$B^2 = 4\pi neV_0 . \tag{6}$$

Here B is the magnetic field strength near the neutral surface, n is the gas density, V_0 is the electric potential difference between the plates and e is the electron charge. Using the values $n = 10^{10}$ cm^{-2}, $V_0 = 10^5$ V, we find $B = 140$ G, which is a reasonable value.

These results indicate that the acceleration mechanism in the first phase of the ε flares possibly is a discharge near a neutral sheet (see also Syrovatskii, 1971).

4. The High-Energy Plasma

Our discussions thusfar indicate that during the impulsive phase of a flare acceleration occurs which produces about 10^{35} electrons of energies between 10 and 100 keV, in a volume which is conservatively estimated at 10^{28} cm^3. At the same time ions should also be accelerated but their energies probably do not exceed those of the electrons. We will now discuss the properties of this energetic particle beam, its interaction with the ambient medium and its consequent evolution in time.

4.1. THE NON-THERMAL PHASE

The spectrum of the energetic electrons, producing the hard X-ray impulsive burst, can be approximated by a power-law with exponent -3. According to Brown (1971) one should be careful in deducing the properties of the accelerated electron beam from its radiation effects, when it is likely that the acceleration operates for most of the duration of the impulsive burst (10–20 s). In the continuous injection model, where the time profile of the X-ray burst reflects the evolution of the acceleration process, the energy losses suffered by the electrons produce an apparent softening of the spectrum of the electrons in the emission region as compared to that of the energetic electrons produced in the acceleration region.

The following energy-loss mechanisms have been investigated in this connection:

(a) Collective plasma effects; according to Brown a dilute beam of high-energy electrons, of number density equal to a fraction λ of the ambient density looses a fraction $\lambda^{1/3}$ of its energy in heating the ambient plasma. If our previous estimates are correct, $\lambda = 10^{-3}$, and hence only 10% of the beam energy is lost through collective plasma effects.

(b) Gyrosynchrotron radiation losses; for non-relativistic electrons the lifetime against gyrosynchrotron losses is given by

$$\tau_{gs} \simeq 2.64 \times 10^8 B^{-2} \quad \mathrm{s}, \tag{7}$$

where B is the magnetic field strength in Gauss. This lifetime is long as compared to the duration of the impulsive burst for $B \lesssim 10^4$ G, which condition is certainly fullfiled.

(c) Collisional losses; of these the electron-electron collisions are most effective. According to Rossi and Olbert (1970) the slowing down time for electrons of energy E keV in a medium of density n and temperature T is

$$\tau_{E,\,\mathrm{sl}} \simeq 2.2 \times 10^9 \frac{E^{3/2}}{n \ln \Lambda} \quad \mathrm{s}, \tag{8}$$

where $\ln \Lambda$ is the well-known Coulomb logarithm; its value is about 20. The slowing down time, for $n = 10^{10}$ cm^{-3}, is 0.25 s and 7.5 s for 10 keV and 100 keV electrons respectively. This calculation shows that collisions with ambient electrons provide the most effective energy losses for the electron beam. A continuous supply of accelerated electrons may be required in order to account for the observed duration of the impulsive X-ray burst. In that case the effects on the distribution function of the energetic electrons discussed by Brown (1971) should be taken into account.

The observed polarization of the X-ray burst calls for a directionally anisotropic beam of electrons. The time needed for an appreciable widening of this beam through scattering with ambient electrons, $\tau_{E,S}$, is related to the slowing-down time by

$$\tau_{E,S} \approx \tfrac{3}{4} \tau_{E,\,\mathrm{sl}} \tag{9}$$

(Rossi and Olbert, 1970). This time ranges from 0.4 s to 12 s in the energy interval considered. Taking into account that the observations were obtained at about 10 keV, the observed polarization can only be accounted for if the acceleration process is operative during the whole impulsive phase with essentially no variation of the direction in which the energetic electrons are injected.

4.2. THE THERMAL PHASE

The energy of the accelerated electrons is virtually completely converted into heating of the ambient plasma through electron-electron collisions and, for a small fraction, through the excitation of cooperative plasma waves. To this heating a significant contribution may be delivered by the accelerated ions; the lack of observational data on this component of the supra thermal plasma at the source, makes it impossible, as yet, to asses this contribution reliably. Anderson *et al.* (1971) estimate that the kinetic energy of the fast electrons of a small, bright flare is 3×10^{28} erg, whereas the total energy expended in that flare is estimated as 10^{29} erg. Judging from these figures, and taking into account the uncertainties due to our lack of knowledge of the time during which the acceleration is operative and of the amount of energy imparted to the accelerated ions, the hypothesis, that essentially all energy emitted by the ε flares can be derived from the initial acceleration process, cannot be ruled out (see also Brown, 1971). On the other hand, however, the processes of direct heating of the flare plasma without impulsive acceleration needs further study, in particular for the θ flares. Let us suppose that the energy supply to the flare region is stopped after the impulsive acceleration and discuss the evolution of the flare emission from there on. As was discussed earlier the maxwellization of the accelerated electrons proceeds fairly rapidly. The kinetic temperature of the electrons can be computed from the relation:

$$T_e = E_k / C_p n_e^* V, \tag{10}$$

where E_k is the kinetic energy of the supra thermal electrons, $C_p \approx \frac{5}{2}k$, and $n_e^* V$ is the total number of accelerated electrons. With $E_k = 3 \times 10^{28}$ erg, $n_e^* V = 10^{35}$ electrons we find $T_e = 10^9$ K, while the emission measure, at this stage, is 10^{45} cm^{-3}. Due to collisions with the ambient electron the energy E_k is distributed over a larger number of electrons, hence increasing the emission measure and correspondingly decreasing the electron temperature. The exact run of temperature and emission measure with time depends greatly on the structure of the region where the acceleration took place. Up till now we have only considered a homogeneous model. In that case the thermalisation of the plasma can proceed fairly quickly, reaching an equilibrium temperature of all the eletrons in the volume of 10^6 K in some 10 s. The emission measure would then become 10^{48} cm^{-3}. If, on the other hand, the acceleration takes place in a number of filaments, in which all electrons are accelerated, the exchange of energy with the ambient plasma proceeds much more slowly. For filaments aligned along the magnetic field lines the energy transport can only take place by heat conduction through the bounding surfaces perpendicular to the magnetic field (Culhane *et al.*, 1970). Within the filaments electron-proton collisions accomplish a thermal equilibrium of the whole plasma at a rate which is about a factor of three slower than electron-electron collisions. According to computations made by Syrovatskii and Shmeleva (1972), the heating of an inhomogeneous region by accelerated flare electrons may satisfactorily explain the observations in the optical and soft X-ray region.

5. Relation with Other Flare Phenomena

Since the discovery of the hard X-ray bursts, by Peterson and Winckler (1958 and 1959), the relation between this flare emission and that in the microwave region has been noted and studied extensively. Attempts to reconcile the X-ray and microwave emissions in term of radiation from the same electrons, the first produced by Coulomb bremsstrahlung and the latter by gyrosynchrotron radiation, meets with the difficulty that 10^3–10^4 more electrons are required for the production of the X-ray burst than for the microwave burst. Two different, but to some extent complementary, explanations of this apparent discrepancy have been presented:

(1) According to Takakura and Kai (1966) the sources of the two types of bursts are different, although the electrons in both source regions have been accelerated at the same time. The major part of the X-ray producing electrons is trapped in a region below the level where the plasma frequency equals the highest frequency observed in the microwave burst; i.e. the radio emission of these electrons cannot escape from the source region. In addition the radio emission from the electrons above, but near, the critical level will be absorbed by the overlying coronal layers. Taking $f = 3000$ MHz as the limiting frequency, the source of the X-ray burst should, according to this picture, be below a level where $n_e \simeq 10^{11}\ \mathrm{cm}^{-3}$.

(2) Holt and Ramaty (1969) argue that it is the absorption of the energetic electrons themselves which makes the source region of the microwave burst opaque to its own radiation. This gyrosynchrotron absorption has been discussed by Ginzburg and Syrovatskii (1969). In addition the interaction of the radiating electrons with the ambient plasma greatly reduces the emissivity of the electrons by the so-called Razin-effect.

In both papers the theoretical considerations are applied to observations of big flares. It seems of interest to perform the same analysis on the more detailed observations of small X-ray flares that have become available.

6. Concluding Remarks

In this review we have discussed some recent developments in the interpretation and the theory of the flare plasma that emits strongly in the X-ray and microwave regions of the spectrum. For two reasons we have concentrated on the rather small flares of the ε type; firstly because important new observational material on this type of flares has become available and secondly because we believe that a study of small flares will be more promising to reveal the important physical processes operative in solar flares. We have not been able to derive a completely consistent picture of the development of a small flare; for this to come within our reach more and better observations are still needed. In this connection mention should be made of the proposed international observing campaign for 1972, CINOF. Of special importance are those observations which provide information on the structure of the flaring region and of the pervading magnetic field.

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DISCUSSION

B. S. Fraenkel: The Cosmos experiment shows polarization of X rays in small flares. Could a possible explanation be that in big flares you have many directions of motion?

L. D. de Feiter: It may very well be that in big flares jets of electrons are accelerated in many different directions, which render the total radiation unpolarized. What astonishes me in the observations with the Cosmos experiment is that the emission in the second part of the flare, which supposedly is thermal, also shows a large degree of polarization.

E. Haug: You have given a collision life time of 8 s. This time is, however, strongly dependent on the electron energy. Which energy did you consider? It is possible that the duration of the impulsive phase of hard X-ray bursts is limited by escape losses. In calculating the contributions of Synchrotron radiation, inverse Compton effect and of bremsstrahlung, Korchak used an electron spectrum in the form of a power-law with a low-energy cut-off at $E_1 = 5$ MeV. Without this cut-off the relative contribution of bremsstrahlung to X radiation would predominate throughout.

L. D. de Feiter: The time for spreading of the electron beam is indeed strongly dependent on the electron energy; the figure quoted refers to about 100 keV electron energy. The escape of electrons does not seem to play an important role in the configuration discussed in this paper. I fully agree with your remark on the predominance of gyrosynchrotron radiation and Coulomb bremsstrahlung.

S. R. Kane: Could you comment on the acceleration time for electrons during the impulsive X-ray bursts? This may be relevant to the question asked earlier by Dr Haug.

L. D. de Feiter: The acceleration time for the electrons may be as long as the duration of the impulsive burst itself; I do not think that the comparison of the relaxation times quoted in the paper with the duration of the impulsive burst allows us to set a definite limit.

Z. Švestka: I agree in principle with the classification you propose: flares without any impulsive non-thermal acceleration (θ), flares with impulsive acceleration to ~ 100 keV (ε), and flares with acceleration to high energies (π). I think, however, that the case θ should be associated with the non-thermal X-ray burst, not with the 'preflare heating', since – and I believe Kane can confirm it – this 'preflare heating' is quite a common phenomenon; quite usually the impulsive burst starts after the non-thermal slow burst began to develop. Further, I believe that the 'slow non-thermal' event you mention as typical for case ε, was quite an exceptional phenomenon. There are many flares which only produce the impulsive hard X-ray burst and the gradual soft burst without any slow hard X-ray component (at least above 80 keV), and they still are sources of very powerful streams of high-energy protons and relativistic electrons in space. For example, as far as I remember, the flares of July 7 and August 28, 1966.

L. D. de Feiter: The association of the preflare heating with the case θ seems quite logical to me; I would be inclined, though, to refer to those cases as a combination of cases ε and θ, which also may occur separately. In discussing the slow non-thermal burst in hard X rays I also meant to indicate that this was a very exceptional case. At energies of 10–20 keV, which one would consider to be in the transition between the soft and hard X-ray region, the impulsive component is often followed by a slow thermal component. I agree that the maximum of this thermal component will be found in the soft X-ray region.

I hesitate to comment on your examples, since those events were really big ones.